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THE PREVENTION OF FIRE SPREAD IN BUILDINGS BY ROOF VENTS AND WATER CURTAINS
PART 1. FIRE EXPERIMENTS

by

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SUMMARY

The rapid horizontal spread of fire in a building compartment is largely the result of the deflection of flames by the ceiling and the flow over large distances of hot gases under it.

Opening enough holes in the ceiling should therefore reduce this rate of spread though the areas of venting required will be much larger than required to reduce smoke logging, but no amount of venting can necessarily stop the fire if it can spread unaided by the ceiling. Such spread could be controlled, where necessary, by water. Water curtains or sprinklers - without vents - control fires before they become too large. In principle the combined use of vents and water could prevent the spread of very large fires.

This report describes some experiments in a building 15.5 m (51.5 ft) long and 4.5 m (15 ft) wide which demonstrate that the combined use of roof vents and water curtains can effectively limit fire spread; further studies are desirable to assess their economic value vis-a-vis, say a sprinkler system or a higher level of compartmentation.

KEY WORDS: Water curtains, building, roof, vents, fire spread, smoke.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
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1. INTRODUCTION

A sprinkler system is frequently employed to prevent a small fire becoming a large one and compartmentation by means of fire division walls is employed to limit the extent of the damage that a fire can produce. The purpose of sprinklers or compartmentation thus overlap but are essentially different and, whilst it is sometimes not necessary to employ both, there are situations where one does not rely wholly on sprinklers in an unlimited area.

Many modern manufacturing processes, e.g. vehicle assembly lines, require factories with very large areas of unobstructed floor. Little compartmentation is possible without unacceptable effects on the economics of the processes and this has led on occasions to disastrous fires, sometimes resulting in the loss of the whole factory. When a fire is relatively small in a large single-storey building roof venting systems can clear smoke sufficiently to permit the fire to be found and fought[1], but, if a fire becomes large, roof venting systems cannot prevent fire spread taking place. Flames may travel along under the ceiling or roof and irradiate extensive areas of fuel[2]. Similarly sprinklers are expected to prevent a fire becoming large, but if for some reason the fire overcomes the sprinklers it can spread quickly over large areas.

Thomas[3] has suggested that this spread of fire could be prevented or reduced without obstruction of the floor by a combination of roof venting with water curtains installed at the base of fixed roof screens. The fixed screens would restrict the sideways movement of flame and hot gases beneath the ceiling and by increasing locally the depth of the hot gas layer, would increase the rate of flow of hot gases through the vents. If the vent area is large enough, no flames or hot gases need flow sideways under the ceiling; it is these that cause rapid fire spread and, sometimes cause too many sprinklers to open for any one of them to be effective. The water curtains would restrict spread over the fuel at low level by wetting it down, and to a much smaller extent by absorbing radiation. It is shown in Appendix I that water might be used as much as ten times more effectively in wetting down fuel than in absorbing radiation as a spray.

Since the whole system envisaged is quite complex and its behaviour is not as yet completely predictable the fire experiments described in this note were carried out on as large a scale as could be managed at present, as a pilot study to judge whether the performance of water curtains was sufficiently promising to justify a more extensive investigation. One of the factors which might reduce the effectiveness of a water curtain could be any substantial deflection of it towards the fire caused by the flow of air induced by the fire itself. This was investigated in a separate series of experiments described in Part 2 of this note.

The economics of the method would also need to be considered vis-a-vis other protective devices, e.g. sprinklers. The cost of a sprinkler system increases as the total area covered, as does the cost of a venting system. The cost of a water curtain system, however, depends not only on the total area to be protected but also on the area of the smallest unit to be surrounded (as does compartmentation) and the cost can therefore be increased or decreased as this area is decreased or increased for a given total area. For some situations water curtains might require a larger water flow than a sprinkler system and should therefore not operate as early in the development of the fire. Similarly the area of roof venting to prevent spread is greater than that required to prevent smoke logging and large areas of roof should not open to a small fire. Therefore, whilst part of the available roof area might be vented automatically, the opening of larger areas should be delayed.

These questions and their economics need further study.

2. FIRE EXPERIMENTS

Five experimental fires were carried out to study the behaviour of a fire in a building with and without a water curtain and a roof vent. It was not possible to explore in detail all possible variables which might affect the result and as far as could be predicted in advance conditions were arranged so that the water curtain would be only marginally successful in arresting the fire. It was thought that the effect of the combination of roof vents and water curtains would then show up more clearly.

2.1. Fire building

The single storey brick building (Figs 1 and 2) used in the experiments measured internally 15.5 m x 4.5 m (51 ft 6 in x 15 ft)[4]. The two end sections had flat roofs of reinforced concrete 2.5 m (8 ft 3 in) high internally, and the central section had a pitched roof

5 m (16 ft 5 in) high at the ridge with slopes of 22° and 57°, constructed of corrugated asbestos-cement sheeting attached to steel purlins lined internally with vermiculite plaster on metal lathing. The roof area of the middle section was divided into two compartments approximately 2.4 m (8 ft) and 3.6 m (12 ft) long by a roof screen of vermiculite plaster on metal lathing, the lower edge being 3.3 m (11 ft) above the floor. There were three low level openings (Figs 1 and 2) each 0.9 m (3 ft) square, an open doorway 0.9 m (3 ft) wide x 1.8 m (6 ft) high and another opening 1.8 m (6 ft) wide x 0.38 m (15 in) high to allow air to flow into the building at a low level. A vent, the area of which could be varied and which could be closed, was incorporated in the roof of the larger portion of the central section.

2.2. Fuel

In each test a crib of 25 mm (1 in) thick square wood sticks spaced 75 mm (3 in) apart, measuring 1.8 m (6 ft) x 3 m (10 ft) x 0.3 m (1 ft) deep was burned on the floor of the central section beneath the vent opening. The stick thickness was chosen to give a fire lasting for 10-15 minutes. To indicate fire spread additional cribs 0.6 m (2 ft) wide and 0.3 m (1 ft) deep and having the same stick thickness and spacing as the main crib extended from the main crib to the end of the north or south compartment or both (Figs 1 and 2).

2.3. Water curtain

This was produced by a line of Lechler flat jet F33/120° or F34/120° nozzles mounted 0.3 m (1 ft) apart on a pipe of 65 mm (2.5 in) internal diameter, one end of which was connected to the water supply. The nozzle diameter was either 3 or 4 mm (0.12 or 0.16 in), so that the pressure drop along the supply pipe was not sufficient to cause any significant variation in nozzle output along the pipe. Details of the nozzles and water curtains are given in Table 1. This rate of application was chosen to be just larger than the value of 0.08 $l\ m^{-2}\ s^{-1}$ (0.10 $gal\ ft^{-2}\ min^{-1}$), shown by O'Dogherty et al[5] to be a critical rate in arresting the spread of fire in deep cribs in a very large building, since it was felt that with such a flow rate there was a strong probability of obtaining spread past the curtain because of the confining effect of the roof on the hot gases and flame produced from the fire.

