Fire Research Note

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FIRE PROBLEMS OF PEDESTRIAN PRECINCTS

PART 3. THE SMOKE PRODUCTION OF SPRINKLERED FIRES (LOW WATER PRESSURES)

by

A J M HESELDEN and H G H WRAIGHT

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SUMMARY

This note reports studies of the action of sprinklers on fires in an experimental building 3.8 m x 7.7 m x 2.85 high, representing a shop, giving on to a corridor 6 m wide and 17 m long, representing a covered pedestrian mall. The water pressure at the sprinkler heads was about 1.2 bar(18 lb/in^2).

The fires were always either extinguished or reduced in intensity by the sprinklers. Substantial quantities of smoke were generated by the sprinklered fires, and smoke extraction would be essential to prevent extensive travel of smoke along the mall. The smoke passed into the mall as a layer of hot or warm gases flowing under the ceiling and the great bulk of this remained in a well defined layer as it flowed down the mall so that extraction of gases at the ceiling could have prevented the travel of smoke along the mall.

Although the sprinklers reduced the temperature of the gases and their buoyancy to a level at which the flow through a natural vent would be reduced, they also lessened the amount of gases to be vented.

Subsidiary experiments enabled estimates to be made of the reductions in the burning rate and the rate of flow and sensible heat of the smoky gas passing along the mall.

DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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1. INTRODUCTION

The problems of fire in modern enclosed town centre developments[1] are raising considerable interest and concern at the present time and earlier notes[2,3] in this series have described relevant experimental work done so far at the Fire Research Station. An experimental building designed to represent part of a shopping arcade has been erected, and experiments carried out to measure the quantities of smoke produced by burning a variety of materials and the ability of a vent to remove sufficient smoke to prevent smoke logging of the mall, which would hinder escape.

To overcome the hazard of the spread of fire many shopping developments with covered malls will have sprinkler systems in the shops fronting the malls and it has been suggested that the presence of sprinklers might remove altogether the problem and hazard of smoke-logging in the malls. The experiments described in this note were carried out to investigate the production of smoke and steam of sprinklered fires, and the cooling of the effluent gases by sprinkler sprays, which if excessive might render the venting less effective.

Each fuel load was intended to represent conditions decidedly more hazardous than the 'average' shop occupancy but still reasonably realistic. The aim was to have several types of fire, of different kinds of combustible material, expected to spread at markedly different rates when ignited at one position, carried out both with and without the operation of sprinklers. Measurements were made of temperature and opacity of smoke in the mall and comparisons made between sprinklered and unsprinklered fires.

2. EXPERIMENTAL ARRANGEMENTS

2.1. Building and instrumentation

The construction details of the building and a description of the measuring instruments used have been reported elsewhere[2,3,4]. The fascia board at the fire compartment opening and the hardboard screen (curtain) were in position for all the tests.

2.2. Sprinkler system

Two upright spray sprinklers, rated at 79°C, were installed in the fire compartment, one near the front and one near the rear, at a separation of 3.8 m and a height of 2.45 m above the floor. Each sprinkler was capable of discharging 1.23 l/s (16.2 gal/min) at a water pressure of 124 kN/m^2 (18 lb/in^2 or 1.24 bar).

2.3. Fuel loads

Three very different types of fire were studied each being burnt first without and then with sprinklers installed. The fuel load was placed centrally beneath the rear sprinkler position in all the tests

A 100 kg crib of wood sticks ignited at one end was selected as providing a slowly spreading fire in what is likely to remain one of the commonest combustible materials even in modern shopping arcades.

The second type of fire was started by igniting one end of a row of ten upright discarded motor tyres, total weight about 64 kg. Tyres were chosen since they give a moderately rapidly spreading fire producing much more smoke than wood, very hard to extinguish.

The third fire consisted of a rack loaded with miscellaneous cellulosic combustibles and foamed plastics to represent a display in a typical 'do it yourself' home handyman's shop. Two shelves were used and the total weight of combustible material was about 100 kg, most of which was contributed by wooden slats and plywood. The top of the rack was filled in with a hardboard canopy for some tests. This represents malpractice of a kind which does sometimes occur and is likely to have a marked effect on the effectiveness of an overhead sprinkler in controlling a fire in the rack contents. The rack was ignited at the centre of one side on the lower shelf and was intended to give a rapidly spreading and smoky fire.

Some further tests were carried out to investigate more carefully the cooling effect of sprinkler sprays. In these tests kerosene was burnt over water in trays about 1.6 m by 0.6 m area, situated beneath a sheet steel canopy shaped like a simple pitched roof with the ridge about 0.7 m and the side edges about 0.5 m above the kerosene.

For the first kerosene test the sprinkler head over the canopy was removed and a vertical pipe fitted to conduct the water down to a sparge pipe just above the ridge of the canopy. This distributed the water through holes located reasonably evenly over both halves of the canopy before it ran to waste at each corner. The other sprinkler head was removed from the pipe and the socket plugged. The kerosene was ignited and the water turned on immediately.

For the second test the sparge pipe and vertical pipe were removed and both sprinkler heads refitted with their bulbs removed. Again the water was turned on immediately after ignition of the kerosene. The third test was a repeat of the second except that the water pressure was increased for the first 5 min 20 s of the burning time from the usual 124 kN/m^2 (18 lb/in^2, 1.24 bar) to 2.76 kN/m^2 (40 lb/in^2, 2.76 bar)

The tests carried out are listed in Table 1.

Table 1
Summary of tests

Test No	Fire load	Sprinklers	Vent
112	Wood crib	No	Closed
113	Wood crib	Yes	"
111	Motor tyres	No	"
114	Motor tyres	Yes	"
110	Display rack with canopy	No	"
115	Display rack with canopy	Yes	"
116	Display rack without canopy	Yes	"
117	Display rack with canopy	Yes	Open
118	32 litres kerosene in tray with canopy	Sparge pipe system	Closed
119	27 litres kerosene in tray with canopy	Yes	"
120	36 litres kerosene in tray with canopy	Yes but a higher pressure for first 5 minutes	"

3. TEST RESULTS

3.1. Progress of tests

Brief comments on tests 110 to 117 are given below. The main visual observations are summarized in Table 2.

3.1.1. Crib without sprinklers - test 112

This fire spread very slowly along the crib and only gave rise to optically thin smoke without large soot particles. The rate of burning and therefore of smoke production was low enough for the hot gas layer to remain fairly shallow under the ceiling of the mall. The fire lasted for over 45 minutes.

3.1.2. Crib with sprinklers - test 113

The burning of the crib was rapidly and substantially reduced by the sprinkler so that 5 min after its operation the fire was almost out.

3.1.3. Motor tyres without sprinklers - test 111

The fire spread fairly rapidly from the ignition point producing very dense sooty smoke for some 15 minutes with thinner smoke to floor level. The tyres burnt fiercely.

3.1.4. Motortyres with sprinklers - test 114

The fire continued burning fiercely after the sprinklers had operated, at about 5 and 10 minutes from ignition. The smoke was very dense and full of soot particles. The mall was smoke logged with thin and acrid smoke almost to floor level for several minutes, the smoke being drawn into the mall from the entrance where a cross wind was causing mixing.

