Fire safety management and risk assessment

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Keywords

Fire, Risk management, Quantitative modelling, Probability

Abstract

The paper discusses the problems encountered in the management and quantitative evaluation of fire risk and safety in a building. Rational methods for obtaining solutions to these problems are provided by non-deterministic mathematical models rather than deterministic models. This is due to the fact that the occurrence and spread of an accidental (not arson) fire are random phenomena affected by uncertainties caused by several factors. Non-deterministic models discussed briefly in the paper include simple statistical and probabilistic models, regression methods, probability distributions, fault and event trees and stochastic models. The paper only provides a framework for applying these models to any type of facility. For any type, it may be necessary to modify these techniques, collect all the relevant data and perform the analyses to derive results and conclusions applicable to that type.

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Facilities
Volume 17 · Number 9/10 · 1999 · pp. 363–376
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Introduction

Fires cause fatal and non-fatal injuries to occupants of buildings and inflict direct material damage to the buildings and their contents. Some fires also cause indirect/consequential losses such as loss of production, profits, employment and exports although, at the national level, these losses do not contribute significantly to total fire loss. This is due to the fact that the loss of a specific unit of productive capacity may be spread among the remaining capacity in the nation. Every year, fires in the UK kill about 800 people and cause non-fatal injuries to 15,000. On average per year, the direct material damage is about £1,200 million and the indirect loss is about £120 million. The direct and indirect losses in the UK represent about 0.21 per cent of the gross domestic product (GDP).

In order to reduce the national wastage due to fires, individuals, organisations and the Government have a clear duty to manage or control the risk posed by fires. The actions taken by the Government for this purpose include fire safety regulations, legislative measures, codes and standards, provision of fire cover by fire brigades, and education and publicity campaigns. A recent Government action in the UK is the Fire Precautions (Workplace) Regulations which came into force on 1 December 1997. Major industrial and commercial firms have already developed schemes for managing fire risk by reducing the frequency of occurrence of fires and the damage to life and property when a fire occurs. The objective of this paper is to discuss briefly the basic features of these schemes and suggest improved methods for risk management.

Fire safety management

Safety is the complement or antithesis of risk. Safety will be increased if the risk is reduced. There is no such thing as absolute safety. Some level of fire risk is virtually unavoidable. A building may be considered to be "very safe" from fire if a sufficiently "low fire risk" is associated with its structure, contents and occupants. The axioms mentioned above are listed in Table I.

The objective of fire safety/risk management is therefore to reduce risk to life and

Table I Fire risk and safety

Fire risk may be defined as the chance for damage to life and property associated with the occurrence of fire.
Some level of fire risk is virtually unavoidable.
Safety is the complement or antithesis of risk.
There is no such thing as absolute safety.
A building may be considered to be "very safe" from fire when a sufficiently "low fire risk" is associated with its structure, contents and occupants.
Fire safety codes, regulations and standards can prescribe an "acceptable level" for fire risk or safety.
However, absolute compliance with any such preset goal is impossible.

property to very low levels acceptable to a property owner and society at large. This aim can be achieved by carrying out fire prevention activities which would reduce the frequency of fires significantly and installing passive and active fire protection measures which would minimise the damage when the fire occurs. By effective maintenance, it is necessary to ensure that, when a fire occurs, all the safety measures provided will be available for use and will perform satisfactorily. It is also necessary to provide adequate fire insurance cover for direct and consequential losses.

The fire prevention, protection and insurance measures mentioned above are to be undertaken before the occurrence of any fire in a building. When a fire occurs, appropriate actions planned well in advance should be initiated to provide all the help and assistance for occupants to reach places of safety inside or outside the building involved in the fire. These include fire drills and staff training in the use of first-aid fire-fighting methods such as fire extinguishers. Actions to be taken after a fire is extinguished include salvage operations, repairs to parts of the building damaged by the fire and submission of claim for insurance compensation. These actions are to ensure that the activity interrupted by the fire is restarted as soon as possible.

Management of fire safety/risk (as shown in Table II) involves three main tasks: risk evaluation, risk reduction and risk transfer. Risk identification and risk quantification are the two components of the first task. These four tasks are discussed in detail in the following sections, with particular reference to workplaces.

Table II Management of fire risk

1 **Risk evaluation**
- Risk identification
  General and special factors
- Risk quantification
  - Probability of fire starting
  - Probable damage in a fire

2 **Risk reduction**
- Reducing the frequency of fire occurrence
  - Publicity, education, smoking lobbies, etc.
- Reducing damage in the event of fire
  - Structural fire protection, automatic detectors, sprinklers, smoke ventilation systems, fire drills, etc.

3 **Risk transfer**
- Full insurance
- Part self-insurance (deductible) plus part insurance

Risk identification

This task involves first the identification or enumeration of general or common factors likely to enhance fire risk. These include potential sources of ignition likely to initiate the starting of fires and materials or objects which can contribute to a rapid spread of fire, smoke and toxic gases. Construction of a building can also contribute to rapid fire spread. Second, the presence or absence of certain fire protection measures which can reduce the risk of fire spread should be identified.

The next step is to identify special factors affecting or contributing to fire risk in certain types of buildings. Examples of the factors mentioned above are given in Table III. These factors are generally known as hazards.

A property should be subdivided into different parts which may have different risk factors and the factors identified for each part. Three major parts of an industrial building are production area, storage area and "other" areas (office rooms, etc.). A department store may be subdivided into assembly or customer area, storage area and another areas. The risk identification process will be facilitated by designing a set of forms incorporating all items which could affect fire risk in the particular property considered. These forms should be completed for each major part of the property by a physical inspection of the property, preferably by a fire surveyor or fire safety engineer.