Table 1

Details of nozzles and water curtains

Test No.	Nozzle type	Nozzle diameter		Nozzle pressure		Water flow rate		Height of nozzles above floor		Width of wetted area		Rate of water application at floor level	
		mm	in	N/m^2	lb/in^2	$l\ s^{-1}m^{-1}$	$gal\ min^{-1}ft^{-1}$	m	ft	m	ft	$l\ m^{-2}s^{-1}$	$gal\ ft^{-2}min^{-1}$
1	The water curtain was not turned on for the first test												
2	F33/120°	3	0.12	27×10^3	4	0.12	0.5	2.4	8	1.2	4	0.10	0.12
3	F34/120°	4	0.16	27×10^3	4	0.17	0.7	3.3	11	1.7	5.5	0.10	0.12
4	F34/120°	4	0.16	27×10^3	4	0.17	0.7	3.3	11	1.7	5.5	0.10	0.12
5	F34/120°	4	0.16	27×10^3	4	0.17	0.7	3.3	11	1.7	5.5	0.10	0.12

Although nozzles of bore diameter as large as 6 mm (0.24 in) were available, smaller nozzles were used in these tests since they produced a reasonably coherent curtain at these low pressures and rates of flow. Each nozzle produced a flat 120° 'fan shaped' spray and to reduce coalescing between sprays from different nozzles these were turned so that the plane of the flat spray made an angle of about 20° with the pipe (Fig.3).

The transmission of the water curtain produced by the 3 mm (0.12 in) dia. nozzles, for various water flow rates, was measured using a narrow-angle total radiation pyrometer 1 m (3 ft 4 in) above the floor aimed horizontally through the curtain at a gas-fired surface-combustion panel. The results, shown in Fig.4, indicate that to achieve a reduction of, say, 50 per cent in the incident intensity a water flow rate of some 0.4 $l\ m^{-1}\ s^{-1}$ (1.6 $gal\ ft^{-1}\ min^{-1}$) would be required. For the same nozzle pressure the 4 mm diameter nozzles would be expected to give a curtain having slightly higher radiation transmission, but this was not actually measured.

At the flow rates in the fire experiments the radiation transmission would have been in the region of 90 per cent.

The drop size distribution at the pressure used in the tests was not known, but it was not thought necessary to determine it at this stage.

2.4. Measurements

(a) The spread of fire at floor level out of the main compartment along the narrow cribs was observed through the low level openings.

(b) Additional indications of fire spread were obtained from 100 mm (4 in) square specimens of fibre insulating board mounted alternately 0.6 or 1.2 m (2 ft or 4 ft) above the floor at 1.2 m (4 ft) intervals from the main crib. Similar specimens were fixed to the middle and near the north and south sides of the ceilings in the north and south compartments. Additional indicator specimens were used in the third and subsequent tests, these were specimens of fibre insulating board 4.8 m x 0.3 m (16 ft x 1 ft) positioned 0.3 m (1 ft) and 2.1 m (7 ft) above the floor extending from above the main crib through the curtain into the north compartment, and pieces of filter paper and cardboard stapled to wood sticks which were suspended in the north compartment and the partition compartment.

(c) Gas temperatures were measured using bare chromel-alumel thermocouples of 0.38 mm or 0.71 mm dia. (28 or 22 SWG) arranged in vertical columns in the main, north and south compartments for the first two tests (Fig.1); for the third and subsequent tests the column of thermocouples in the south compartment was moved to the north side of the roof screen in the main compartment (Fig.2). The larger diameter thermocouples were used in the upper 1.5 m (5 ft) of the main compartment where conditions were expected to be most severe. The couples were spaced at 0.3 m (1 ft) intervals from the roof to within 0.9 m (3 ft) of the floor in the end compartments and to within 1.5 m (5 ft) of floor level in the main compartment.

(d) Radiation levels were measured by radiometers and total radiation pyrometers mounted 1 m (3 ft 4 in) above the floor on the end walls of the north and south compartments and facing towards the main compartment. The radiometers had a large field of view (about 120°), the pyrometers had low acceptance angles (less than 6°).

2.5. Test conditions

The test conditions are summarised in Table 2. Test 1 was carried out to establish fire conditions in the building in the absence of a water curtain and a roof vent. In Test 2 a water curtain was operated in position X (Fig.1) but proved too effective in arresting fire spread, so in Tests 3, 4 and 5 the water curtain was placed in position Y (Fig.2) where its task was more difficult. Tests 4 and 5 were carried out with the water curtain turned on at different times and with a vent 4.5 m^2 (49 ft^2) in area in the roof to assess what improvement venting the building would produce. Detailed results of the tests are given in Appendix II.

Table 2

Summary of test conditions

Test number	Position of water curtain (see Figs 1 and 2)	Roof vent	Notes
1	None	Closed	
2	X	Closed	Water curtain on at 3 min
3	Y	Closed	Water curtain on at 2 min 30 s Further indicator specimens added (also Tests 4 and 5)
4	Y	Open	Water curtain on at 5 min 40 s
5	Y	Open	Water curtain on at 2 min 15 s

3. GENERAL DISCUSSION

We can assess as follows the relative value of the parts played in these experiments by the water curtain and the roof vent in arresting or retarding the spread of fire outside the central compartment.

When the water curtain was operated soon after ignition and the roof vent was open (Test 5) there was no spread of fire past the curtain either at a high or low level. The only damage beyond the curtain was scorching of some of the specimens close to the water curtain due to their proximity to the flame and the inability of the curtain to absorb more than a tiny fraction of incident radiation.

Although the vent was insufficiently large to completely prevent hot gas from spilling under the roof screen, the temperature registered by thermocouples near the roof was not more than 220°C which is not high enough for example to endanger unprotected structural steel. There is a suggestion that temperatures even in the central fire compartment were lowered by the circulation current induced by the water curtain.

The building was almost completely clear of smoke, indeed the gas temperatures beyond the water curtain were low enough to permit people to enter and stand erect inside.

The performance of the roof vent alone, in the absence of a water curtain, can be judged from the first five minutes of test 4. The roof vent was very effective in clearing combustion products from the building since the interior was clear of smoke up to 2.5 m (8 ft) above the floor and the temperatures, though higher than with the water curtain, were still fairly low, not more than 360°C.

However, there was no way in which the roof vent could prevent the fire spreading along the continuous fuel at both low and high levels (Table 3). In the absence of fire fighting this could only be checked by the wetting down action of the water curtain.