3.1.5. Display rack with canopy but without sprinklers - test 110

The fire spread very rapidly from the ignition point producing large quantities of very dense black sooty smoke with some thinner smoke at a low level in the mall, until the plastic material had been largely consumed. After this the wood fuel continued burning producing an optically thinner smoke.

3.1.6. Display rack with canopy and sprinklers - test 115

The fire spread very rapidly up the side of the rack above the ignition point and the sprinklers operated at about 2 minutes. About 3 min from ignition the mall contained steamy smoke almost down to floor level, this having been drawn back into the mall from the entrance. The fire was gradually reduced in intensity. Wetting of unburnt fuel prevented further spread and the burning fuel was rapidly consumed. The fire was finally extinguished by about 12 minutes.

3.1.7. Display rack without canopy and with sprinklers - test 116

After a rapid spread of fire from the ignition point the sprinklers operated (at 2 and $2\frac{1}{2}$ min). The fire was quickly reduced in intensity as the cellulosic fuel in the rack became saturated with water. After 5 min no flames were visible (but the rack was obscured by steam and smoke), and the sprinklers were turned off. Several minutes later small flames could be seen but these were easily put out with a little water.

3.1.8. Display rack with canopy and sprinklers and with roof vent open - test 117

This fire burnt as in previous tests with the rack but the smoky layer was much shallower in the mall and this never became badly smoke-logged. After 10 min the sprinklers were turned off and the fire was found to have been reduced to a very low intensity.

3.2. Gas temperature

The temperature of the hot gases flowing immediately beneath the mall ceiling was considerably lower when sprinklers were operating. This reduction was proportionately similar at positions I, J and K. Figures 1 and 2 show temperature time curves for position J at 0.15 m below ceiling for the three types of fire. Curves for similar tests with and without sprinklers, with and without canopy and with and without roof vent open are shown together.

3.3. Layer depths

The depths of the layer of hot gases in the mall were estimated from the vertical temperature profiles by two different methods. Method A involved inspection of the curve of temperature profile and finding the depth at which the temperature took a comparatively sudden upward turn from the low values recorded in the lower part of the mall. This method was more or less identical to that described by Hinkley[5]. Method B took the layer depth at the level where the temperature above ambient was a quarter of the maximum value obtained in the particular profile. It was found in both methods that all four positions I, J, K and L gave broadly similar estimates with only random variation between them. The mean layer depths for I, J, K and L for both methods are tabulated in Table 3. On the whole the depths of the layer are slightly smaller for the sprinklered fires.

Table 2. Summary of visual observations

Event	Flames reach fire compartment ceiling (min and s)	Smoke reaches fascia board and spills beneath it (min and s)	Smoke reaches screen near open end of mall (min and s)	Rear sprinkler (over fire) operates (min and s)	Front sprinkler (nearer mall) operates (min and s)	Mean depth of smoky layer in mall at certain times	Fire beginning to decrease in intensity (min)
112 crib	-8.00	1.05	2.30	-	-	1.0m at 5.00 1.5m at 10.00 1.5m at 16.00 1.5m at 37.00	37
113 crib with sprinklers	Not noted	0.30	-	4.45	Not fitted	1.0m at 4.30 1.5m at 7.00	5
111 tyres	"	0.45	2.00	-	-	c.1.5m from 5 to 20 minutes after ignition	13
114 Tyres with sprinklers	"	1.15	3.15	5.10	10.05	1.0m at 4.00 1.5m at 6.30	16
110 Display rack with canopy	1.30	1.00	1.45	-	-	1.5 - 1.7m for several minutes	-
115 Display rack with sprinklers with canopy	1.15	0.50	1.40	1.40	2.10	1.5m at 2.10 c. 3.0m at 2.30 over 1.5m at 4.00 and very variable	-
116 Display rack with sprinklers without canopy	1.40	-	2.00	2.00	2.30	1.5m at 2.30	-
117 Display rack with sprinklers with canopy vent open	1.20	1.20	2.00	2.00	2.15	1.0m for most of test	-

Table 3. Comparison of depths of layer of hot gas obtained from the temperature profiles by two methods

Test No	Temperature profiles taken at	Mean depth of hot gas layer from profiles I, J, K, and L	
		Method A	Method B
112 wood crib	5 minutes	1.3 m	1.2 m
113* wood crib	6 minutes	1.4 m	1.1 m
111 motor tyres	9 min 30 sec	1.8 m	1.6 m
114* motor tyres	9 min 30 sec	1.6 m	1.5 m
110 Display rack	3 min 30 sec	2.0 m	1.7 m
115* Display rack	4 minutes	1.6 m	1.5 m
116* Display rack No canopy	4 minutes	1.6 m	1.4 m
117* Display rack Vent open	4 minutes	1.0 m	0.9 m
118 Kerosene with sparge pipe system	5 minutes	2.0 m	1.8 m
119* Kerosene	3 minutes	1.8 m	1.8 m
120* Kerosene	4 minutes	1.6 m	1.9 m

*Sprinklers operating.

Method A – Turning point of curve (see section 3.3)
Method B – 1/4 maximum temperature (see section 3.3)

3.4. Smoke densities

The temperature profiles show that there was a well defined hot or warm layer of gas under the ceiling, and the optical density measurements show that this layer contained smoke several times denser than that below this layer. Thus it is clear that the bulk of the smoke particles from the fire were contained within a hot or warm layer under the ceiling and this means that most of the smoke from the fires could have been removed by a suitable extraction system in the ceiling.

4. RESULTS AND DISCUSSION

4.1. Wood crib fires

Without sprinkler operation (Test 112) the wood crib fire developed slowly, the temperature at J in the mall continuing to rise until the crib had almost burnt away (Fig 1). In test 113 the sprinkler head operated at 4 min 45 s, when a layer 1 m deep of optically thin smoke had built up in the mall, and very soon caused the temperature of the gases in the mall to fall. For the period when the fire was being reduced in intensity by the sprinkler the depth of the hot gas layer is difficult to obtain since the temperatures were very low, but the layer appears to be a little shallower with the sprinklered fire, as might be expected since the burning rate was lower due to the action of the sprinkler.

The sprinkler steadily reduced the intensity of the fire so that in about 5 min (i.e. at 10 min from ignition) the fire was virtually extinguished. Between 5 and 10 min the smoke layer in the mall was changed from a moving layer replenished by the fire to a static layer which, because it was slightly warmer than the air beneath and because there was no way in which it could flow away, still remained under the ceiling of the mall, though it was less stratified than the layer earlier in the test. After 10 min the fire began to produce dense acrid smoke, though at a very low total rate of production, and this gradually filled the fire compartment and slowly entered the mall at a low level.

Up to 10 min, when the sprinklered fire was virtually extinguished, the optical density per metre, 0.3 m from the ceiling, rose to about 0.2 for both fires. After 10 min the optical density per metre of the sprinklered fire did not change markedly, whilst that of the unsprinklered fire increased substantially as the burning rate increased.