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

Table III Risk identification

A Causes or sources of ignition
- Careless disposal of smoking materials
- Misuse of, defects in and defective wiring to electrical appliances or equipment
- Defects in multi-point adaptors in electrical sockets
- Flame or spark from a work process, e.g. cutting, welding and grinding

B Factors contributing to rapid flame spread
- Flammable substances or combustible materials or objects, e.g. polyurethane upholstered settee
- Materials used in the construction and lining of roof, walls and ceilings and construction and covering of floors, e.g. hardboard, chipboard, blockboard, plastic ceiling or wall tiles
- Constructional features: prefabricated buildings or temporary structures built from untreated timber or lined with hardboard or other non fire-resisting boarding

C Special factors
- Highly flammable liquids
- Materials ignitable even by a low energy smouldering source, e.g. latex foam, finely powdered rubber
- Number of occupants in a building and their location
- Number of very young, elderly and disabled people

D Fire prevention measures – lack of:
- Smoking lobbies
- Frequent disposal of rubbish materials

E Fire protection measures – absence or inadequate maintenance of:
- Fire detection systems, sprinklers, smoke ventilation systems, fire doors, fire extinguishers

F Action during a fire – lack of:
- Fire drills
- Fire instruction notices
- Staff training
- Fire emergency plan

Qualitative risk assessment

The information contained in the forms mentioned above would enable the user to carry out a qualitative evaluation of fire risk for each major part of a building. The objective of this exercise is to assess the likelihood of a fire or number of fires which may occur over a period and the damage to life and property expected in each fire. A range of fire scenarios may be considered for this purpose.

If necessary, the forms may be split into worksheets dealing with different aspects such as ignition sources, flammable substances, building construction, means of escape facilities, active fire protection systems, fire prevention measures and so on. Examples of worksheets are contained in the document "Fire Precautions (Workplace) Regulations" which came into force on 1 December 1997. The worksheets can contain questions to which "yes" or "no" answers may be given. Based on the answers in different worksheets a qualitative assessment may be made to arrive at a fire risk categorisation of each part of a property as low, normal or high fire risk. The assessment should be carried out separately for life risk and property damage. Multiple fatality would be a high risk for life safety and a large fire a high risk for property damage. The risk assessment scheme discussed above will be a straightforward and simple procedure for most of the buildings. Large and complex buildings would require the advice of a specialist.

Points scheme (Ramachandran, 1982)

The qualitative risk assessment procedure can be improved by assigning points or scores to answers to questions in a worksheet with the numerical values of the scores increasing with the level of risk. A low value will be assigned to the presence of a fire protection measure such as sprinklers in the corresponding worksheet. The scores would also depend on whether life safety or property damage were being considered. The scores may be on a scale ranging from zero to ten, to 20 or to 100 depending on the accuracy with which the risk is required to be assessed. The scores for answers to questions in each worksheet may

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

be added to give the total score for the worksheet.

The final or overall total score for the part of the property considered for, say, life safety is obtained by adding the corresponding total scores for the different worksheets. A final total score less than a threshold level may indicate a low fire risk while a score greater than a higher threshold would indicate a high risk. A score between these two threshold levels would indicate a normal fire risk.

The qualitative risk assessment technique described above may be further refined by carrying out the risk categorisation separately for the likelihood (L) of a fire occurring and the likely consequences (C) if a fire occurs. The consequences may be considered in terms of life risk or property damage. The next step is to combine L and C to provide a joint measure of the risk. Let the subscripts S, N and H denote respectively the three risk categories low, normal and high based on the overall total score for all the worksheets. Combining these with L and C, nine risk categories provided by a 3×3 matrix may now be identified as shown in Table IV.

The combination $L_S C_S$ denotes the lowest risk since the risk is low in regard to both the likelihood of fire starting and the likely consequences. Likewise, the combination $L_N C_N$ would denote a normal risk and $L_H C_H$ the highest risk. A building categorised as $L_S C_H$ would have a small chance of a fire starting but the consequences are likely to be high when a fire occurs. On the other hand, a building categorised as $L_H C_S$ may have fires frequently but none of these fires are likely to lead to serious consequences. The nine risk categories generated by the combinations of the three basic risk categories S, N and H with L and C can be classified into the three categories low, normal and high as suggested in Table IV.

Table IV Refined risk categorisation technique

Likelihood or frequency of fire occurring		–	**L**
Likely consequences if a fire occurs		–	**C**
Basic risk categories	Low	–	**S**
	Normal	–	**N**
	High	–	**H**

Combined risk categories:

L_S C_S	–	Low frequency, low consequences
L_S C_N	–	Low frequency, normal consequences
L_S C_H	–	Low frequency, high consequences
L_N C_S	–	Normal frequency, low consequences
L_N C_N	–	Normal frequency, normal consequences
L_N C_H	–	Normal frequency, high consequences
L_H C_S	–	High frequency, low consequences
L_H C_N	–	High frequency, normal consequences
L_H C_H	–	High frequency, high consequences

Risk categorisation of combined categories:

Low: L_S C_S, L_S C_N, L_N C_S

Normal: L_N C_N, L_H C_S

High: L_S C_H, L_N C_H, L_H C_H, L_H C_N

Border cases: L_H C_S may be categorised as low risk
L_H C_N may be categorised as normal risk

Gretener method

In this method (Gretener, 1968), which is essentially a points scheme, the following formula is used:

$$R = \frac{P.A.}{N.S.F.} \qquad (1)$$

where R is a numerical measure of fire risk. The P factors include fire load, combustibility, potential ground surface area of a fire, building height and tendency to produce smoke, toxic and corrosive gases; these characterise the inherent hazard of the building. The factor A measures the propensity of a fire to start. The factor N refers to "normal" fire precautions such as fire brigade and water supplies. The S factors are concerned with "special" protective measures such as automatic fire detection systems and sprinklers and F denotes the fire resistance of the building. For a given building, the factors P, A, N, S and F and their components are enumerated and points assigned to them to reflect their relative contribution in enhancing or reducing fire risk.

Merits and demerits of points schemes

Points schemes are simple analytical tools which are easy to develop and apply in risk assessment problems. They provide qualitative indicators of relative fire risk which may be useful for comparing the risk level in a particular building or part of the building against a "norm" and identifying areas requiring actions to improve fire safety. However, for the reasons listed in Table V, points schemes do not constitute a rigorous approach to fire risk evaluation. More accurate and quantitative estimates of fire risk are provided by mathematical models which are discussed later in this paper.

