Fire Safety Journal **21** (1993) 299–311

Effectiveness of Sprinklers in Reducing Fire Severity

S. J. Melinek

Building Research Establishment, Fire Research Station, Borehamwood, Hertfordshire WD6 2BL, UK

(Received 25 January 1992; revised version received 9 February 1993; accepted 25 March 1993)

ABSTRACT

The effectiveness of sprinklers is examined by comparing fires they extinguish or control with fires they fail to extinguish or control. It is shown that sprinklers substantially reduce the probability of fire area exceeding $100\,m^2$ *but that they normally have little effect until the fire area reaches* $3\,m^2$*. The effect, of sprinklers on the incidence of damage to the building fabric is also looked at.*

This paper is part of a research study aimed at developing quantitative fire engineering methods for the assessment of fire risk. The results will be used to calibrate the mathematical models on which these assessments are based.

INTRODUCTION

The effect of sprinklers can be estimated by comparing fire size in sprinklered and unsprinklered buildings.[1–3] However, this procedure has the disadvantage that sprinklered and unsprinklered buildings may differ in compartment size and hazard. This paper therefore estimates the effect of sprinklers by comparing fires extinguished or controlled by sprinklers with fires in sprinklered buildings which the sprinklers fail to extinguish or control.

Sprinkler performance may on occasion depend on the initial fire severity or rate of growth. It is assumed for the purpose of this paper that all fires are initially identical and that fire severity therefore depends on sprinkler performance rather than sprinkler performance depending on fire severity.

The effect of sprinklers on fire size is looked at in detail. Financial loss and the proportion of fires causing damage to the building are also looked at. The figures for fire size and structural damage are taken from unpublished fire brigade data for 1987. The figures for losses are taken from Rogers.[4]

It should be borne in mind that fire brigade statistics include only fires to which the brigade is called. Hence, they may exclude many fires which, as a result of sprinkler operation, are extinguished without fire brigade assistance. This paper presents evidence of such an effect and makes an allowance for it.

Fire brigade reports specify only whether fires occur in a sprinklered area. Hence, references in this paper to fires in sprinklered buildings include fires in sprinklered areas of partially sprinklered buildings. References to fires in non-sprinklered buildings include fires in non-sprinklered areas of partially sprinklered buildings. Most industrial buildings are wholly sprinklered or wholly non-sprinklered.[5]

No distinction is made between automatic sprinklers and manual sprinklers. Fire brigade statistics indicate that about 96% of sprinkler installations are automatic.

Most of the data are for industrial and commercial buildings, which are assumed for this purpose to include transport, communications and distribution but to exclude agriculture, public administration and defence, residential homes, medical and educational services, hotels and places of recreation and entertainment. For agricultural buildings (largely barns) the probability of spread is much higher than for most other buildings.

Fire size is defined as the horizontal area damaged by heat (DBAD). Fires damaging only vertical surfaces have zero horizontal area.

The data for fire size appear in many cases to be rounded. The proportion of fire areas recorded as round numbers depends on the type of fire, which could bias any analysis. It has therefore been assumed that half the fires for which the area is recorded as a round number fall just above the round number and half just below.

This paper is part of a research study aimed at developing quantitative fire engineering methods for the assessment of fire risk and the economic evaluation of different fire protection methods. The results will be used to calibrate the mathematical models on which these risk assessment methods are based.

RESULTS

Fire size

Figure 1 shows the probability of spread for fires in sprinklered and non-sprinklered industrial and commercial buildings. It can be seen that there is comparatively little difference between fire spread in sprinklered and non-sprinklered buildings, possibly because sprinklered buildings differ in nature from unsprinklered buildings.