The flow of gases through a vent is caused by pressure differences created by differences in temperature and hence density between gas in the layer under the vent and that outside the building. At temperatures, in the gas layer, above about 100°C the mass flow through a vent is not very sensitive to temperature (Fig 3) but at lower temperatures the mass flow can depend substantially on the temperature rise of the hot gas layer above ambient temperature. In the test without sprinklers the temperature of the gases took nearly 20 min to reach 100°C but nevertheless a venting system designed to cope with the smoky gases from the fully developed crib fire would have been large enough to extract all the gases from the earliest stages of the fire despite their low temperature.

The temperature of the gases in the mall after the sprinkler operation was very low but these gases nevertheless formed a layer under the ceiling and in the absence of unfavourable wind pressures would have passed through an open vent. However it must be remembered that in this test the sprinkler very soon stopped the fire from generating any substantial quantity of hot smoky gas so that even if this could not be vented efficiently the length of mall which would be drastically smoke logged would be small.

The quantities of gases generated in these tests were small and hard to estimate. However it was possible to make estimates for the tests employing rubber tyres and the display rack: these are given in the appropriate sections below.

4.2. Motor tyre fires

Without sprinklers the motor tyre fuel load gave a rather slowly spreading but intense fire producing very dense smoke. A slight cross wind at the entrance to the mall produced enough mixing of smoke into the inflowing air to render the conditions within the mall very unpleasant for observers after about 7 min, i.e. before the fire had reached its height.

In the test with sprinklers operation of the first head appeared to have little effect on the fire. However Fig 1 shows that the temperature of the gases in the mall immediately stopped rising rapidly, increasing only slightly until the second sprinkler operated, after which the temperature remained constant for several minutes.

Comparison of the temperature profiles of both fires at their peak shows that the depth of the hot gas layer was then nearly the same.

In both tests the maximum optical density per metre, at 0.3 m and 0.9 m from the ceiling was very high, about 4.5.

At 1.7 m below ceiling level the optical density per metre in both tests was about 0.5, still much too high to permit safe evacuation, for it corresponds to a visibility of only about 2.5 m (8 ft)[6].

A rough measure can be obtained[4] of the relative smoke production of wood and motor tyres in terms of the optical density per metre generated within the same volume by the same weight of fuel. It can be shown that the standard optical densities (D_c) for wood and rubber tyres are in the ratio 1 : 23. The standard optical density is the optical density per metre produced by burning 1 g of fuel in a stirred volume of 1 m^3.

The above ratio is larger than the difference found previously[2] between the smoke production from a wood crib and foam rubber (D_c for wood $\sim$ 0.1 and D_c for rubber $\sim$ 0.6, i.e. (1 : 6) but apart from the crudeness of the calculation and differences in types of rubber and modes of combustion a motor tyre will contain a substantial proportion of carbon filler* which might increase the smoke production.

Rough estimates of the 'effective' thermal outputs of the fires, both sprinklered and unsprinklered, can be obtained by comparison with previous tests[3] with trays and kerosene where the rates of burning were known. Similar layer depths at the screen and similar temperatures in the gases at the screen and along the length of the mall imply similar rates of flow of gas and of heat into the mall.

The 'effective' thermal output is taken as the output of an unsprinklered fire in the fire compartment which would produce the same temperatures and gas flows in the mall. The effective output of the sprinklered fire is reduced not only because the rate of burning of the fire is actually reduced but because of the cooling caused by the sprinkler spray.

Values obtained for peak thermal outputs are given in Table 4.

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*33 per cent was a value quoted for one type of tyre[8]

Table 4

Rough estimates of the 'effective' peak thermal outputs

Test number	Test conditions: Fuel	Canopy	Sprinklers	Vent	Time of peak output (min)	Peak thermal output (MW)
110	Display rack	Yes	No	No	$3\frac{1}{2}$	3.2
115		Yes	Yes	No	3	∼ 0.8
117		Yes	Yes	Yes	3	0.8
116		No	Yes	No	4	≯ 0.3
111	Motor tyres	–	No	No	$9\frac{1}{2}$	1.1
114		–	Yes	No	$9\frac{1}{2}$	∼ 0.2

Table 5

Flow of heat and hot gas under screen

Test number	Nominal peak thermal output MW	Peak temperature rise of gases passing under screen °C	Peak flow of gases under screen m^3/s*	Peak flow of heat under screen MW	as % of nominal output
110	3.2	167	4.0	0.8_2	26
115	∼ 0.8	70	2.3	0.20	∼ 25
117	0.8	(8(Under screen) (36(Up vent)	(0.05(Under screen) (2.9 (Up vent)	0.13+	16+
116	≯ 0.3	32	1.1	0.04_3	≮ 13
111	1.1	80	2.3	0.22	20
114	∼ 0.2	24	1.1	0.03_2	∼ 15

*Reduced to ambient temperature

+Including heat flow up vent

Estimates of the peak flow of gases under the screen at the end of the arcade obtained from equation 18 of reference 5 and the heat contained in this flow are given in Table 5. The result of the sprinkler operation has been to reduce the heat flow under the screen from 0.22 to 0.03_2 MW, a reduction by a factor of about 7. From the experiments described in section 4.4 with a canopy over burning trays of kerosene it will be shown that the cooling effect of the sprinkler (at the water pressure of test 114), i.e. with the burning rate unchanged, is to halve the heat flow under the screen (compared data for tests 118 and 119 in the last column of Table 7). If we take this as applying to test 114 and if we assume that heat losses up to the screen are in the same proportion, roughly half of the reduction in heat flow between tests 111 and 114 would be due to the cooling action of the sprinkler spray on the hot gases and the remainder of the reduction, i.e. a factor of about $3\frac{1}{2}$, would be due to the reduced burning rate given by the sprinkler.

Clearly no high accuracy can be claimed for these ratios in view of the assumptions made but nevertheless thay may give some idea of the relative importance of cooling in the sprinkler spray and reduction of burning rate.

The temperature of the gas passing along the mall was reduced by the sprinkler to a level at which a vent would not operate efficiently (Fig 3). Nevertheless the gas flow was also reduced (Table 5) so that a venting system capable of extracting all the smoky hot gases in the absence of sprinklers would have been large anough to extract the gases from the sprinklered fire.

Since we have values for the optical density, temperature and flow rate of the gases in these tests we can obtain the relative rates of production of smoke in mass terms. We assume that the particle size and optical properties are the same for sprinklered and unsprinklered fires. At $9\frac{1}{2}$ min (i e at peak temperature) values for optical density per metre, temperature rise (Fig 1) and flow rate of gases (Table 5) are 4.0, 140°C, and 2.3 m^3/s respectively for test 111. For test 114 corresponding values are 4.0, 40°C and 1.1 m^3/s. The flow rate value has been reduced to ambient temperature, but the optical density was as measured in gas at 140°C and therefore needs to be corrected by a factor $\left(\frac{290 + 140}{290}\right)$ to yield the optical density of gas cooled to ambient temperature.

Then the ratio of the mass rates of production of smoke for test 111/test 114 is, approximately,

$$\frac{2.3 \times 4.0 \times (290 + 140)}{1.1 \times 4.0 \times (290 + 40)} = 2.7$$

and this figure is close to the ratio of rates of burning, estimated as about 3.5.