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

Table V Demerits of points schemes

- Highly empirical
- Allocation of points to answers to question is somewhat arbitrary or subjective
- The overall total points for a building or part of a building is usually calculated by simply adding the total points for different worksheets. This is tantamount to applying equal weights to the points for the worksheets. This procedure is somewhat fallible. The totals for the worksheets should be assigned weights depending on the relative importance of the safety aspect concerned with each worksheet to the likelihood of fire starting or to likely damage in the event of a fire occurring
- Points schemes do not take into account interactions between fire safety measures
- Points schemes do not consider sufficiently statistical information on real fires although it might be argued that such data are consciously present in the minds of those applying the schemes or in the allocation of points
- Points schemes cannot provide quantitative estimates of fire risk required for cost-benefit analyses of fire safety measures

Risk reduction

For any building or part of the building, if an assessment scheme indicates a risk level for life safety or property damage which exceeds an acceptable limit, adoption of additional fire safety measures should be considered for reducing the risk to a level below the acceptable limit specified. In a qualitative analysis "high" risk should be reduced to a "normal" or, if possible, to a "low" level. Possible actions in this respect are listed in Table VI. For facilitating these safety actions to be carried out promptly, an inspection check-list may be maintained for each item showing dates of inspection, defects or faults observed and remedial work carried out. For fire drills, the dates when these exercises were staged should be recorded together with the estimated times taken to evacuate all the occupants to places of safety.

Details of staff training in fire safety matters should also be recorded and assessed for identifying areas requiring improvement. The staff should be trained in the execution of a fire emergency plan when a fire occurs. This plan, prepared in advance, would include tasks such as informing the fire brigade, attacking the fire with first-aid means such as buckets of water or sand and fire extinguishers and assisting the fire brigade.

After some or all of the risk reduction strategies are implemented, the risk should be re-evaluated to ensure that it has been reduced to an acceptable level. If this has not been achieved, additional risk reduction

Table VI Possible actions for risk reduction

Examples	
Short-term measures	
1	Reducing the stock of flammable substances or combustible materials
2	Improving the general housekeeping
3	Reducing the risk of fire from smoking materials
4	Frequent disposal of waste and rubbish
5	Checking whether electrical fuses are suitable for the purpose
6	Improving fire safety information, training and instruction for employees
Long-term measures	
1	Replacing flammable substances and combustible materials by suitable alternatives
2	Replacing open fires or radiant heaters with fixed convector heaters or a central heating system
3	Filling-in openings in floors and partitions to prevent the rapid spread of smoke
4	Cleaning oil-soaked timber floors
5	Removing flammable linings or ceiling tiles
6	Continuing to replace materials and processes by others of a lower fire risk
7	Replacing old or damaged upholstered furniture
8	Considering the installation of automatic fire detection systems and sprinklers
9	Keeping highly flammable substances or combustible materials in specially constructed stores segregated from the main building

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

strategies should be identified and implemented. It should be recognised that the final risk category can only be based on existing fire safety measures, not on those planned for the future. The fire risk assessment is not a one-off procedure. It should be carried out periodically to ensure that the risk is maintained at a low or normal level.

Risk transfer

Even after all the necessary fire safety strategies are implemented, there will be a small chance of a large fire occurring which might seriously disrupt or even bankrupt a business or industrial activity. Hence it will be prudent to transfer this risk to an insurance company by providing insurance cover for direct and consequential loss. This protection strategy converts an uncertain loss into a known cost, the premium payable at a certain date. Some property owners may take risk to make self-insurance provisions in their financial planning for losses up to a deductible level and only insure for losses exceeding this level. It would be economically worthwhile to consider this self-insurance plus insurance strategy particularly for a property provided with adequate fire safety measures.

Mathematical models

Unlike points schemes, mathematical models provide quantitative assessments of extent of spread of fire and smoke in a building of given characteristics. These models are of two main types: deterministic and non-deterministic. The fundamental features distinguishing these two types are mentioned in Table VII.

Only basic features of deterministic models are described in the next section. A detailed discussion about these models is beyond the scope of this paper. This paper discusses in some details non-deterministic (probabilistic and stochastic) models and statistical techniques applicable to fire risk assessment. A short course on probabilistic evaluation of fire risk has been planned to be held in the University of Leeds in November 1999. A book on this subject is currently being written by Ramachandran for publication in the year 2000.

Deterministic models

Several types of deterministic models are widely used in fire safety engineering in conjunction with scientific theories and experimental studies. Each type places the emphasis on a particular aspect of fire and tends to simplify or neglect the complementary aspects. Models must therefore be selected carefully according to the nature of the problem considered. Deterministic models are mainly of two types: field models and zone models.

Field models are mainly concerned with the flow of air and smoke in an enclosure under the influence of heat and gravity. They are based on fluid dynamics theory and provide an accurate representation of energy and mass flow but it is difficult to incorporate the effects of radiation and the chemical fire reactions within the same framework. They take "first principles" approach in solving classical Navier-Stokes equations of motion for the gas phase at many discrete points in space and time. Hence they are generally applicable to a wide range of scenarios. Field models led to the development of the computer program JASMINE by the Fire Research Station to predict the movement of smoke in single and multi-compartment enclosures.

Zone models emphasise the geometry of the room in which the fire takes place and details of the objects in the room including their size, location and composition. The space within the room is divided into zones or layers in which conditions such as temperature and product concentrations are assumed to be homogeneous. As the model runs, the fire spreads from one object to another according to pre-assigned parameters. From these, the temperature and smoke density prevailing in each zone can be calculated. Zone models are generally problem specific and hence only applicable to a limited range of fire scenarios. The computer program FAST developed by the National Institute of Standards and Technology, USA is based on a zone model.

Simulation models constitute the third type of mathematical models used in a quantitative assessment of fire risk. Both deterministic and non-deterministic models and their combinations can be used to develop computer software packages for predicting various fire scenarios and estimating their consequences in terms of mean or extreme (worst-case) values.

A simulation model can be used to perform probabilistic (Monte Carlo) simulations. It permits all the critical factors, processes and events that characterise a real system to be internally represented so that alternative

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

Table VII Deterministic and non-deterministic models

Deterministic models (e.g. zone, field)

1. Using functional relationships derived from scientific theories, a deterministic model predicts the pattern of fire growth and smoke spread for a particular fire scenario in exact terms. This is unrealistic since several factors cause uncertainties in real fires and generate several possible scenarios. Deterministic models cannot quantify these uncertainties although time-consuming and costly simulations based on these models would depict the variations in the patterns of fire development. The models do not estimate the likelihood of each pattern occurring in a real fire.
2. Deterministic models do provide a reasonably accurate prediction of fire risk for a particular fire scenario and set of initial conditions but several scenarios are possible in a real fire
3. Model validation is mainly based on experimental data, not on statistics of real fires

Non-deterministic (probabilistic/stochastic) models

1. These models take account of uncertainties and estimate the probable (not exact) risk in several scenarios likely to be generated by real fires. The uncertainty and variation around the average are quantified by probabilistic confidence limits
2. Non-deterministic models do not provide a very accurate prediction of fire risk for any particular scenario; the prediction is only approximate or probable
3. The models mainly use statistics of real fires for validation but data from experiments and other sources can be used in the models

behaviour patterns may be identified by varying the numerical values of the input parameters. It can give information about the time-varying behaviour of the system it represents. It therefore deals with a wide range of processes and activities rather than one or two in great detail. It can be used to simulate the effects of a standard fire at different locations and indicate the relative damage and loss of life in each case. Two important examples of simulation models are: building fire simulation model (BFSM) of the National Fire Protection Association, USA, and comparison of risk indices by simulation procedures (CRISP) of the Fire Research Station, UK.