Table 1 shows fire size data for different occupancies. It can be seen that in most cases there is little variation between occupancies. The

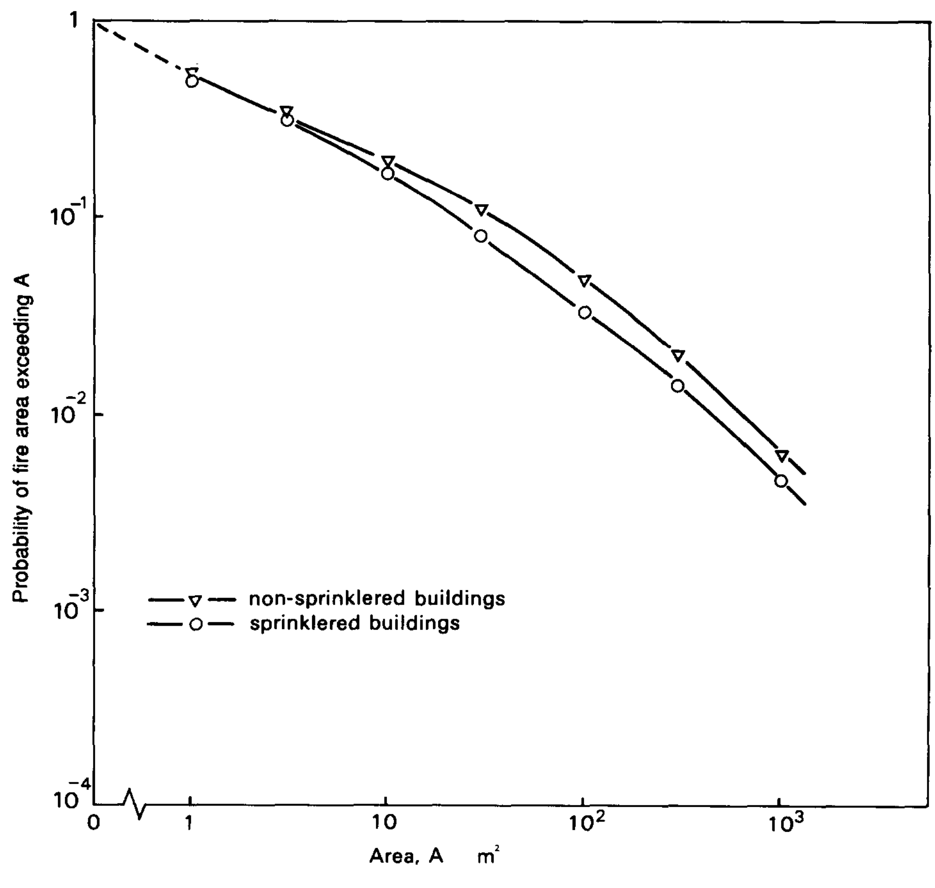

Fig. 1. Fire size for sprinklered and non-sprinklered industrial and commercial buildings.

TABLE 1

Fire Size in Occupied Industrial and Commercial Buildings, UK, 1987 (Occupancy Defined by 1968 Standard Industrial Classification (SIC).)

Sprinklered buildings				*Non-sprinklered buildings*			
No. of fires	*Fire size*[a] *(m^2)*			*No. of fires*	*Fire size*[a] *(m^2)*		
	Under 1	*1 to 10*	*Over 10*		*Under 1*	*1 to 10*	*Over 10*
SIC = 4 000–4 599 (Textiles, clothing, etc)							
338	34%	44%	22%	519	44%	35%	21%
SIC = 4 770–4 899 (Timber, furniture, paper, printing, etc.)							
320	52%	32%	16%	936	38%	36%	26%
SIC = 7 000–8 399 (Transport, distribution)							
231	40%	44%	13%	5 157	39%	40%	21%
Other							
465	43%	40%	17%	8 968	41%	39%	20%
Total							
1 354	42%	40%	17%	15 580	40%	39%	21%

[a] Assuming that one-half of fires classified as of size $10\,m^2$ were just under $10\,m^2$ and one-half were just over $10\,m^2$.

type of room in which the fire started (e.g. production, shop, storage) also had little effect.

The possible differences between sprinklered and non-sprinklered buildings makes it difficult to draw conclusions from direct comparison of these types of building. It was therefore decided to look at the effect of sprinkler behaviour. Figure 2 shows the probability of spread in sprinklered industrial and commercial buildings for different patterns of sprinkler behaviour, namely:

- —sprinklers failed to operate because fire was too small (fire extinguished by other means) (coded 0A);
- —sprinklers extinguished or controlled the fire (coded 2 or 3);
- —sprinklers failed (did not operate for reasons other than fire being too small, or operated but failed to control fire) or behaviour not specified.