4.3. Display rack fires

For the test without sprinklers (No 110) the very rapid spread of fire is indicated by the rate of temperature rise of the gases flowing along the mall (Fig 2). Peak temperatures were reached in $3\frac{1}{2}$ min but were not sustained because they were generated by the burning of thin fuels (cardboard, wood wool) and plastics (expanded polystyrene and polyurethane) which quickly burnt out, leaving the fire maintained by thicker wood fuel elements (board, sticks). Much lower temperatures were attained with sprinklers with a canopy present, (Test 115 Fig 2), but their operation did not stop the temperature from rising rapidly and substantially, as the sprinklers were prevented by the canopy from effectively attacking the fire.

Without the canopy much lower peak temperatures were obtained (Test 116) since the sprinklers were able to reduce the rate of burning considerably.

The sprinklers caused considerable mixing in the fire compartment, which was filled from floor to ceiling with dense swirling smoke, however the smoke flowed out of the top part of the opening and formed a well defined layer under the ceiling of the mall.

The rate of flow of smoke-laden hot gases out of the mall has been calculated approximately, assuming that the layer depth at L is the same as that at the screen between L and M and that the flow is given by equation (18) of ref (9). For test 117, with the vent open, the calculated flow up the vent has also been included. These values are given, as a function of time, in Fig.4 and the total quantity of gas produced up to various times in Fig 5 The large reductions in the amounts of smoky gases caused by the sprinkler operation are noteworthy and lend support to the use of sprinklers in the shops of a shopping complex quite apart from the primary benefits gained by reduction or elimination of fire spread.

The gas temperatures were much lower with sprinklered fires (Fig 2) and a vent would not be able to extract gas at this temperature so efficiently as at a higher temperature (Fig 3). However the amount of gas to be removed was reduced by the sprinklers so that a vent designed to deal with all the gases from the unsprinklered fire would have easily been able to cope with the gases from a sprinklered fire.

The values of heat flow under the screen given in Table 5 and 7 enable rough estimates to be made of the reduction in burning rate due to the sprinklers. With the same assumptions as in Section 4.2 we can say that if in test 110 there had been sprinkler cooling of the gases but no effect on burning rate, then we would have obtained a heat flow under the screen about half of that measured, viz 0.4 MW. This suggests (Table 5) that the peak burning rate in tests 115 117 and 116 was reduced by factors of about 2, 3 and 10 respectively below that of test 110. Again, it must be remembered that these are very rough values. The layer depths when the sprinklers were reducing the intensity of the fire were only slightly smaller with the sprinklered fires than with the unsprinklered fire at its peak.

All the display rack fires produced dense smoke. With a canopy, but no vent there was little difference in optical density between sprinklered and unsprinklered fires either at high or low levels except that after 4 min the optical density 0.3 m from the ceiling remained higher in the sprinklered fire. In both cases the optical density at the lowest positions rose to at least 0.5 (corresponding to less than 2.5 m visibility) for about 2 min around the period of peak burning, apparently because of smoke drawn in after mixing at the entrance due to a cross wind. With no canopy, the optical density was lower than in test 115 at first. It eventually rose to values comparable with those of the other display rack fires with vent closed, but only when the fire was nearly out and the gas layer must have been almost stagnant.

As with the rubber tyres the data permit an estimate to be made of the relative smoke production of the fuels in the display rack (for the peak burning period largely polystyrene, polyurethane and some cardboard and wood). Firstly assuming that the predominant fuel burning is polystyrene with a calorific value of about 40 kJ/g[10,11], the standard optical densities of wood and 'display rack fuel' are in the ratio 1 : 17.

However, the polyurethane, cardboard and wood were also burning and would have contributed to the heat release and to some extent to the smoke production. Taking a mean calorific value of 25 kJ/g gives a ratio of standard optical densities of wood and 'display rack fuel' of 1 : 11 and these ratios may be compared with a ratio of up to 1 : 9 between wood and polystyrene obtained in another experimental series[2].

These ratios are naturally only crude estimates but they do serve to show again how the smoke production per unit mass can vary widely between different materials.

The optical density of the smoke produced by the vented fire, Test 117 was much smaller at all levels than that of the corresponding fire with vent closed, test 115, apart from one reading at 3 min, and fell away much more rapidly as the fire began to die down. This is no doubt because the vent allowed smoke laden gases to flow out of the mall; at the end of the fire they were not trapped in a stagnant layer as in the tests with the vent closed. Furthermore, the air entering to replace the gas passing up the vent maintained much clearer conditions in the lower part of the mall - the optical density per metre at 1.4 m from the floor did not exceed 0.15, corresponding to a visibility of 8 m.

This test thus demonstrates the benefits of venting, viz a shallow smoke layer under the ceiling in the mall, smoke extraction so that the flow of smoke can be arrested at the screen more rapid dispersal of smoke after the fire has been controlled and also clearer air at a low level.

As in the previous section we can estimate the relative mass rates of production of smoke particles. The data are given in Table 6.

Table 6
Data for estimates of relative mass rates of smoke production at peak burning

Test number	Optical density/m	Temperature rise of gases at J °C	Flow rate of smoke-laden gases m^3/s (Reduced to ambient temperature)
110	4.5	255	4.0
115	4.0	115	2.3
116	2.3	60	1.1

The ratio of the mass rates of production of smoke for tests 110/115 is

$$\frac{4.0 \times (290 + 255) \times 4.5}{2.3 \times (290 + 115) \times 4.0} = \underline{2.6}$$

and for tests 110/116 is

$$\frac{4.0 \times (290 + 255) \times 4.5}{1.1 \times (290 + 60) \times 2.3} = \underline{11}$$

and these results are very similar considering the assumptions made and the crudeness of the calculations, to the values for relative burning rates

for 110/115 of 2

and 110/116* of 10

*It is more difficult to use data for test 117 in this way as the vent was open

These results and the corresponding result for the motor tyres fuel (Section 4.2) show that the sprinkler did not materially affect the constant in the proportionality relationship between the mass rate of fuel decomposition and the mass rate of production of the smoke particles.

4.4. Kerosene fires (cooling effect of sprinkler spray)

These fires enabled a measure to be obtained of the cooling of the hot gases from a fire by their passage through a sprinkler spray, separately from the action of a sprinkler on the burning of the fire by cooling the fuel bed. In all three fires the fuel tray was protected with a cooled metal cover which prevented all but a few drops of water from falling into the trays. With the sparge pipe (Test 118) water ran down from the corners and lower edges of the cover in thick streams which would have had very little cooling effect on the flames passing under the edge and rising up. In the tests with sprinklers (119, 120) the rising flames encountered the sprinkler spray and were substantially cooled by their passage through it.

The duration of the fires to the point at which large flames began to subside was proportional to the amount of kerosene used so that the burning rate and heat release did not differ substantially between tests.

The temperature of the gases in the mall was substantially lower in the tests with sprinklers than in the test with the sparge pipe and these temperatures alone could be used to give a measure of the cooling produced by the sprinkler spray. However the downward thrust of the spray may affect flame size, air entrainment and therefore the amount of air mixing with the combustion gases, which can itself affect the temperature of the gases in the mall.