Non-deterministic models (Ramachandran, 1991)

These models are of two types: probabilistic and stochastic. The first type only deals with final outcomes such as financial loss, area damage and fatalities. Critical events occurring during fire spread and leading to the final damage are not considered. The first type provides approximate solutions to problems in fire protection and insurance which do not require a detailed knowledge of the underlying physical and chemical processes. These problems are generally concerned with fire risk in a group or type of buildings.

In stochastic models, critical events occurring sequentially in space and time during fire spread form a chain and are connected by probabilities of transition from event to event. These models can be applied to any particular building with known design features and other characteristics to predict spread of flame, heat and smoke within and beyond the room of fire origin. Physical parameters such as heat output and fuel mass loss can be incorporated in stochastic models. There are several models within probabilistic and stochastic models (see Table VIII).

Probabilistic concepts are enunciated in Table IX with a further breakdown of probable damage in Table X. Fire risk may be defined quantitatively as the product of probability of fire starting or number of fires during a period, say, a year, and probable damage if a fire breaks out.

With reference to life risk, the product is the expected (mean) number of people killed or injured in fires occurring during a period. Risk to property may be expressed as the mean financial loss or area damage in fires during a period. A quantitative measure of the worst case scenario is provided by the

Table VIII Non-deterministic models

A Probabilistic models
- (a) Simple probabilistic and statistical analysis
- (b) Regression models
- (c) Probability distributions
- (d) Logic trees

B Stochastic models of fire spread
- (a) Random walk
- (b) Markov processes and chains – state transition model
- (c) Probabilistic networks

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

Table IX Probabilistic concepts

Risk implies uncertainty; the concept of safety is one of uncertainty

Several factors cause uncertainties in the occurrence of fire, pattern of fire development, behaviour of escaping occupants and effectiveness of fire protection measures and systems

The uncertainties can be quantified by probabilities

Fire risk in a building is the product of:

(a) Probability of fire starting or mean (average) number of fires likely to occur during a period, say a year and

(b) Expected (average) damage to life and property when a fire occurs

Instead of average values, maximum values of (a) and (b) may be estimated and used to estimate the probable maximum damage likely to be sustained in fires in the building during a period

Table X Probable damage in a fire

In some cases it would be useful to express the probable damage (P) in the event of a fire occurring as the product of Q and C

Q – probability of occurrence of an undesirable event

C – probable concequences or damage if the undesirable event occurs

$P = Q \times C$

The total performance (effectiveness) of a building design and installed fire protection measures should ensure that the value of P will not exceed a level acceptable to society

The acceptable level would depend on consequences in terms of life loss, fatal and non-fatal, and property damage

Undesirable events would include:

(a) Fire spreading beyond room of origin
(b) "Failure" of a fire-resistant compartment
(c) Visual obscuration due to smoke
(d) Incapacitation due to burns and toxic gases

maximum values of the two components and their product for life or property damage.

Simple probabilistic/statistical models

According to statistical and actuarial studies, probability of fire starting (or number of fires) during a period, say a year, has a "power" relationship with the size of a building expressed in total floor area or financial value of risk. Probability of fire starting depends on the nature and number of ignition sources. Probable area damage or financial loss in a fire has a similar "power" relationship with building size. Probable damage and value of β depend on the presence or absence of fire protection measures. These "power" relationships developed by Ramachandran (1979/1980, 1988) are shown in Table XI. Values of the constants in these equations for major occupancy types are available but they need to be updated (see Rutstein (1979)).

Figure 1 (Ramachandran, 1990, 1995a) on a (log $\times$ log) scale is an example (textiles industries, UK) showing the application of the "power" relationship for estimating the probable area damage in a compartment. According to this Figure, if a damage of $153m^2$ is acceptable, a sprinklered compartment of about $4,000m^2$ is equivalent in damage potential to a compartment of $500m^2$ without sprinklers. The size of the sprinklered compartment will reduce to about $3,000m^2$ if a probability of 0.1 is assigned for the non-operation of sprinklers.

Table XI Building size

If A is the size of a building in terms of total floor area>

F(A) = Probability of fire starting
= KA^{α}

D(A) = Probable area damage in a fire
= CA^{β}

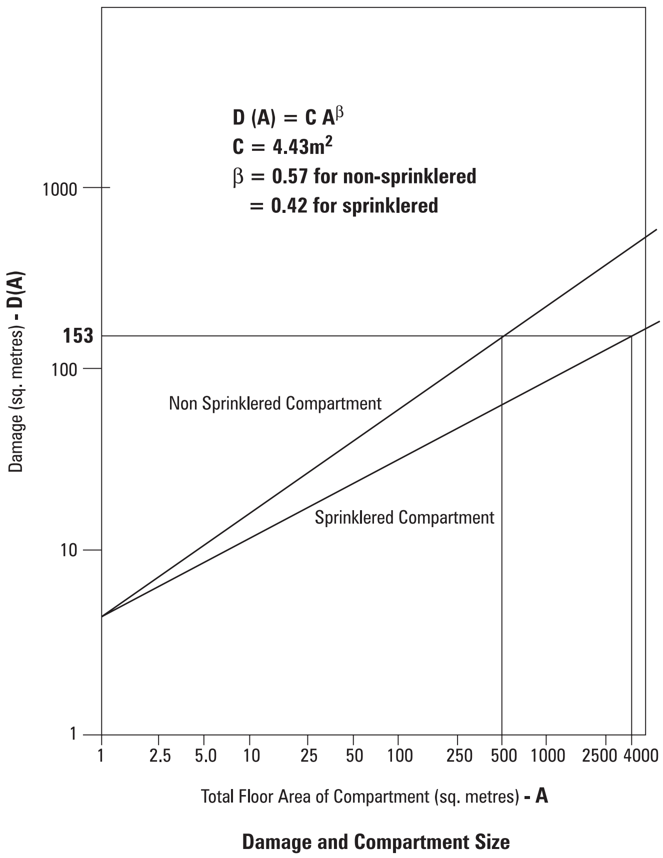
The values of the constants K, α, C and β, depend on the risk category of the building

F(R) = A measure of fire risk for the building
= $K.\ CA^{\alpha+\beta}$

F(R) per year can be estimated by obtaining the value of F(A) per year

According to another statistical model (Table XII) developed by Ramachandran (1986) the area damage in a real fire increases exponentially with time during the period commencing with "established burning". The fire growth parameter θ takes into account the probability of fire spread from object to object.