A fire is classified as being controlled by sprinklers if they contain the fire but do not extinguish it. The small number of fires in which the

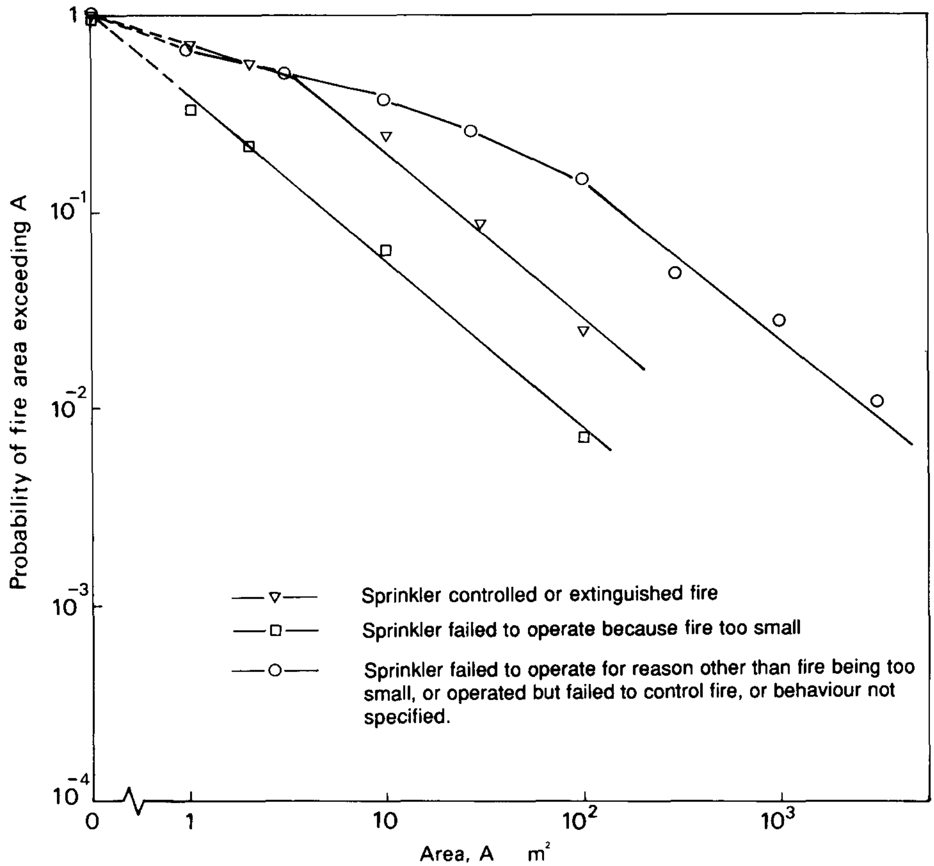

Fig. 2. Effect of sprinkler on fire size in sprinklered industrial and commercial buildings.

sprinkler behaviour was not specified are included with 'sprinklers failed' because they seemed from their size to fit most closely in that category.

Figure 2 shows a clear distinction between fires extinguished or controlled by sprinklers and those in which the sprinklers fail to operate or fail to control the fire. The former are 80% less likely to reach a size exceeding $100\,m^2$.

Figure 2 shows that the proportion of fires reaching a size of $100\,m^2$ is approximately 15% for the 180 fires in which the sprinklers fail (or their operation is unspecified), 2·5% for the 516 fires extinguished or controlled by the sprinklers and 0·7% for the 658 'small fires'. Hence, the expected number of fires reaching $100\,m^2$ is 44. If, in the absence, of sprinklers, 15% of the fires extinguished or controlled by sprinklers would have reached a size of $100\,m^2$ (instead of 2·5%), the total number of fires reaching $100\,m^2$ would be $44 + 0{\cdot}125 \times 516 = 108$.

It is likely that sprinklers substantially reduce the probability of the brigade being called to a fire. If it is assumed, following Rogers,[4] that fires in sprinklered buildings are 33% less likely to be reported to the brigade then the total number of reported fires in sprinklered buildings would, in the absence of sprinklers, be 2031 (i.e. 1354/0·67), which is 677 greater than the actual number reported.