Table 7 gives estimates of the rate of flow of gases under the screen, which suggest that whilst the low pressure sprinklers of test 119 have affected the flow very little, the high pressure sprinklers of test 120 have reduced the flow substantially. It seems reasonable to use as an overall measure of sprinkler cooling, the reduction in the sensible heat of the gases passing the screen.

Table 7 shows that low pressure sprinklers (Test 119) have reduced the sensible heat passing the screen to about $\frac{1}{2}$ and high pressure sprinklers (Test 120) to about $^{1}/10$ of that without sprinkler (Test 118).

The sprinklers had very little effect on the depth of the layer in the mall or its optical density.

Table 7

Rates of gas flow under screen
(Tests 118, 119 and 120)

Test number	Conditions	Time (min)	Depth of layer at L (m)	Peak temperature rise of layer at L (°C)	Gas flow under screen (m^3/s reduced to ambient temperature)	Heat flow under screen MW
118	Sparge pipe	5	1.0_5	105	5.1	0.65
119	Sprinklers (low pressure)	3	1.0	65	4.1	0.3_3
120	Sprinklers (high pressure)	4	0.7_5	25	1.9	0.06

5. GENERAL DISCUSSION

5.1. Effect of the sprinklers on the fire itself

Although these tests were not primarily made to see how well sprinklers can extinguish a fire nevertheless some comments on this aspect can be made.

The experiments illustrate various outcomes for a fire which has operated sprinkler heads. The sprinkler may extinguish the fire, reduce its rate of burning but not extinguish it or, if the spray is obstructed from reaching the seat of the fire, may have little effect on it.

The wood crib fire is an example where the fire was rapidly reduced. Only 45s after the sprinkler had operated the flame height had been halved and 5 min later flaming had almost ceased.

The rubber tyres were less successfully dealt with – clearly these were a difficult problem for the sprinkler system in part because the fire was started in the space within a closely packed row of tyres where the water could not penetrate easily. Nevertheless the data discussed in Section 4.2 show that the peak burning rate was substantially reduced by the sprinkler.

The display rack fire was dealt with quite effectively when there was no canopy, the fire being virtually extinguished 3 min after operation of the first head, but when there was a canopy the peak burning rate was only halved by the sprinkler spray.

It must of course be remembered that a very important role played by the sprinkler, even with a fire which is difficult to extinguish, is in preventing or reducing fire spread by wetting down fuel adjacent to the fire.

5.2. Smoke production of a sprinklered fire

It has not proved possible to estimate the rate of flow of the smoke-laden hot gases for the wood crib fires and we can therefore only note that optically thin smoke was produced in these tests and that the generation of smoke was rapidly checked by the sprinkler operation.

For the fires with motor tyres fuel the peak rate of flow of smoke-laden gases under the screen (and this would be typical of that required to be dealt with by a vent system some distance down the mall) with a sprinklered fire was about half of that without a sprinkler (Table 5), the optical density of the gases being very similar in both cases.

The sprinklered fire gave a rate of flow of gas under the screen of about 1 m^3/s (reduced to ambient temperature) and a rate of flow of this magnitude was sustained for at least 10 min.

Estimates of the production of smoke laden gases from the display rack fires have been made (Fig's 4 and 5) and these show the smaller quantities given by the sprinklered fires.

The question arises, whether the amount of smoke from the sprinklered fire was so small that no provision would need to be made for smoke extraction or dispersal. In considering this it must be remembered that the smoke produced by the fire was very dense. It had an optical density per metre measured in the mall, in the region of 4, corresponding to a visibility of 0.5 m[7], and even if diluted with 9 times its own volume of clean air (i.e. diluting by a factor of 10) would still have had a visibility of only some 3 m - still far too low to be tolerated.

Fig 5 shows that up to 8 or 9 min, test 115 (with canopy and sprinklers) produced about half the quantity of gases as did test 110 (no sprinklers) and had sent a total of some 450 m^3 of heavily smoke-laden gas under the screen near the end of the mall. This is sufficient smoke to obscure a 250 m length of the mall from floor to ceiling to a visibility of 3 m so that there can be little doubt that in this case smoke extraction is required to prevent travel of smoke along the mall.

In test 116 (no canopy, with sprinkler) where the sprinkler was better able to reach and control the fire the total quantity of gas flowing under the screen was only 150 m^3 but, if diluted, for example by mixing due to cross flows, even this quantity would be capable of causing dangerous smoke logging over a considerable distance.

5.3. Effect of sprinklers on the removal of smoke by venting systems

The temperature profiles and the optical density measurements show that the great bulk of the smoke production from the fires, both sprinklered and unsprinklered was in a hot or warm layer flowing under the ceiling of the mall. This means that a ceiling extraction system of suitable capacity together with ceiling screens could arrest the travel of smoke along the mall.

The sprinkler spray always cooled the gases, or at least always gave lower temperatures in the gases reaching the mall, but nevertheless at the water pressure used the smoke formed a hot or warm gas layer under the ceiling which could be vented. The sprinkler never cooled the fire gases so much that venting could not have occurred except when the fire was almost extinguished.

The gas temperature in the mall was reduced in some cases to a value low enough to make venting inefficient, but in these cases the rate of production of gases required to be vented was lowered.

Table 5 gives estimates of the peak gas flows from the various fires which could be used to obtain the desired vent capacity.

5.4. Effect of sprinklers on smoke conditions within mall

It has already been mentioned that the bulk of the smoke production of the sprinklered fires was in a layer under the ceiling. Thinner smoke was found below this down to a low level in some of these tests, apparently always due to smoke cooled at the entrance (usually by mixing by a cross wind) being drawn back into the mall. With a proper smoke extraction system this would not have occurred, and thus there is no reason to believe that at these pressures, sprinklers would give more smoke logging at a low level in the mall.

However the smoke at a low level in the mall was decidedly more acrid and irritant to the eyes when sprinklers were in operation.

The optical density of the smoke in the ceiling layer was generally not different with sprinklers operating, so that even under conditions giving more mixing of this layer with the air beneath, the lessening of visibility would not be worse for the sprinklered fires.

One test (117), with sprinklers, illustrated the benefits of venting, viz a shallow smoke layer under the ceiling in the mall smoke extraction so that a ceiling screen could have arrested smoke travel along the mall, more rapid dispersal of smoke after the fire has been controlled and clearer air at a low level.

The sprinkler spray does not appear to wash out any of the heavier soot particles as might perhaps be expected.

5.5. Layer depths in mall

The depth of the hot layer beneath the mall ceiling has been estimated from the vertical temperature profiles. The temperature profiles were used in two ways to obtain layer depth and from Table 3 it is seen that both give broadly similar values though there is a tendency for the turning point method to give larger values than the 25 per cent of maximum temperature method.

The visual estimation of depth of smoky layer was complicated in these tests by the cross wind at the entrance to the mall causing swirling and mixing with clear outside air so that the layer appeared to be especially deep at the entrance. To observers standing outside the conditions in the mall probably appeared worse than they really were, partly due to the contrast between the outdoor light and the darker conditions in the mall.

6. CONCLUSIONS

6.1. The operation of the sprinklers at 1.24 bar 124 kN/m^2 (18 lb/in^2) reduced the peak burning rate, the rate of flow of hot smoky gases along the covered mall and the temperature of these gases.