Figure 1 Damage and compartment size



Source: Ramachandran, 1990, 1995a

The expected value, standard deviation and confidence limits of θ have been estimated for several occupancy types and fire scenarios (Ramachandran, 1992). The average area initially ignited, A (O), can be assumed to be, say, one square metre or estimated for a given occupancy type. The parameter "doubling time", which is a constant for an exponential model, denotes the time taken for area damage to increase, say, from $20m^2$ to $40m^2$, $30m^2$ to $60m^2$, $80m^2$ to $160m^2$ and so on. For the textile industry UK, Ramachandran (1988) estimated for the period after established burning doubling times of 5.8 mts ($\theta = 0.12$) and 3.5 mts ($\theta = 0.20$) for sprinklered and unsprinklered compartments respectively.

Regression models

A simple regression model predicts or estimates the expected value of a dependent variable for any given value of an independent variable or factor. These two variables are assumed to have a linear relationship. Figure 1 is an example in which, on a (log $\times$ log) scale, the dependent variable, area damage, has a linear relationship with the independent variable, compartment size (total floor area). Similarly, by taking logarithms on both sides, the dependent variable A (T) denoting area damage in Table XII can be expressed as a linear function of the independent variable, time (T). This relationship provides an estimate of the fire growth parameter θ, by using pairs of known values of A (T) and T for fires for which these data are available. The estimates for the regression parameters such as log A (O) and θ are usually obtained by applying the method of "least squares" and solving the "normal equations".

Figure 2 is another example of a simple regression model which shows the relationship between the discovery time of a fire and number of deaths per 1,000 fires. According to this Figure, for every 10 minutes' delay in discovering a fire, the number of deaths per 1,000 fires would increase by eight in single occupancy dwellings and by six in multiple occupancy dwellings. Hence for every minute's delay in discovering a fire, the number of deaths per 10,000 fires would increase by eight and six respectively in these two occupancy types.

A multiple regression model predicts or estimates the expected value of a dependent variable for any given set of values of several (more than one) independent variables or factors. Instead of assigning points or scores arbitrarily, Gretener's formula in equation (1), omitting the factor A, can be converted into a multiple regression model by taking logarithms on both sides. The regression parameters for the factors P, N, S and F can then be estimated by using the values observed in real fires for the dependent variable expressed as, say, area damage and the corresponding values, known or assumed, for the independent variables P, N, S and F. For any given set of values of P, N, S and F, the predicted value of area damage can be multiplied by the probability of fire starting, A, to provide an estimate of the risk factor R.

Probability distributions

A probability distribution function G (x) expresses the probability with which a random variable x will attain various values. This distribution is skewed (non-normal) for area damage and financial loss in a fire, which are random variables. This is due to the fact that the damage is small in many fires; only a few fires grow large and cause severe damage. Statistical and actuarial studies have shown

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

Table XII Exponential model of fire growth

The (deterministic) growth of a fire over a period of time can be described by an exponential model according to which area damaged in T minutes is given by

$A(T) = A(0) \exp(\theta)$

where

$A(0)$ = area initially ignited

θ = fire growth parameter

The time at the end of the initial stage involving the object first ignited can be taken as "zero time" which corresponds to the beginning of "established burning"

Doubling time = $\log_e 2/\theta = (0.6931)/\theta$

that fire damage has a log normal or Pareto probability distribution.

Figure 3 is an example of log normal distribution for loss; logarithm of loss has a normal distribution. Figure 4 is an example of Pareto distribution for area damage. In this distribution, logarithm of $Q(d)$, probability of area damage exceeding d, has a linear relationship with logarithm of area damage. The Figures show that sprinklers reduce the probability of damage exceeding any given level.

In real fires, fire severity and resistance are random variables with probability distributions which are realistically assumed as normal. If severity exceeds resistance, a compartment would "fail" and violate performance criteria relating to stability, integrity and thermal insulation. The probability of this undesirable event occurring can be estimated by using the joint probability distribution of severity and resistance (see Table XIII and Ramachandran, 1998a). This distribution provides a basis for determining the fire resistance required for a compartment.

A compartment would only fail if and when a fire reaches the post-flashover stage. Sprinklers reduce the probability of flashover by a factor of 3. Hence, the fire resistance required for a sprinklered compartment can be reduced to about 60 per cent of the resistance required for a non-sprinklered compartment.

For a successful evacuation of a building, the total time (H) taken by occupants of, say, a floor to reach a safe place should be less than the time (F) for smoke or toxic gases to travel from the place of fire origin and produce untenable conditions on an

Figure 2 Discovery time and fatality rate (current risk level)