Since the sprinklers prevent these 677 fires being reported, these fires must be large enough to operate the sprinklers. If, in the absence of sprinklers, 15% of these additional fires would reach a size of $100\,m^2$, the total number of fires reaching a size of $100\,m^2$ in the absence of sprinklers becomes $108 + 0{\cdot}15 \times 677 = 210$. Hence, allowing for fires not reported to the brigade, sprinklers appear to reduce the number of fires reaching a size of $100\,m^2$ by a factor of 210/44, which is about five.

The 'small fires' category (code 0A) includes fires generating insufficient heat to operate the sprinklers. The results indicate that about one-quarter of fires reaching a size of $100\,m^2$ in the presence of operative sprinklers are 'too small' to operate the sprinklers. This conclusion may represent a genuine feature of those fires (the heat output was too low despite the large fire area). Alternatively, it may indicate that the fires in this small group were misclassified.

The probability of fire growth at any point is indicated in Fig. 2 by the gradient of the curves, a steep gradient indicating low probability of spread. The initial gradient for 'sprinkler controlled or extinguished fire' is similar to that for 'sprinkler failed to operate or operated but failed to control fire', indicating that sprinklers have little effect on the probability of spread until the fire area reaches $3\,m^2$.

This result, which has been observed previously,[3] suggests that $3\,m^2$ is the minimum fire size at which conventional sprinklers normally operate. Calculations[6] confirm that sprinklers typically operate when the fire size reaches about $5\,m^2$. It should be noted that rapid response sprinklers, not yet in widespread use, are able to control somewhat smaller fires.

The apparent similarity between fire spread in sprinklered and non-sprinklered buildings may be partly due to the wide variety of buildings in each occupancy. It is sometimes possible to classify buildings and parts of buildings by type rather than industry. Sprinklers have been found to reduce fire area in office buildings[2] and in public areas of retail premises.[1]

Fire loss

Fire losses have been investigated by Rogers,[4] who found that sprinklers reduce the average fire loss substantially in some occupancies. Figure 3 shows data for the occupancy (textiles) in which the effect of sprinklers was greatest.

Rogers found that sprinklers reduce average loss more in multi-storey buildings than in single-storey buildings. This effect seems to result from a high average loss in unsprinklered multi-storey buildings. It was not possible to investigate the effect of buildings height in more detail