Comparison of test 4 with the tests 1, 2 and 3 in which the roof vent was kept closed indicates the very large changes inside the building brought about by venting. Without venting the building rapidly filled with smoke laden gas which besides obscuring visibility would have tended to heat up nearly the whole of the building, and indeed to radiate itself. When the water curtain was operated (test 3), fire was arrested at a low level at the barrier formed by wetting down, but hot gases and smoke penetrated the curtain very easily and caused exposed specimens of fibre insulation board to char (Table 3).

With or without the water curtain, the temperatures registered by thermocouples near the roof were rather high in the absence of venting; bare structural steelwork would have failed rapidly in the main compartment and would have been in contact with gases at a temperature in the region of the critical temperature of steel in the partition compartment.

Thus in these experiments, the greatest benefit from the water curtain was only realised when a roof venting system prevented hot gases from penetrating the curtain. Alternatively, it can be said that the benefit of venting large fires can be enhanced by the use of water curtains and this would probably be all the more true with tall piles of fuel. Neither system alone could prevent fire spread but the combination of both together exerted a very powerful restraint on fire spread.

The experiments demonstrate too that a water curtain in the form of a thin flat spray is unsuitable, indeed the name 'curtain' is something of a misnomer. What is required is a spray form which can wet down material over a sufficient horizontal depth so that dry material on the side remote from the fire is far enough away from the fire not to ignite. It is not a question of absorption of radiation by the spray, but of the configuration factor of the flame.

Although these experiments demonstrate the effectiveness of water curtains and roof vents in some situations, further experiments and studies are required to judge their effectiveness in other types of fires, particularly those in high piled stock.

Clearly water curtains - or a sprinkler system - need not be employed in addition to large venting, if there is no risk of the fire spreading horizontally when the effect of the roof is removed. The amount of water needed to prevent such horizontal spread as does take place owing to the extensive radiation from the flames depends on the nature and amount of flammable materials at risk. The wider the gaps that can be left at floor level between piles of goods the less water needs to be used. Indeed, there may be situations where water may not be necessary because the horizontal rates of spread in the absence of a ceiling can sometimes be very small. If the purpose of any water applied is to wet down materials and prevent spread, the amount necessary per unit area would be significantly less than is required from sprinklers, though because it must be applied over a perimeter of a burning area the total rate of application may not be less.

The mode of operation of such water curtains requires further consideration and the design of a system of water curtains or sprinklers and roof vents may need to be different for different risks. Also, because the combined use of water and vents can be viewed as an alternative to compartmentation the economic comparison with sprinklers is not straightforward.

4. CONCLUSIONS

(i) With the fire effectively vented a water flow rate of only 0.17 l m^{-1} s^{-1} (0.7 gal ft^{-1} min^{-1}), corresponding to a rate of application per unit area of wetted floor of 0.10 l m^{-2} s^{-1} (0.12 gal ft^{-2} min^{-1}), was sufficient to arrest fire spread in cribs 0.30 m (1 ft) high as expected from the work of O'Dogherty et al[5] for crib fires in the 'open'. There was then little or no tendency for hot gases to penetrate the curtain. One would expect that the rate of flow required in any given occupancy could differ, but would be the rate of flow appropriate to a fire in the 'open'.

(ii) Very little radiation was absorbed by the curtain and its action therefore lay in wetting down the fuel over a sufficient depth so that the intensity on the far side of the curtain was below the threshold for ignition. Thicker curtains would have to be used in situations where larger, or more radiating flames could occur.

(iii) Although the curtain extinguished an unvented fire wherever it wet down, and therefore prevented spread in a continuous fuel system piercing the curtain, the penetration of hot gases beyond the curtain caused specimens to char as far away as 4 m (13 ft) from the fire.

(iv) Fire spread could not be prevented by venting alone.

(v) In view of the success of the water curtain/roof venting combination demonstrated in these experiments, further studies are desirable to explore their performance over a wider range of conditions.

5. ACKNOWLEDGMENT

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APPENDIX I

Consider a stack of fuel 3 m high, irradiated by a parallel flame of source intensity 13.2 W/cm^2, the average configuration factor of the flame w.r. to the fuel being $\frac{1}{2}$. The average intensity of radiation falling on the fuel is $\frac{13.2}{2} = 6.6$ W/cm^2 and this could be reduced to 3.3 W/cm^2, the critical value for spontaneous ignition, by the interposition of a water curtain having an average transmission of radiation of 50 per cent.

To obtain such a low transmission a water flow of some 5 g/s per cm length of curtain would have to be used[7] even with the most efficient nozzles.

If now instead of providing a curtain, the water was used to cool the fuel directly by spraying it on to the irradiated face, the minimum amount of water required per cm length of curtain would be on average $(6.6 - 3.3)\ 300/q$ where q is the heat required to convert 1 g of cold water into steam, and assuming no run off. Inserting a value for q of 2600 J gives a water flow rate of 0.4 g s^{-1}cm^{-1}, i.e. in the order of one-tenth of the water flow which would give sufficient radiation absorption in the spray.

APPENDIX II

DETAILED TEST RESULTS

Test 1

The fire burned up rapidly, flames reaching eaves level in 1 min and filling the entire roof space of the main compartment within 1½ min. The building was smoke logged to within 1.2 m (4 ft) of the floor from about 2½ to about 8 min, when the temperatures had begun to fall. At 12½ min only glowing charcoal remained of the main crib, but fire was still spreading along the narrow cribs and the flames from these reached the ceilings of the north and south compartments, giving temperatures up to 600°C in these compartments after the fire in the main crib had subsided. The average rate of spread of fire along the narrow cribs was 0.3 m/min (1 ft/min), a speed indicating that the spread was controlled by the general heating in the compartment or by supporting radiation.

For the whole period during which fire spread along the narrow cribs the fire front sloped forward, at times as much as 30° to the horizontal, which also suggests that the spread was substantially assisted by downward radiation from flames above the main crib or from the heated building.

The intensities of radiation registered by a narrow angle radiation pyrometer and a wide angle radiometer in one of the end compartments are shown in Fig.5. The pyrometer showed an initial peak followed by a marked fall in intensity as the flame of the main fire was obscured by the build up of smoke. The second peak was caused by the clearance of smoke as the fire died down. The intensity registered by the radiometer was less variable perhaps because the obscuration by the smoke of the flame of the main fire was compensated for by radiation emitted by the smoke itself. Although the smoke was of course cooler than the flame it occupied a much larger proportion of the field of view of the radiometer.

The temperature 0.3 m below the ceiling in the end compartment is shown in Fig.6 as a function of time.

At the end of the test all the specimens of fibre insulating board were completely charred away but because the building had been completely smoke logged during much of the fire it was not possible to tell if the specimens had ignited, or had decomposed without actually flaming. A summary of the damage sustained by the various specimens in all the tests is given in Table 3.