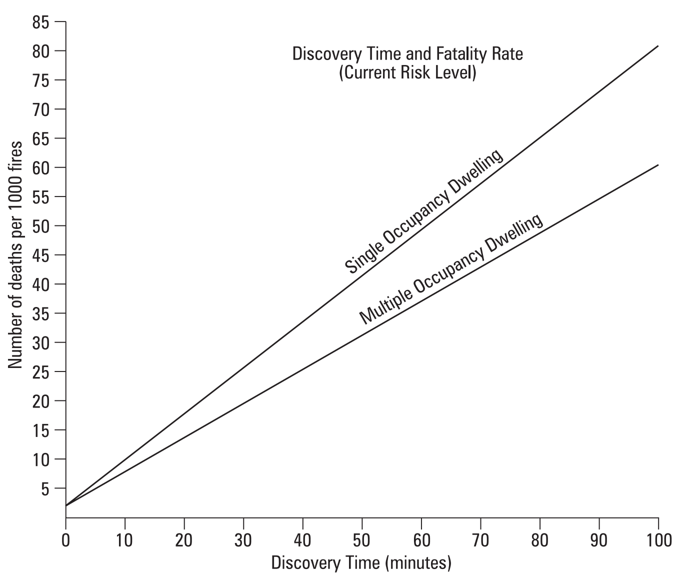
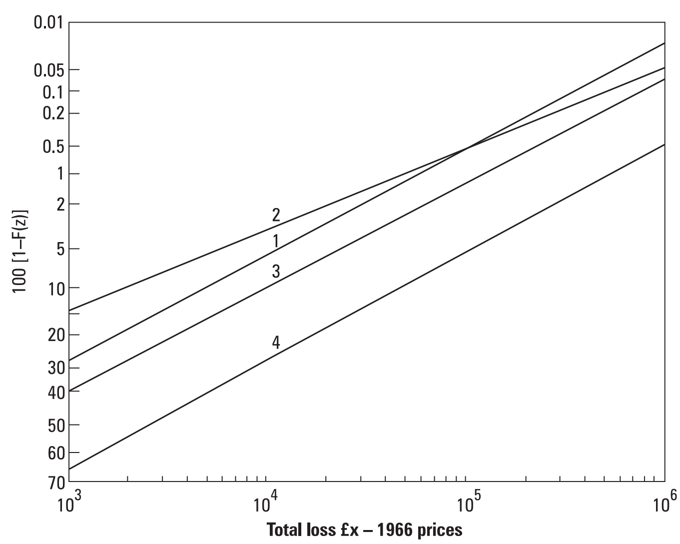


Figure 3 Cumulative distribution function of fire loss for each class in the textile industry



Line	Subpopulation
1	Sprinkler/single-storey
2	Sprinkler/multi-storey
3	Non-sprink/single-storey
4	Non-sprink/multi-storey

$1 - F(z) = 1 - V(x)$ = Probability of loss exceeding x or z; $z = \log x$

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

Figure 4 Pareto distribution of area damage – retail premises (assembly areas)

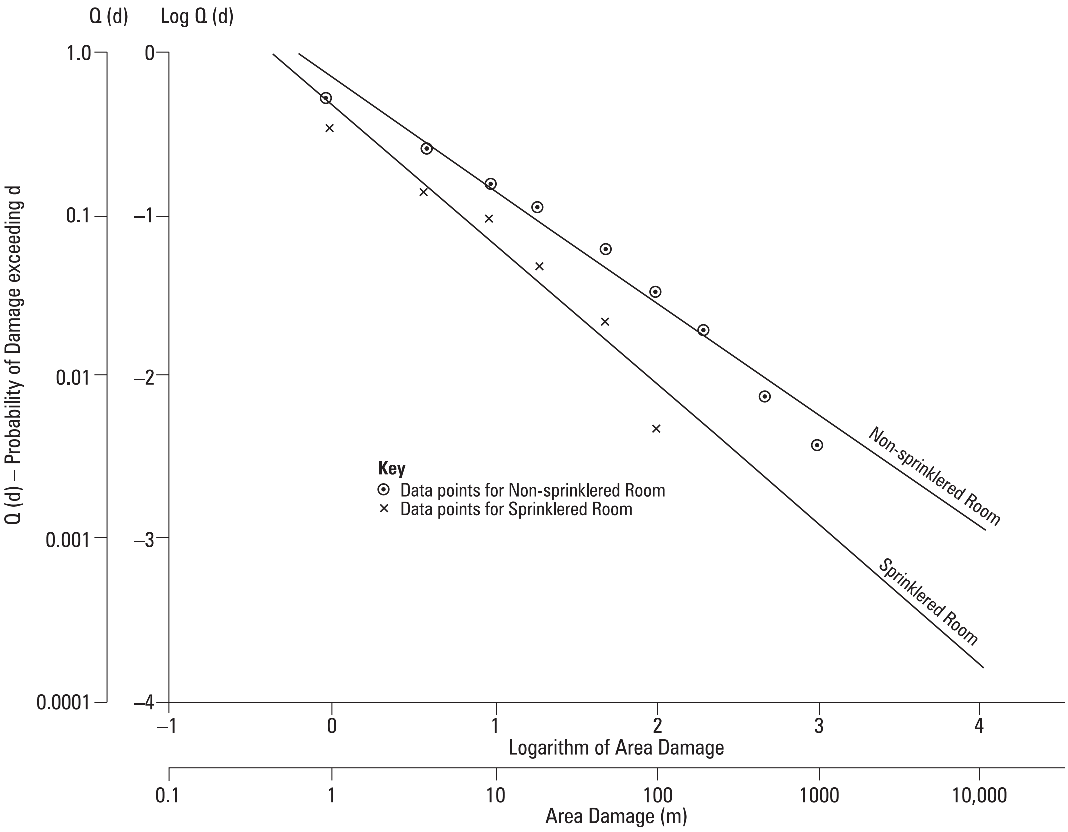


Table XIII Compartment failure

In an application of joint probability distribution, both fire resistance *R* and severity *S* are random variables. In this method, the safety index is given by:

$$\beta = (\mu_r - \mu_s)/(\sigma_r^2 + \sigma_s^2)^{1/2}$$

where μ_r and σ_r are the mean and standard deviation of *R* and μ_s and σ_s the mean and standard deviation of *S*

If both *R* and *S* have normal probability distributions, the probabilities of compartment failure for different combinations of μ_r and μ_s can be evaluated with the aid of β and tables of (standard) normal distribution. For example, the probability of failure would be 0.025, if β = 1.96, 0.01 if β = 2.33 and 0.001 if β = 3.09. The probability of failure would be equal to 0.5 if $\mu_r = \mu_s$, less than 0.5 if $\mu_r > \mu_s$ and greater than 0.5 if $\mu_r < \mu_s$

Depending on the consequential damage to life (and property), a level can be prescribed for the probability of compartment failure and corresponding value of β obtained from a table of standard normal distribution

The fire resistance should then be set according to:

$$\mu_r = \mu_s + \beta(\sigma_r^2 + \sigma_s^2)^{1/2}$$

Deterministic formulae such as equivalent time of fire exposure would provide an estimate of μ_s for a compartment of known dimensions, fire load density and ventilation factor

escape route. H is essentially the sum of three time periods – ignition to discovery of fire, *D*, discovery to commencement of evacuation, *B*, and commencement of evacuation to reaching a safe place, *E*, e.g. entrance to a protected staircase. Several factors affect the time periods and cause uncertainties. Hence, *H* and *F* are random variables which may be assumed to have normal distributions.