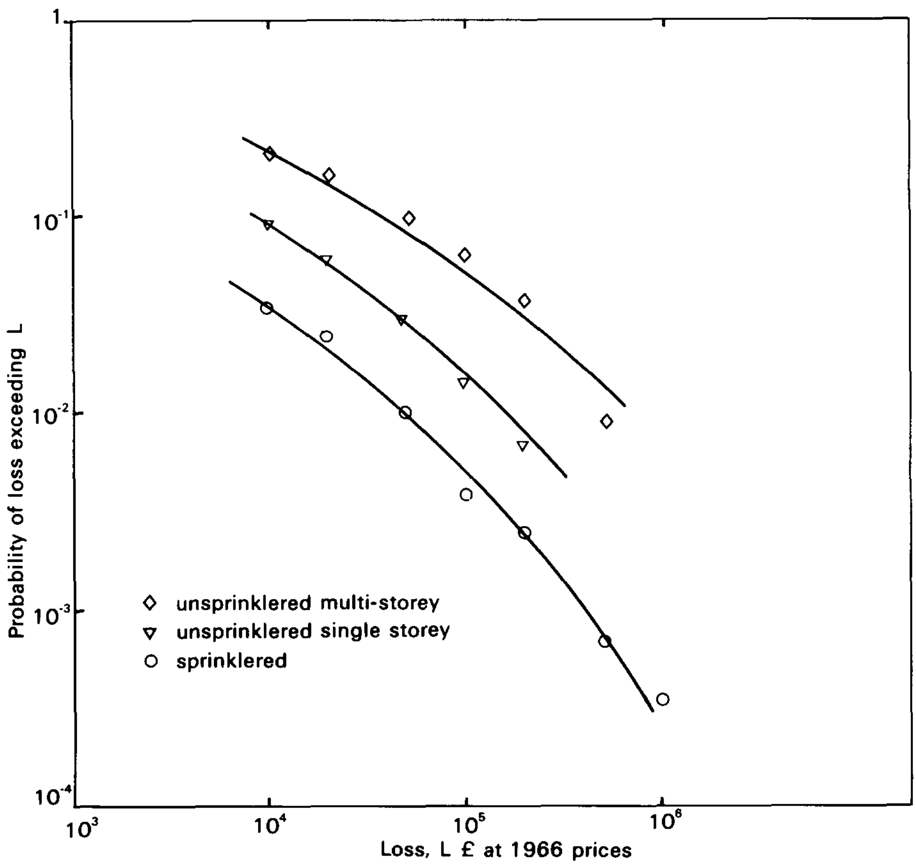

Fig. 3. Loss in buildings of the textile industries, 1966–1972.

since building height (number of storeys) is normally coded only for fires causing structural damage.

It should be borne in mind that financial losses will depend in part on the value of the buildings and contents at risk. Buildings are more likely to be sprinklered if the value at risk is high.[4] Large losses in some sprinklered buildings may be due to smoke and water damage to stock rather than failure of the sprinklers to prevent fire spread.

Structural damage

One measure of whether a fire threatens the structure is whether it causes heat damage to the building fabric (code HDMG). Table 2 shows the effect of sprinkler behaviour on the proportion of fires causing such damage.

TABLE 2

Effect of Sprinkler Behaviour on Proportion of Fires Causing Heat Damage to the Building Structure (HDMG) in Sprinklered Industrial and Commercial Buildings, UK, 1987

Sprinkler behaviour (and code)	*No. of fires*	*No. and % of fires causing heat damage to the building fabric*
Failed to operate because fire too small (0A)	658	39 (6%)
Extinguished fire (3)	169	17 (10%)
Controlled fire (2)	347	102 (30%)
Operated but failed to control fire (1)	61	26 (43%)
Failed to operate other than because fire too small	109	41 (38%)
Behaviour not specified (9)	10	2 (20%)
All fires in sprinklered industrial and commerical buildings	1 354	227 (17%)
All fires in unsprinklered industrial and commercial buildings	15 580	6 375 (41%)

For fires in which the sprinklers fail to operate other than because the fire is too small or operate but fail to control the fire, the probability of heat damage to the building fabric is 0·39. If it is assumed that the probability of such damage in fires extinguished or controlled by sprinklers would, in the absence of sprinklers, also be 0·39, the number of fires causing such damage in sprinklered buildings if sprinklers never work becomes:

$$39 + (169 + 347) \times 0{\cdot}39 + 26 + 41 + 2 = 309$$

If (as previously estimated) the fire brigade would, in the absence of sprinklers, be called to 677 additional fires and if 39% of these additional fires would cause heat damage to the building fabric, the number of fires causing such damage if sprinklers never work becomes $309 + 0{\cdot}39 \times 677$, which equals 573. Hence, allowing for unreported fires, sprinklers appear to reduce the incidence of heat damage to the building fabric from 573 to 227, a factor of 2·5.

For fires in unsprinklered buildings, the probability of heat damage to the building fabric is 0·41. Hence, sprinklered buildings clearly differ from unsprinklered buildings, possibly because many sprinklered buildings have very large rooms in which a small fire is unlikely to damage the structure. It is therefore not possible to assess sprinkler effectiveness by directly comparing sprinklered and unsprinklered buildings.

Probability of call to fire brigade

There are many fires to which the fire brigade is not called.[7–9] The proportion of fires requiring fire brigade assistance is likely to be lower in sprinklered buildings than in unsprinklered buildings.[4] Table 3 shows the expected number of fires in sprinklered buildings and the numbers to which the brigade is called. These figures confirm that the brigade attend fewer fires than expected in sprinklered buildings.

Table 3 assumes, following Clark,[10] that fire frequency in each industry is proportional to the number of buildings multiplied by the square root of the average building area and that fires in partially sprinklered buildings occur mostly in the sprinklered parts.