Table 3

Summary of damage sustained beyond the water curtain

Test No.	Narrow wood crib 0.3 m high	Fibre insulation board specimens					Paper specimens (distributed over whole height)
		Height above floor (m)					
		0.3*	0.6+	1.2+	2.1*	2.5x	
1	Burned out completely	N/A	All burned away	All burned away	N/A	All burned away	N/A
2	Scorched close to curtain	N/A	All charred	All charred	N/A	All charred	N/A
3	No damage	No damage	Some charred	Some charred	Charred along whole length	Scorched or blackened	Upper specimens charred to end of compartment
4	No damage	No damage	Charred close to curtain	Charred close to curtain	Charred for half its length	No damage	Charred close to curtain
5	N/A	No damage	Scorched close to curtain	No damage	No damage	No damage	Scorched close to curtain

*Long strip

+Small vertical specimens

xSpecimens on ceiling

N/A = not applicable

Test 2

For this test the narrow crib extending from the main compartment into the north compartment was omitted. The fire otherwise developed in a manner similar to that of the first test until the water curtain was operated, at 3 min*. The fire in the main crib had then almost reached its peak and fire had spread about 1.5 m (5 ft) along the narrow crib to a point directly below the water pipe of the curtain, the criterion chosen in advance for turning on the water curtain. Fire was immediately extinguished over the wetted area beneath the curtain, so that flaming extended for only about 0.9 m (3 ft) from the main crib. Flames filled the whole of the centre compartment until about 8 min after ignition when fire severity decreased.

Up to 6 min temperatures in all compartments were similar to those in test 1, i.e. they were as high in the south compartment, beyond the water curtain, as in the north compartment, but after 7 min fell away more rapidly because of the absence of continuing fire in the narrow cribs (Fig.6). After the test examination of the narrow crib beyond the sector wetted by the water curtain revealed scorching and blackening of the sides of the top layer of sticks facing the main crib, indicating that a high level of radiation, in the region of 1.5 W/cm^2[6], had been transmitted through the water curtain. This suggests that if under somewhat different conditions, e.g. a larger main fire larger intensities could have been produced on the far side of the curtain, ignition could have occurred.

The radiometer readings were very similar to those of test 1, between about 0.5 and 1 W/cm^2, but fell off more rapidly because of the absence of fire in the narrow cribs. As in test 1 the pyrometer readings show much larger variation, rising to a peak at 6 to 7 min as the fire was dying down.

The higher temperatures attained later in test 1 in the end compartments were not found in test 2 because the water curtain prevented fire spreading along the narrow crib.

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*It was difficult to decide when to turn on the water curtain. If turned on at the start of the test the narrow crib would be thoroughly soaked, if turned on too late too much smoke and hot gases would have passed beyond the curtain, so a compromise time was adopted.

Test 3

As the second test had shown the water curtain was very effective in preventing fire spread, it was moved to a position (Y, Fig.2) where its task was made more difficult. Additional indicator specimens of fibre insulating board, filter paper, cardboard and wood were included in this and subsequent tests, to supplement temperature records. Most of these specimens were positioned so that the water curtain was between them and the fire, the exceptions were the fibre insulating board specimens in the ceiling of the south compartment, those 0.9 m from the main crib on the curtain side and the long, high and low level specimens which passed from above the main crib through the curtain into the north compartment. The water curtain was turned on at 2 min 30 s, when fire had spread to a point directly under the water curtain supply pipe.

As in the previous tests the building quickly became smoke logged and 2 min after operating the curtain smoke logging extended down to within 0.6 m (2 ft) of the floor and persisted until about 7 min after ignition, when the smoke began to clear. Temperatures in the centre compartment for this period were similar to those obtained in the previous test.

The water curtain failed to prevent fire spread completely, as the high level specimen of fibre insulating board was completely charred through along its whole length. The thermocouples indicated a temperature rise of about 300°C at the height of the specimen (1.8 m (6 ft) above the floor) in the partition compartment and at this temperature it is probable that fibre insulating board would have ignited, had the time of exposure been greater than in this test. On the far side of the water curtain, paper and cardboard specimens were charred at heights exceeding 1.2 m (4 ft) from the floor; fibre insulating board specimens 0.6 m (2 ft) and 1.2 m (4 ft) above the floor were charred up to 3.6 m (12 ft) from the main crib. However, specimens attached to the ceiling of the north compartment were intact, although blackened.

As all the roof specimens had charred through or ignited in Test 1 it seems likely that this was caused by fire spread along the narrow extending cribs which was prevented by the water curtain in Test 3. Thus even in an unvented building, a water curtain may render conditions less severe by preventing fire spread at low level along a continuous fuel.

Peak temperatures registered by thermocouples in the north compartment were a little lower than in the previous test (Table 4) and the intensity received by the radiometer was about half that of the previous test, (Table 5), these results probably reflect a cooling effect of the water curtain.

Test 4

The roof was vented in this and the following test. Although the fire burned up briskly it took almost twice as long for the main crib to be fully involved as in the previous test. After 1 min 30 s flames were issuing from the roof vent and at 2 min the end of the long, high level specimen of fibre insulating board was burning. Compared to the previous test fire spread more slowly along the narrow crib even in the absence of the water curtain and fire took 5 min 38 s to reach a point directly under the water pipe, when the water curtain was turned on. In this period fibre insulating board specimens near the fire were either ignited or were smouldering and the water curtain quickly extinguished those that it wetted as well as immediately reducing burning of the narrow crib to a 0.3 m (1 ft) length adjacent to the main crib. Most of the building remained substantially smoke-free. A clear layer about 2.4 m (8 ft) high existed above the floor throughout the test and although some of the specimens received thermal damage much of this occurred before the water curtain was operated.

The upper wood, cardboard and filter paper specimens between 4.1 m (13 ft 6 in) and 3.6 m (12 ft) above the floor in the partition compartment and 1.5 m (5 ft) from the main crib were found to be unaffected at the end of the test; these specimens were shielded from radiation from the main crib by the roof screen. Below 3.6 m (12 ft) above the floor the specimens were charred on their surfaces facing the fire whilst their rear surfaces were unaffected, indicating that this damage was due to radiation from the main fire penetrating the water curtain. The condition of all these specimens indicated the absence of hot gases at heights of less than 4.1 m (13 ft 6 in) above the floor throughout the test. The specimens suspended in the north compartment 3.6 m (12 ft) from the main crib showed slight signs of scorching but those at 5.7 m (19 ft) and the fibre insulating board specimens on the ceilings of the end compartments were not noticeably affected.