The joint probability distribution of *H* and *F* will provide a design value for *H* for any acceptable level for the probability of egress failure, *Q* (see Table XIV). This level will depend on the consequences, *C*, of egress failure (see Table X). Depending on the

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

Table XIV Probability of egress failure (Q)

The value of Q depends on the values of H and F and their probability distributions
The random variables H and F can be considered jointly through the function:

$$Z = F - H$$

The probability of egress failure (Q) associated with any value of Z is given by the safety index

$$\beta = (\mu_f - \mu_h)/(\sigma_f^2 + \sigma_h^2)^{1/2}$$

where μ_f and μ_h are the means and σ_f and σ_h are the standard deviations of F and H
If F and H are normally distributed, β has a standard normal distribution
$Q = 0.5$ if $\mu_h = \mu_f (\beta = 0)$
$Q < 0.5$ if $\mu_h < \mu_f$ (β is positive)
$Q > 0.5$ if $\mu_h > \mu_f$ (β is negative)
The value of Q for any β can be obtained from tables of the normal distribution

presence or absence of automatic detection and other communication systems, the design value of H can be adjusted to provide a design value for E, the design evacuation time. This value need not be 2.5 minutes or any other arbitrarily determined design time.

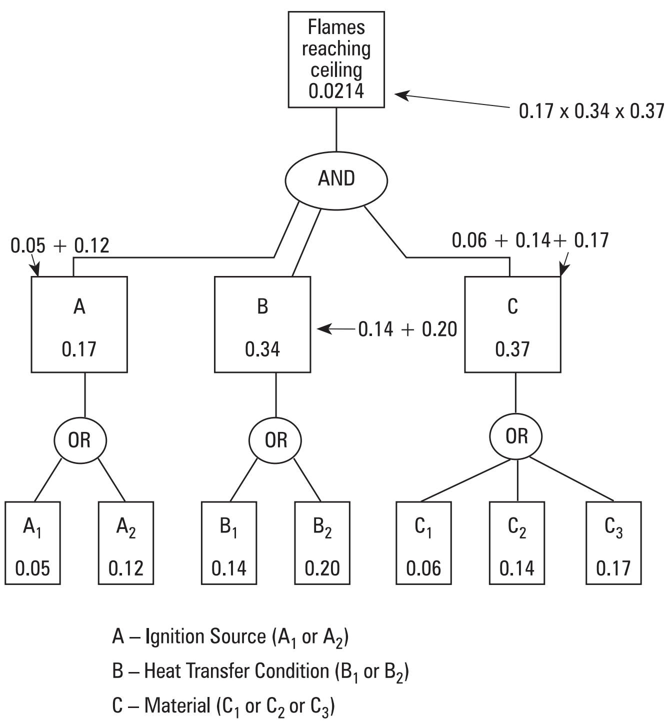
Logic trees

In fire risk assessment, fault trees and event trees are the most widely used logic trees. The fault tree requires the specification of an unwanted event (top event) and an analysis is carried out of the various ways in which this top event can occur. This is generally done by working backwards from the top event and finding what faults or conditions can cause the top event, working from each of these secondary top events, to a final set of basic events or conditions whose probabilities of occurrence are known or may be judged with some confidence. A diagrammatic representation of the process would then resemble the branches of a tree. Several fault trees have been developed in the chemical industry for hazard analyses of processes that might lead to detonation and in the nuclear industry to predict the likelihood of certain types of nuclear accidents. Figure 5 (Ramachandran, 1998b) is an example of a fault tree for flames reaching the ceiling of a room. Another example is contained in a paper by Beard (1979) in which a fire in Coldharbour Hospital was used as a base to estimate the improved safety that might have been obtained by changing a number of factors that could have influenced the course of the fire.

The events in a fault tree are connected by one of two types of logic gates. These are AND gates in which all the constituent events have to be present and OR gates in which any one of the constituent events needs to be present to cause the occurrence of a specific top event. The multiplication theorem is applied to the probabilities of the constituents of an AND gate and the addition theorem to the probabilities of the constituents of an OR gate. This method only provides an approximate value for the probability of occurrence of the undesirable primary top event. A more accurate value of this probability can be obtained by applying complex calculation techniques relating to cut sets or path sets.

An event tree starts from an initiating event and leads to the final undesirable top event. It follows a series of branches, each denoting a

Figure 5 Fault tree for flames reaching the ceiling of the room

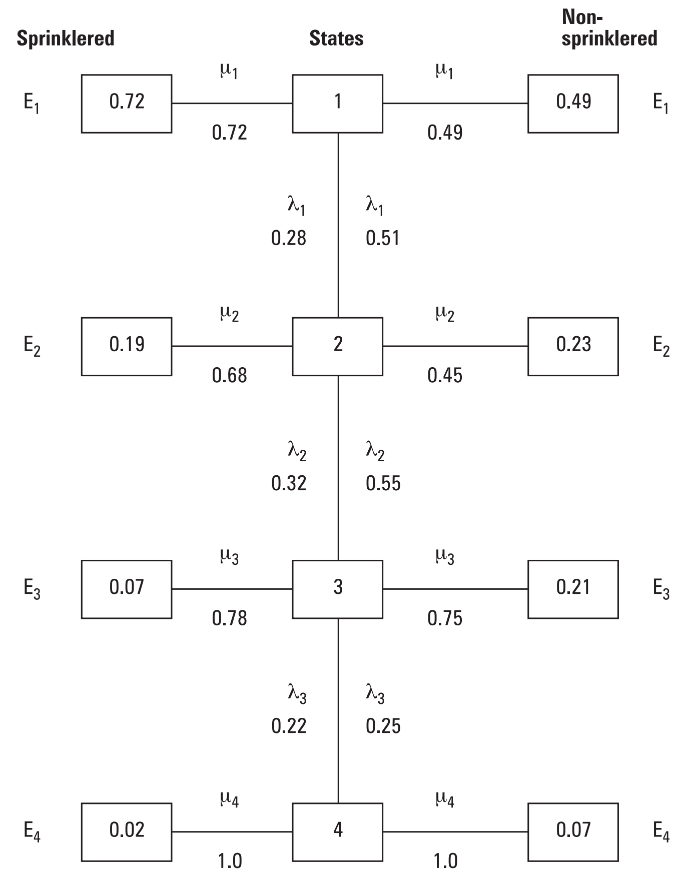


Source: Ramachandran, 1998b

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

possible outcome of a chain of events. An example of an event tree is shown in Figure 6 (Ramachandran, 1995b), in which fire starting in a room or compartment is the initiating event and spread beyond the room but confined to the building of origin is the final top event (see next section for definitions of symbols used in this Figure). It may be observed that sprinklers reduce the probability of a fire spreading beyond the room by a factor of 3.5. Such event-probability trees based on UK fire statistics have been constructed by Ramachandran for some types of occupancies and areas of fire origin – production area, storage area, etc. (These are available in an unpublished report produced under a research contract from the Fire Research Station.)