6.2. The wood crib fire was rapidly controlled and extinguished, the display rack fire was controlled and extinguished fairly quickly without a canopy but less well when a combustible canopy obstructed the sprinkler spray. The motor tyres fire was not extinguished.

6.3. Rough estimates have been made of the reductions in peak burning rate caused by the sprinklers. There were reductions to about $\frac{1}{3}$ (motor tyres), $\frac{1}{2}$ to $\frac{1}{3}$ (display rack with canopy) and $^1/10$ display rack without canopy) of the corresponding burning rate without sprinklers.

6.4. The cooling action of the sprinklers on the hot gases, apart from the effect on burning rate, halved the sensible heat in the gases flowing along the mall.

6.5. In all the sprinklered fires the great bulk of the smoky gases emerging from the fire compartment formed a layer flowing along under the ceiling of the mall. Optically thinner smoke was present in some tests down to ground level in the mall and this appeared to have been drawn back from the open end of the mall where cross winds had produced mixing and cooling. There was little evidence that this low level smoke logging was worse for the sprinklered fires. The smoke from sprinklered fires was however particularly acrid.

6.6. The quantities of smoky gas generated by the sprinklered fires were large enough to make smoke extraction from the mall essential if substantial travel of smoke along the mall was to be prevented.

6. 7. The temperature of the smoky gas layer was reduced by sprinklers to a level at which vents would not be operating efficiently, but the sprinkler also reduced the quantity of gas requiring to be vented so that a venting system capable of extracting the smoke from the unsprinklered fire would have been able to deal with the smoke from the sprinklered fires.

6.8. The sprinklers had only a very small effect on the depth of the hot gas layer.

6.9. The optical density of the smoke produced by the sprinklered fires was very similar to that of the unsprinklered fires. The sprinkler did not substantially affect the mass of smoke particles produced per unit mass of fuel decomposed. The sprinkler spray does not appear to 'wash out' smoke particles.

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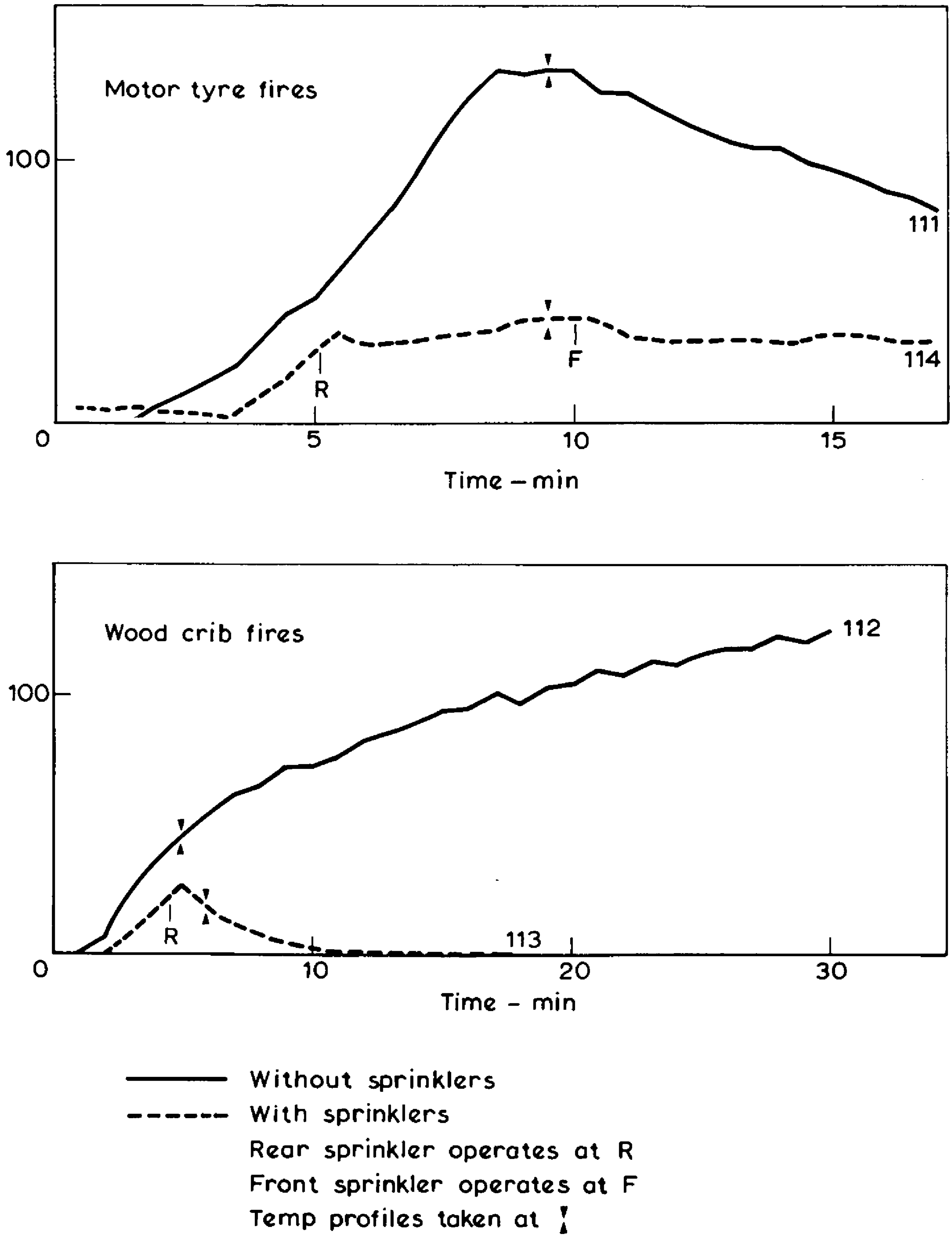

Figure 1 Effect of sprinklers on gas temperature in the mall – top thermocouple at J