Maximum temperatures were substantially lower (Fig.6) than the corresponding temperatures in Test 3 where there was no roof vent. Temperatures of about 330°C in the upper part of the partition compartment were measured, indicating that the vent was insufficient to remove all the hot gases produced by the fire and some spill-over into the partition compartment occurred. However, it is thought that the readings recorded below 4.1 m (13 ft 6 in) above the floor were affected by radiation from the main crib.

Although the pyrometers indicated very much higher intensities than in Test 3 (probably due to the absence of smoke obscuration and to the cleaner combustion caused by entrainment of air rather than smoke logged and vitiated gases), the radiation intensities monitored by the radiometers were less than those in Test 3 (Table 5). This is a reflection of less heating of the walls and ceiling of the north compartment by the penetration of hot gases into the compartment. The low temperatures of the thermocouples in the north compartment (Fig.6) show that the gases penetrating into this compartment were much cooler than in previous tests, indeed some of the heating of these thermocouples may be due to radiation from the main fire. Operating the water curtain produced a temporary decrease in the reading of the north compartment pyrometer but had no detectable effect on the adjacent radiometer.

Test 5

Fire had spread slowly along the narrow cribs in test 4 and reached a point directly under the water curtain pipe (when the water curtain was turned on) at 5 min 38 s - much later than in tests 2 and 3. In test 5 the water curtain was accordingly turned on earlier, at 2 min 15 s, to see what difference this made and particularly to determine whether some of the thermal damage sustained by the exposed specimens in test 4 could have occurred before the water curtain was turned on.

Temperatures were appreciably lower in this test than in test 4 (Fig.6 and Table 3). The paper and wood specimens in the partition compartment 1.5 m (5 ft) from the main crib were scorched on their surfaces exposed to the main crib fire at heights between 0.9 m (3 ft) and 3 m (10 ft) above the floor and the ends of the long, high and low specimens of fibre insulating board were charred, but fire had not spread along them as it had in test 4. One specimen of fibre insulating board 1.2 m (4 ft) above the floor and 0.9 m (3 ft) from the main crib was charred to a depth of about 1.5 mm (0.06 in) on the face towards the main crib and a similar specimen 0.6 m (2 ft) above the floor and 1.8 m (6 ft) away was scorched.

The intensity of radiation registered by the radiation pyrometer and the radiometer 4 min after ignition are shown in Table 5. For most tests this time corresponds to the peak burning of the fire, although not necessarily to peak radiation intensity. The intensities given by the pyrometer are effectively those of the radiation source and for tests 4 and 5 are several times those for tests 1, 2 and 3 because the building was not smoke logged when the fire was vented. However, the intensities given by the radiometer, which are those received at the radiometer, are quite different. The low readings for tests 4 and 5 arise because the end compartments were cool and the only radiator was the flame above the main crib, which, since it was some distance away, gave a low intensity at the

Table 4

Peak temperatures registered in various compartments

Test No.	Peak temperatures registered by thermocouples (°C)		
	0.9 m below apex of roof in main compartment	0.6 m below apex of roof in partition compartment	0.3 m below ceiling in north compartment
1	890	-	550
2	900	-	450
3	870	540	380
4	480*	360	170*
5	310	230	60

*Peak temperature obtained before water curtain turned on.

radiometer. The reading of 0.3 W/cm^2 in test 3, although similar to the readings of tests 4 and 5, is much more a measure of conditions within the end compartment - either the heating of the compartment walls, or the smoke itself radiating, since the pyrometer reading shows that comparatively little radiation was being received from the flame above the main crib.

Similar arguments apply in the case of tests 1 and 2, although the radiometer readings were higher than in test 3. Although no reason can confidently be given for this, the radiometers were much closer to the fire and some geometrical effect, for example the heating of the ceiling of the south compartment, may have caused this difference.

Table 5

Intensities of radiation on far side of water curtain

Test No.	Intensity of radiation 4 min after ignition (W/cm^2)	
	Pyrometer	Radiometer in end compartment
1	1.2†	0.8†
2	0.7	0.7
3	1.4	0.3
4	7.0*	0.2*
5	7.8	0.2