Figure 6 Event tree (textile industry)



E_1 = Probability of confinement to item first ignited = μ_1

E_2 = Probability of spreading beyond item first ignited but confinement to contents of room of fire origin = $\lambda_1 . \mu_2$

E_3 = Probability of spreading beyond item first ignited and other contents but confinement to room of fire origin and involvement of structure = $\lambda_1 . \lambda_2 . \mu_3$

E_4 = Probability of spreading beyond room of fire origin but confinement in the building= $\lambda_1 . \lambda_2 . \lambda_3 . \mu_4$, ($\mu_4 = 1$)

Source: Ramachandran, 1995b

Stochastic models

A number of stochastic models have been developed for predicting the spread of fire in a particular building. Ramachandran (1995b) has reviewed these models, a discussion about which is beyond the scope of this paper. A widely used stochastic model is the state-transition model (STM) which can be based on fire statistics or a physical parameter such as heat output or both the sources of data. Like other stochastic models, STM is time based. The probabilities of a fire "staying" in different states and spreading or "transition" from state to state are expressed as functions of time. The probabilities are expressed per minute or per second. Estimates of these probabilities can be obtained by introducing the time factor in an event tree such as the one in Figure 6. In this Figure μ_i (i = 1 to 4) is the conditional probability of a fire being extinguished in the state i over a period of time if it has spread beyond the previous state (i – 1). The parameter λ_i (i = 1 to 3) is the conditional probability of a fire spreading beyond the ith state if it has not been extinguished in that state; $\lambda_i = 1 - \mu_i$. We also have $E_i = \lambda_1 \lambda_{2 \ldots} \lambda_{i-1} \mu_i$ which is the ultimate probability of confinement to or extinguishment in the ith state. A fire spreading beyond the building of origin is not considered in this model.

The product $\lambda_1 \lambda_2$ may be regarded as the probability of flashover. The parameter λ_3 is the probability of failure of the structural barriers of a room given that flashover has occurred. Information on whether a room is a fire compartment is not given in reports on fires completed by the fire brigades. As discussed earlier, the value of λ_3 can be estimated for any compartment with a known or given level of fire resistance.

General discussion

The paper only provides a general framework for evaluating fire risk in a facility qualitatively and quantitatively and identifying appropriate safety measures and management actions to reduce or control this risk. Risk evaluation techniques, safety measures and management actions would vary from one type of facility to another. Reducing life risk is the main objective for facilities such as hotels, hospitals, shopping complexes, department stores, cinemas, drama theatres and other places of entertainment and recreation centres. Property protection is the main objective for industrial and commercial premises.

Facilities
Volume 17 · Number 9/10 · 1999 · 363–376

An application of the risk evaluation and management methods proposed in this paper would depend on the extent to which data are available for analysis. It may be necessary to modify these methods and collect additional information required for performing the analysis; results based on data for a group of buildings belonging to any type of facility can be modified to derive results and conclusions for a particular building within that group.

References

Beard, A.N. (1979), "Applying fault-tree analysis to the Coldharbour Hospital fire", *Fire*, Vol. 71 No. 885, p. 517.

Gretener, M. (1968), "Attempt to calculate the fire risk of industrial and other objects", 3rd International Fire Protection Symposium, Eindhoven.

Ramachandran, G. (1979/80), "Statistical methods in risk evaluation", *Fire Safety Journal*, Vol. 2, pp. 125-45.

Ramachandran, G. (1982), "A review of mathematical models for assessing fire risk", *Fire Prevention*, May, pp. 28-32.

Ramachandran, G. (1986a), "Exponential model of fire growth", *Fire Safety Science: Proceedings of the First International Symposium*, Hemisphere Publishing Corporation, New York, NY, pp. 657-66.

Ramachandran, G. (1986b), "Statistically-determined fire growth rates for a range of scenarios", Report to the Fire Research Station (unpublished).

Ramachandran, G. (1988), "Probabilistic approach to fire risk evaluation", *Fire Technology*, August, pp. 204-26.

Ramachandran, G. (1990), "Probability-based fire safety code", *Journal of Fire Protection Engineering*, Vol. 2 No. 3, pp. 75-91.

Ramachandran, G. (1991), "Non-deterministic modelling of fire spread", *Journal of Fire Protection Engineering*, Vol. 3 No. 2, pp. 37-48.

Ramachandran, G. (1995a), "Probability-based building design for fire safety", *Fire Technology Part 1*: Vol. 31 No. 3, pp. 265-75; Part 2: Vol. 31 No. 4, pp. 355-68.

Ramachandran, G. (1995b), "Stochastic models of fire growth", *SFPE Handbook of Fire Protection Engineering*, 2nd ed., Section 3, Chapter 15, pp. 296-311, National Fire Protection Association.

Ramachandran, G. (1998a), "Probabilistic evaluation of structural fire protection: a simplified guide", *Fire Note*, Vol. 8, Building Research Establishment.

Ramachandran, G. (1998b), "The economics of fire protection", E&FN Spon, London.

Rutstein, R (1979), "The estimation of fire hazard in different occupancies", *Fire Surveyor*, April, pp. 21-5.

Further reading

"Early detection of fire and life risk" (1993), *Fire Engineers Journal*, Vol. 53 No. 171, pp. 33-7.

"Fire resistance periods for structural elements – the sprinkler factor" (1993), *Proceedings of the CIB W14 International Symposium on Fire Safety Engineering*, University of Ulster, Part 3, pp. 71-94.

"Probabilistic evaluation of design evacuation time" (1993), *Proceedings of the CIB W14 International Symposium on Fire Safety Engineering*, University of Ulster, Part 1, pp. 189-207.

"Probability modelling" (1984), Seminar on cost-effective approach to fire safety, LIFE 1984, Olympia, London, April.

"Stochastic modelling of fire growth" (1985), ASTM STP 882, American Society for Testing and Materials, pp. 122-44.

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