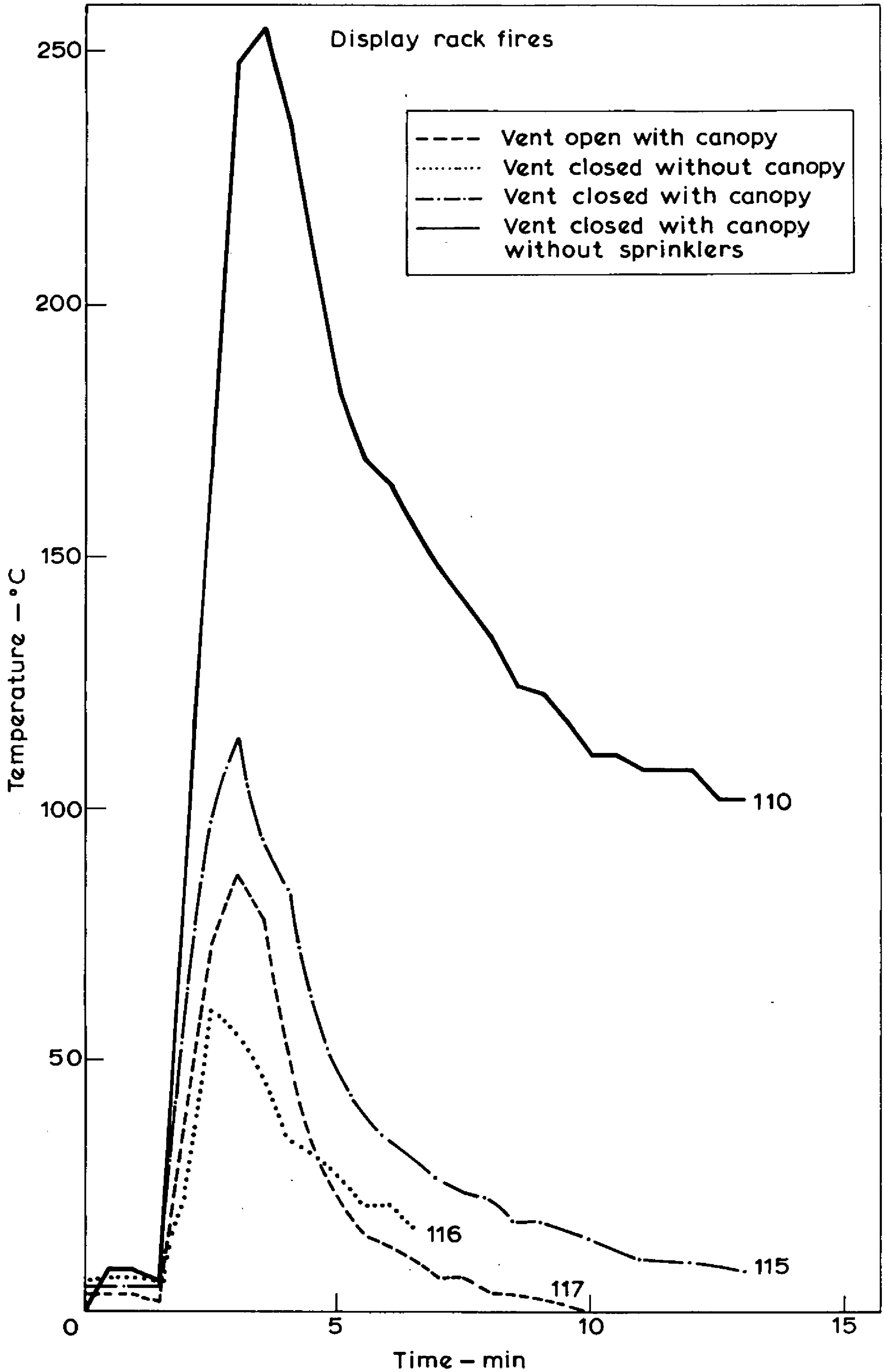

Figure 2 Effect of sprinklers on gas temperature in mall

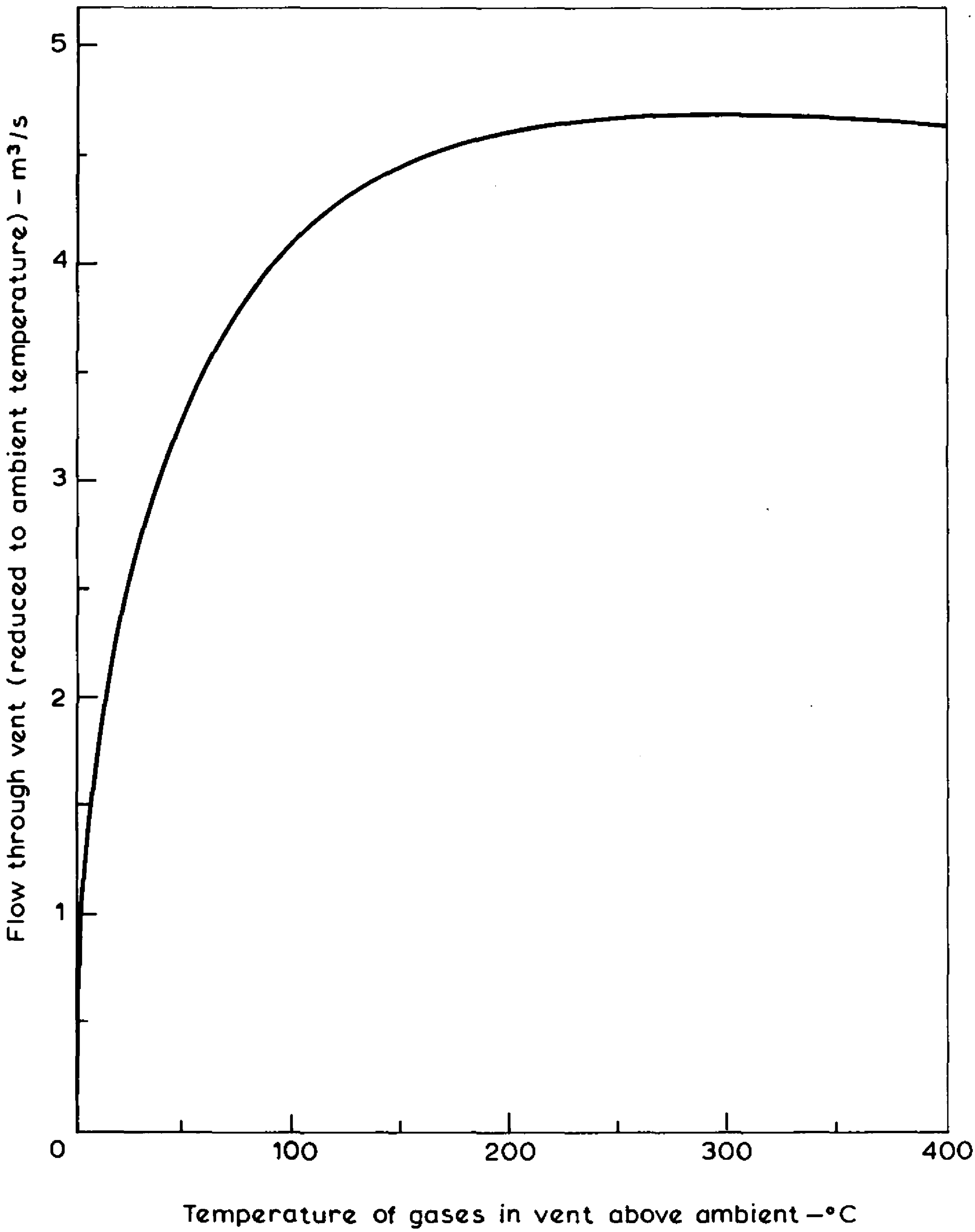

Figure 3 Effect of temperature on the flow through the vent(5)