†Mean of readings from both sides of fire

*Before water curtain operated

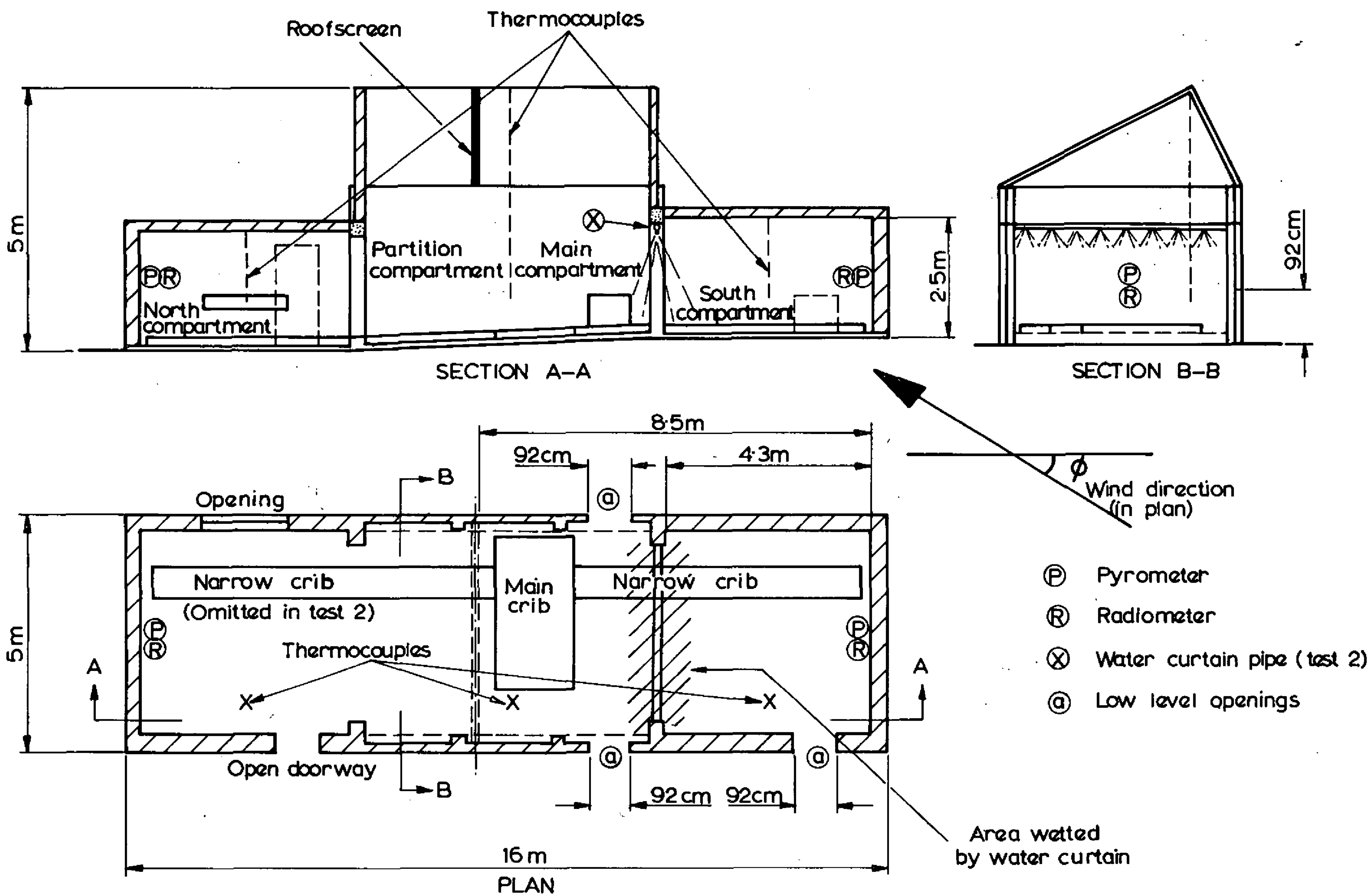


FIG.1. EXPERIMENTAL ARRANGEMENT FOR TESTS 1 AND 2

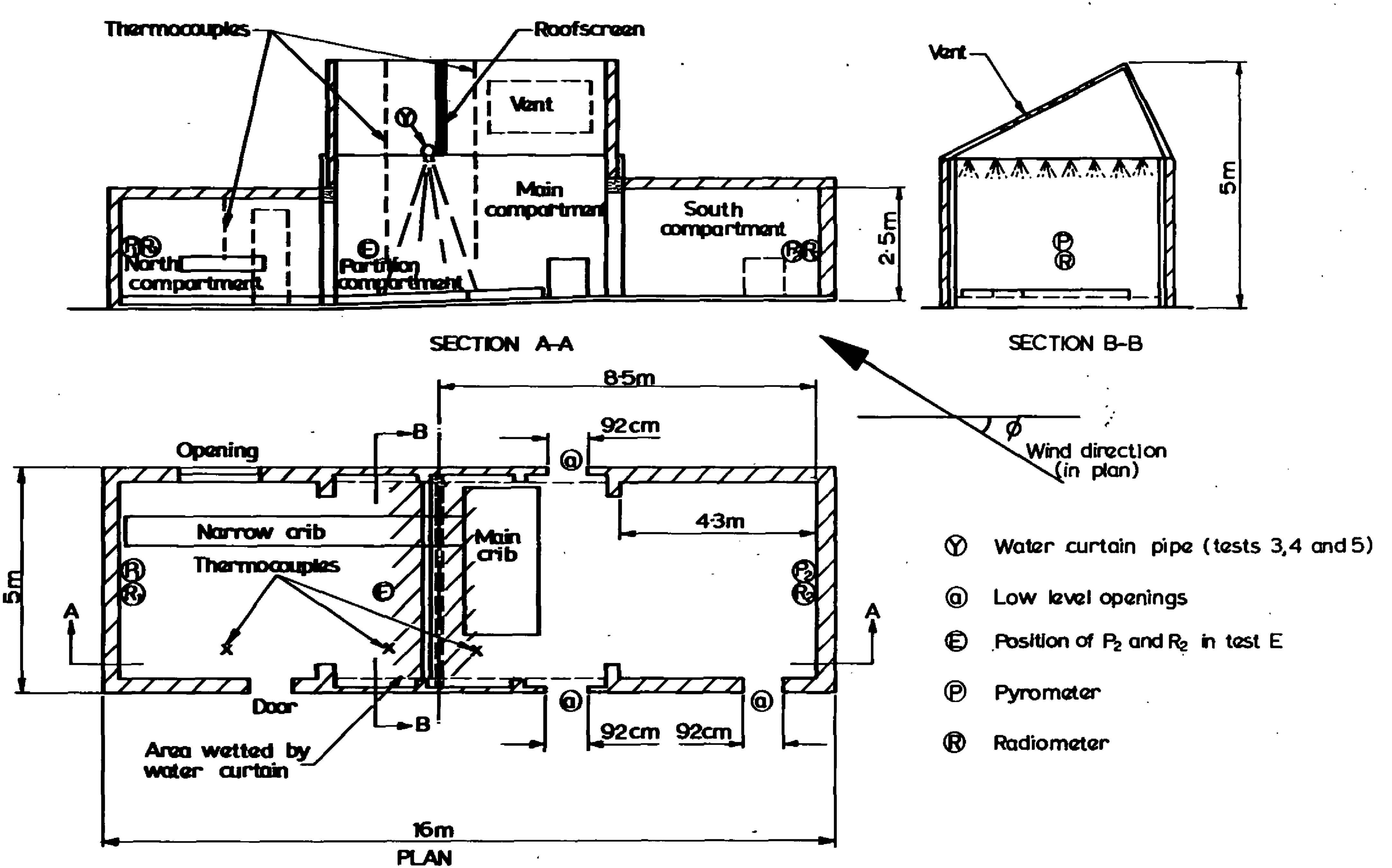