Sprinkler operation normally activates a fire alarm. Hence, it might be expected that the presence of sprinklers would result in a large number of automatic calls to the brigade. In fact, only about 17% of

TABLE 3
Annual Number of Fires in Sprinklered Industrial Buildings Attended by the Fire Brigade, UK, 1966–1972

Industry (a)	*(b)*	*(c)*	*(d)*	*No. of fires in sprinklered buildings attended by brigade*	
				Expected (e)	*Actual (f)*
Textiles	0·562	6·87	300	442	391
Timber and furniture	0·423	3·01	529	388	143
Paper, printing and publishing	0.220	7·24	254	150	114
Chemical and allied	0·261	4·08	370	195	82
Metal manufacture, etc.	0·067	3·47	1862	234	46
Total				1 409	776

[a] As defined by Rogers.[4]
[b] Number of sprinklered or partially sprinklered buildings divided by the number of unsprinklered buildings (from Ref. 9).
[c] Average size of sprinklered buildings divided by average size of unsprinklered buildings (from Ref. 9).
[d] Annual number of fires in unsprinklered buildings attended by the fire brigade (from Ref. 4).
[e] $(d) \times (b) \times (c)^{1/2}$.
[f] From Ref. 4.

calls from sprinklered premises are automatic. Moreover, the proportion of calls which are automatic appears to be unaffected by whether the sprinklers operate.

DISCUSSION

It is important to bear in mind when interpreting the results that sprinklered buildings are on average larger than nonsprinklered buildings.[4] It may be that high-risk buildings are more likely to be sprinklered than low-risk buildings. It may also be that sprinklered buildings are less likely to be equipped with a rapid detection system or other fire precautions.

The analysis, being based on fire brigade statistics, will reflect the views of fire brigade personnel on the sprinkler behaviour. The analysis, in estimating the effect of sprinklers on the number of large fires and the number of fires damaging the building, also assumed that the brigade are called to all such fires.

Sprinkler behaviour

It can be seen from Table 2 that the probability of damage to the building fabric where the sprinklers fail to control the fire is approximately equal to that where the sprinklers fail to operate at all (other than because the fire is too small). Excluding small fires, 145 of the 188 fires causing heat damage to the building fabric are fires in which the sprinklers operated. Analysis of Fig 2 suggests that about half the very large fires (fires exceeding $100\,m^2$) are fires in which the sprinklers operate. Hence, sprinkler effectiveness cannot be assessed solely from the probability that they will operate.

In only 38 of the 109 fires where the sprinklers failed was the sprinkler system clearly inoperative. There were a further 27 cases in which the reason for non-operation was classified as other or unknown.

The probability of fires in sprinklered buildings becoming large is far lower in Australasia than in the UK or the USA.[11] This reduction may result from:

—a low incidence of freezing;
—frequent monitoring of sprinkler systems,[12] including electronic monitoring;
—automatic call to fire departments,[12] leading to rapid fire brigade response.

In addition, the automatic call systems will result in many more small fires being recorded. The recording of more small fires will decrease the apparent probability of fires becoming large.

Effect of sprinklers on optimal level of fire resistance

The optimal level of fire resistance is the level which minimises the total cost of fire (i.e. the fire loss plus the cost of fire protection). Hence, if the number of fires which threaten the structure is reduced, the fire resistance of the structure can be reduced. A theoretical analysis[13] has shown that the optimal response is to keep the overall probability of failure approximately constant. Hence, if sprinklers reduce the number of fires causing heat damage to the building fabric by a factor of 2·5, the probability of structural failure in each such fire can be allowed to increase by a factor of 2·5.

The fire resistance required by any structure to survive a fully developed fire is generally assumed to be proportional to the fire load density.[14] It has been recommended[15] that the design fire load density be the value which has a 20% probability of being exceeded. In these circumstances, a 2·5-fold increase in failure probability corresponds to reducing the design fire density to the value which has a 50% probability of being exceeded.

Fire load density (i.e. fire load per unit floor or surface area) typically has a coefficient of variation of about 0·5.[16] It can be shown that the fire load with a 50% probability of being exceeded is then approximately 25% less than that with an 80% probability of being exceeded. Hence, the optimal level of fire resistance with sprinklers is about 25% less than that without sprinklers.