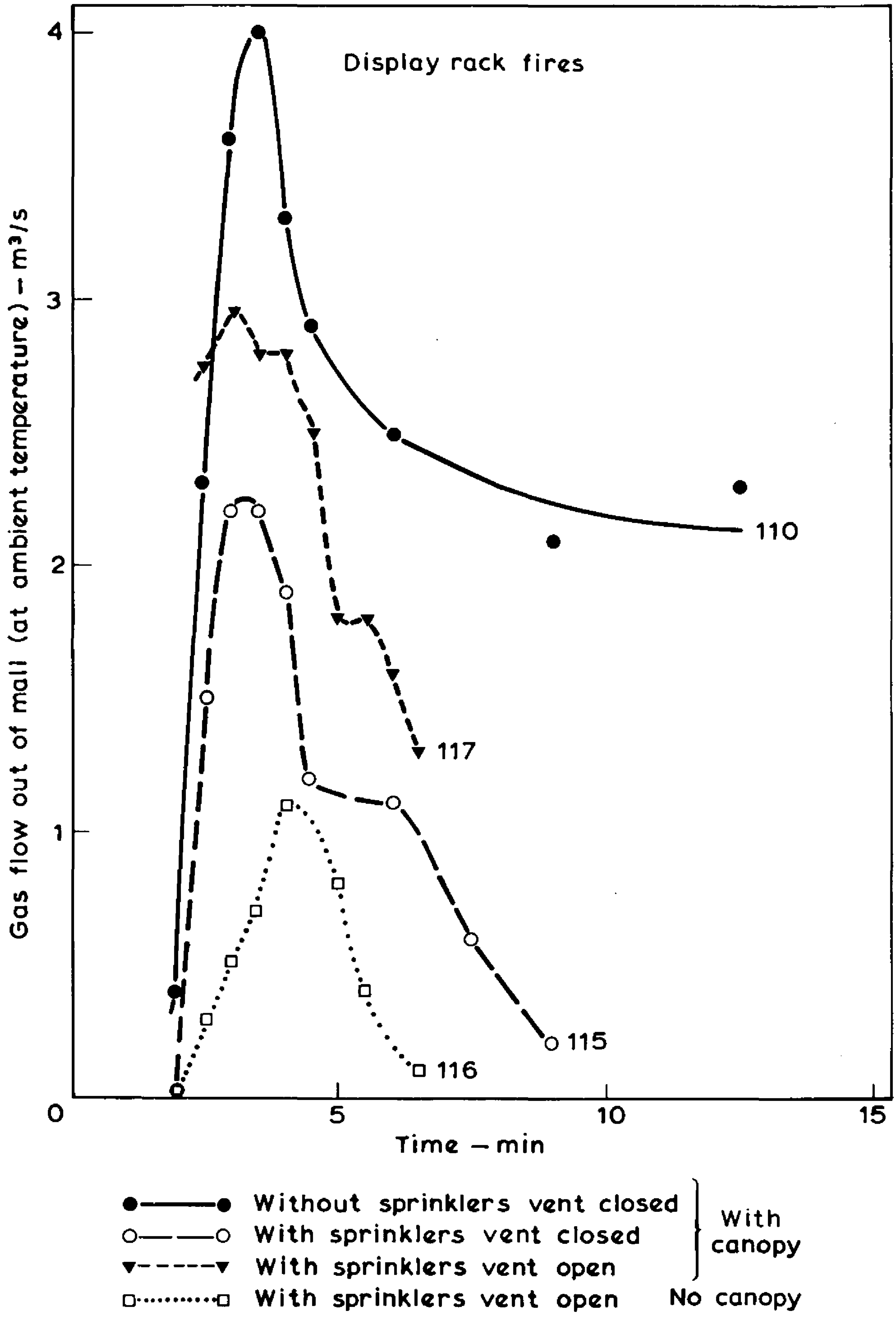

Figure 4 Effect of sprinklers on rate of flow of smoke-laden gases

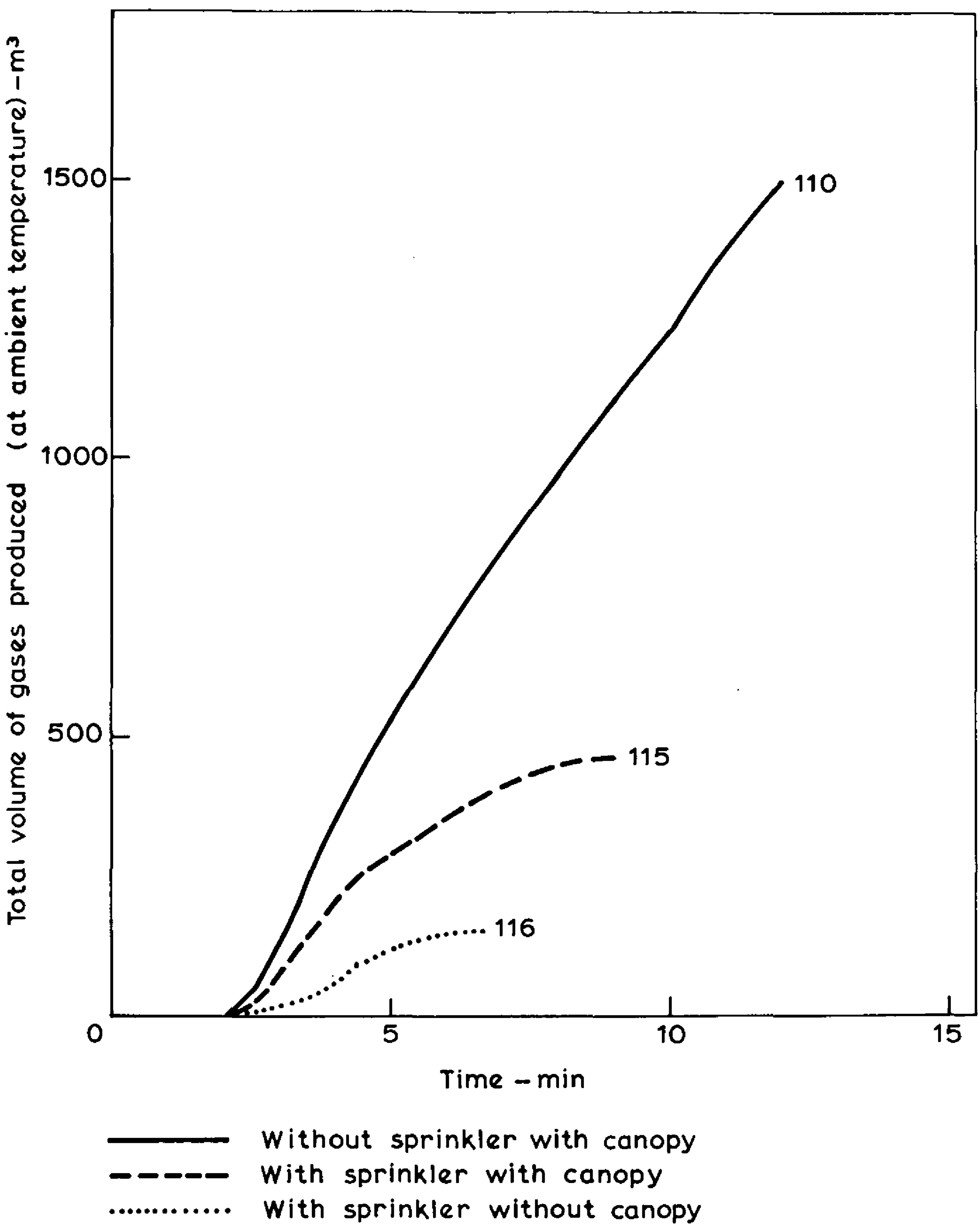

Figure 5 Effect of sprinklers on total quantity of smoke produced up to various times