FIG. 2. EXPERIMENTAL ARRANGEMENT FOR TESTS 3,4 AND 5

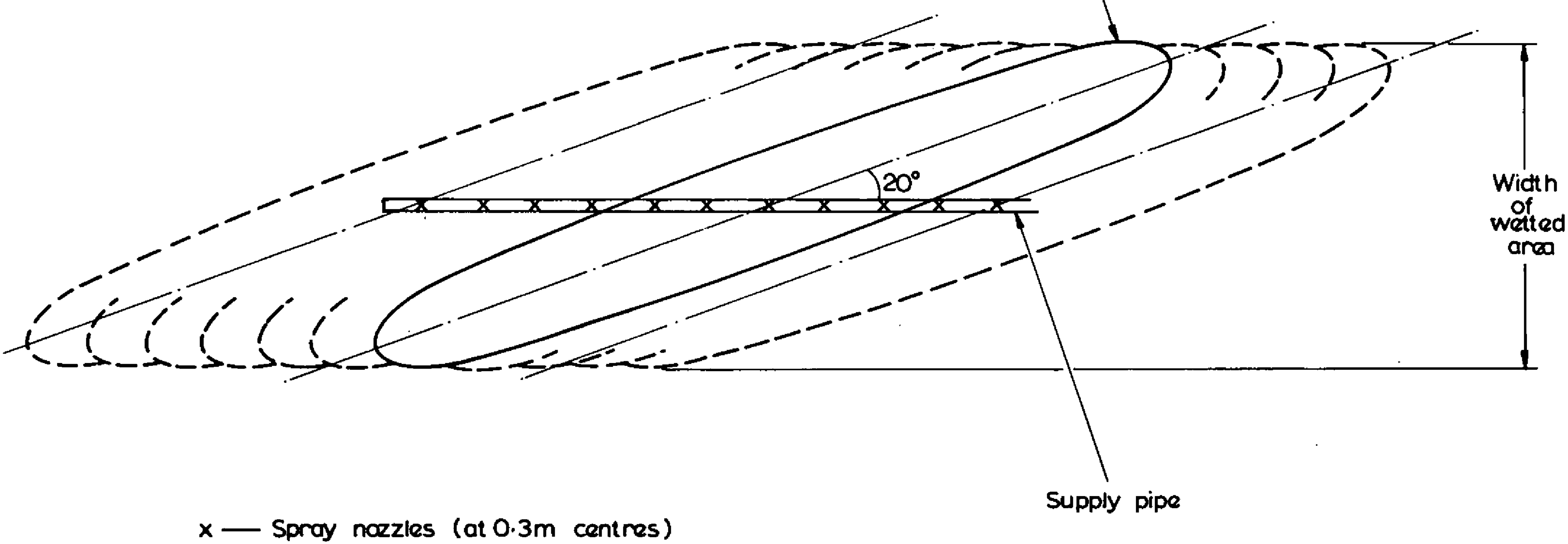


FIG. 3. PLAN VIEW OF WATER CURTAIN PRODUCED BY FLAT JET NOZZLES

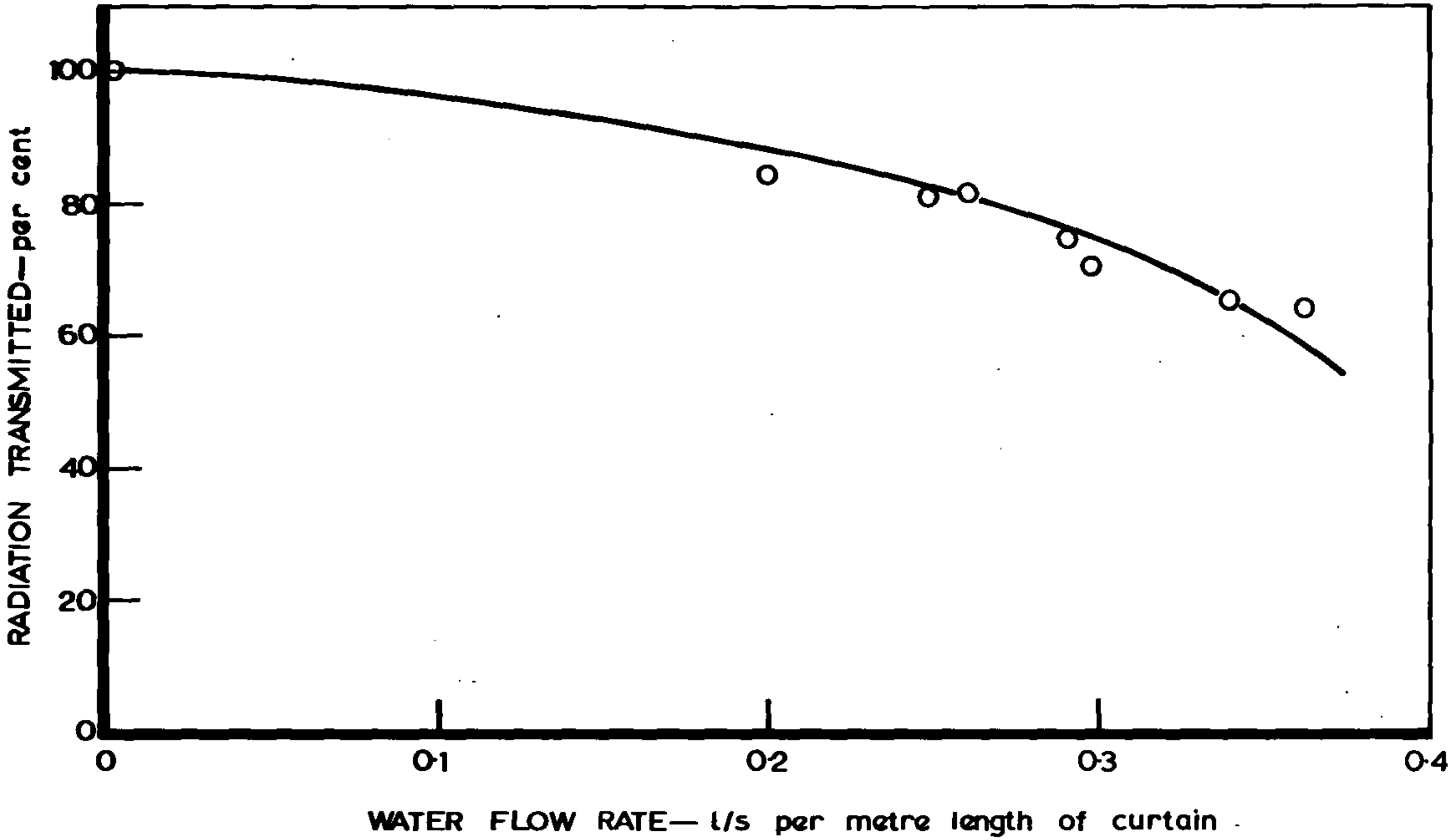
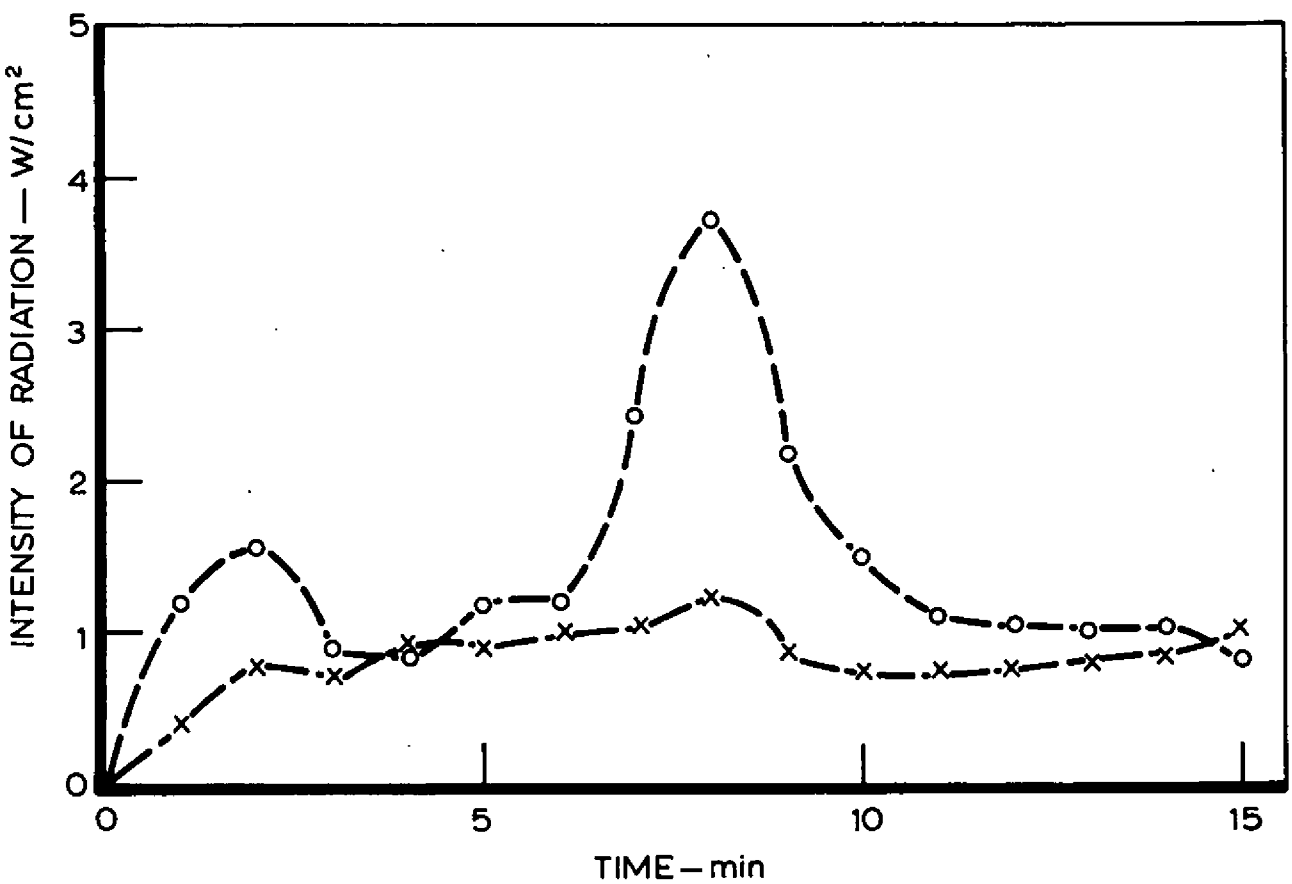