The fact that sprinklers reduce the optimal level of fire resistance does not mean that high fire resistance without sprinklers is equivalent to a lower fire resistance with sprinklers. Fire resistance reduces only the risk of structural failure or spread beyond compartment boundaries. About 50% of fire deaths and three-quarters of non-fatal fire casualties occur in fires confined to the room of origin.[17] Sprinklers can provide protection against such fires while additional fire resistance cannot.

CONCLUSIONS

(1) Data on structural damage indicate that sprinklered buildings differ substantially from unsprinklered buildings. Hence, it is not possible to assess sprinkler effectiveness by directly comparing fires in sprinklered and unsprinklered buildings.

(2) Sprinklers have little effect on the probability of fire spread until the fire size reaches $3\,m^2$, which suggests that $3\,m^2$ is the minimum fire size at which conventional sprinklers normally operate.

(3) Sprinklers reduce the probability of fire size in industrial and commercial buildings reaching $100\,m^2$ by a factor of about five.

(4) Sprinklers reduce the probability of damage to the building by a factor of about 2·5.

(5) Sprinklers reduce optimal fire resistance times by about 25%.

(6) About half the large fires in sprinklered buildings and three-quarters of the fires causing damage to the building are fires in which the sprinklers operate. Hence the effectiveness of a sprinkler system cannot be assessed solely from the probability that it will operate.

ACKNOWLEDGEMENTS

The author acknowledges valuable discussions with Mr P. Burry, Mr H. P. Morgan, Mr W. G. B. Phillips, Mr B. B. Pigott, Mr P. G. Smith and Mr J. S. Webb.

REFERENCES

1. Morgan, H. P. & Chandler, S. E., Fire sizes and sprinkler effectiveness in shopping complexes and retail premises. *The Surveyor,* **10**(5) (1981) 23–8.
2. Morgan, H. P. & Hansell, G. O., Fire sizes and sprinkler effectiveness in offices—Implications for smoke control and design. *Fire Safety J.,* **8** (1984/85) 187–98.
3. Ramachandran, G., Trade-offs between fire safety measures: Probabilistic evaluation. *Fire Surveyor,* **19**(2) 4–13.
4. Rogers, F. E., Fire losses and the effect of sprinkler protection of buildings in a variety of industries and trades. *Building Research Establishment Current Paper* CP 9/77. BRE, Borehamwood, 1977.
5. Review of Fire Policy: An examination of the deployment of resources to combat fire. Paragraph 694. Home Office, London, 1980.
6. Hinkley, P. L., The effect of vents on the opening of the first sprinklers. *Fire Safety, J.,* **11** (1986) 211–25.
7. May, C., Surveying fires in the home. *Fire Prevention,* **231** (1990) 20–2, 24.
8. Table 2.1 of Fire in the United States—Death, injuries, dollar loss, and incidents at the national, state and local levels in 1978. Second edition. Federal Emergency Management Agency Report FEMA–22. Washington, DC, 1982.
9. Fires controlled by sprinklers. *Fire Prevention,* **226** (1990) 48; **227** (1990) 30.
10. Clark, M. B. J., Fire and Fire Protection—A survey of manufacturing industry. Home Office Scientific Advisory Branch Report 10/78. Home Office, London, 1978.
11. How successful are sprinklers? Part 3. AFPA Monthly Bulletin No. 251, AFPA, Melbourne, Sept. 1983.
12. Marryatt, H. W., Sprinkler trade-offs and the Australasian experience. *Fire J. (NFPA),* **75**(1) (1981) 59–60, 62.
13. Melinek, S. J., Estimation of optimal safety levels. *Fire Safety J.,* **20** (1993) 71–82.
14. Thomas, P. H. & Heselden, A. J. M., Fully-developed fires in single compartments: A co-operative research programme of the Conseil International du Bâtiment (CIB report no. 20). Fire Research Station Fire Research Note 923. Building Research Establishment, Borehamwood, 1972.
15. Pettersson, O., Magnusson, J. & Thor, J., *Fire Engineering Design of Steel Structures.* Swedish Institute of Steel Construction, Stockholm, 1976, Publication 50.
16. Design guide, structural fire safety. CIB W14 workshop. *Fire Safety J.,* **10** (1986) 75–137.
17. *Fire Statistics United Kingdom* 1989. Home Office, London, 1991.