FIG. 4. RADIATION ABSORPTION OF WATER CURTAIN (3mm NOZZLES)



x— — — —x Radiometer in south compartment

o— — — —o Pyrometer in south compartment

FIG. 5. RADIATION INTENSITIES MEASURED IN TEST 1

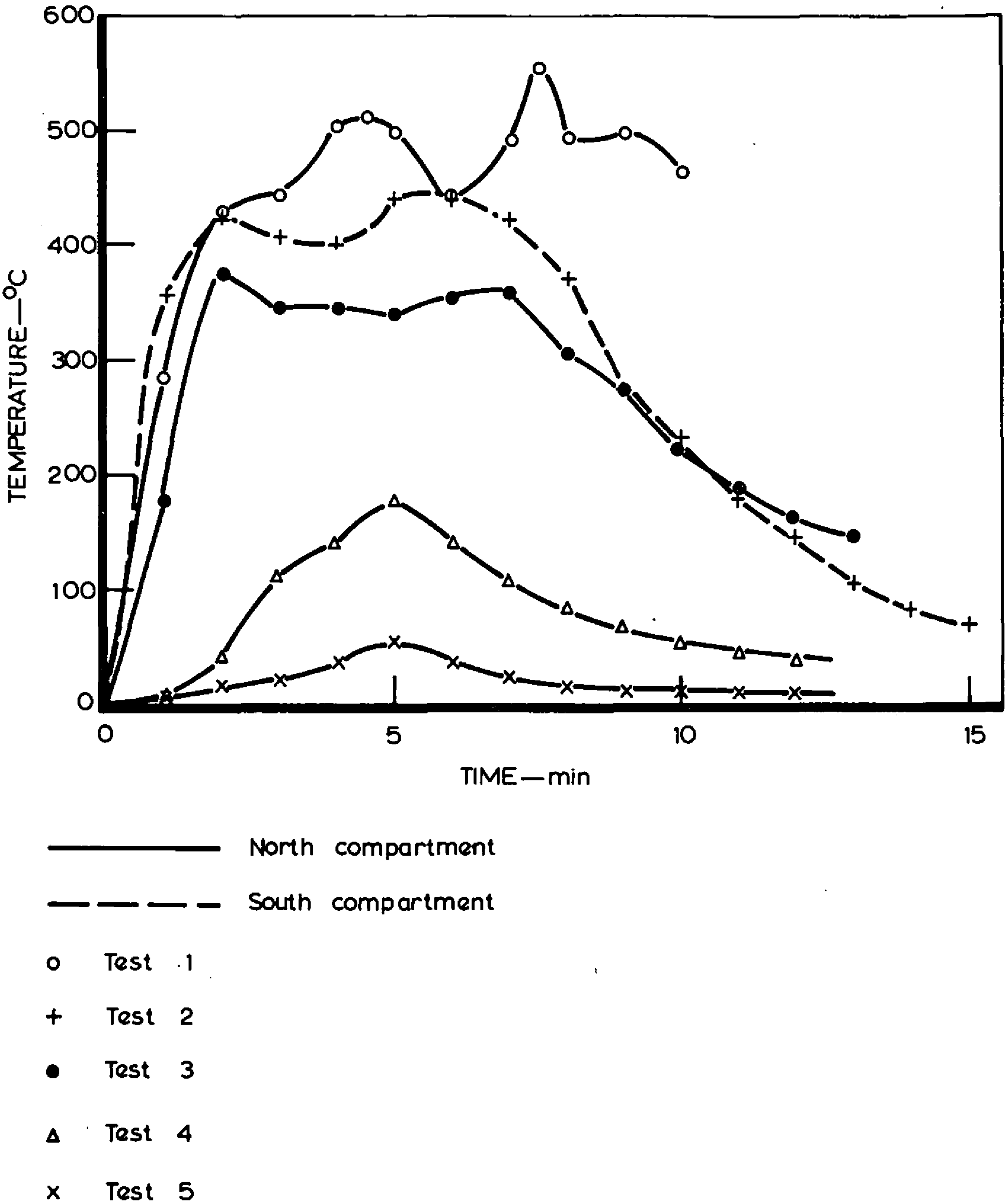


FIG. 6. TEMPERATURES MEASURED 0·3 m BELOW CEILING IN THE END COMPARTMENTS