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SOME EXPERIMENTAL STUDIES OF THE CONTROL OF DEVELOPING FIRES IN HIGH-RACKED STORAGES BY A SPRINKLER SYSTEM

by

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SUMMARY

This report gives an account of six large-scale tests on goods stored on pallets in a system of racking at 6 levels. The storage was protected by a sprinkler system mounted centrally within the racking at each level. The effect of varying the numbers of sprinklers per pallet cell, the use of each and alternate sprinkler levels and the size of the sprinklers (10 or 15 mm bore) on the development of the fires was studied.

This arrangement was found to give good general protection to the racking and goods, in that the fire would have been contained and subdued, but in all but one experiment the fire spread throughout the height of the racking. Lateral spread was restricted to the width of the cell of origin.

Automatic detection equipment was found to operate about two minutes before the operation of the first sprinkler.

The operation of the sprinklers caused the production of a certain amount of cool smoke which sank to ground level.

KEY WORDS: Detector, fire; Fire spread; High-piled; Sprinkler; Storage

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1. INTRODUCTION

In recent years, the method of storing industrial and commercial goods in high-racked storages has become widespread in Europe and America, and at the present time, racked warehouses up to one million square feet in individual area, and up to 36.6 m (120 ft) height, are in being or in prospect. The properties which render these storages commercially valuable, render them hazardous from the fire aspect, and it is therefore essential to decide what fire protection measures are necessary to control growing fires within them, so that huge financial losses may be avoided.

While the chances of a fire occurring are probably small, they are nevertheless finite, and adequate fire protection is essential. The high stack combined with easy access of air for combustion, and the combustible nature of the packaging materials used means that a fire will grow rapidly and beyond a certain stage will be extremely difficult to control.

The following requirements have been suggested[1] as a prerequisite of a good detection/control system.

(a) That the fire shall be detected <u>anywhere</u> that it may occur within the storage system while it is still well within the "cell" of pallets in which it starts; that is, within a volume bonded by the adjacent upright and horizontal members. This suggests a detection time of not more than two minutes after ignition, for a normally-developing fire.

(b) That the extinction system should respond to the detection system in not more than a further one minute and should be capable of controlling, and probably extinguishing, the fire in not more than eight minutes after detection, preferably within the first one or two cells.

(c) That the system should not endanger personnel and, by the rapidity of its action, should prevent the fire from doing so. It should keep the production of smoke to an absolute minimum.

The need for definite information on the hazard of high stacked goods, and the potential performance of detection/extinction systems has led the J.F.R.O. to study this problem. An initial series of four experiments on racked goods protected by sprinklers was made at J.F.R.O. in 1969/70[2] and was followed by a further series of six experiments on the same fire configuration protected by high expansion air foam[3]. As the racking used was only about 6.1 m (20 ft) high, it was considered desirable to carry out further experiments using higher racking.

A third series of experiments has now been completed, using racking of some 11.4 m (37.3 ft) in height, filled with packaged goods and protected by a typical sprinkler layout. These experiments are the subject of this report.

2. EXPERIMENTAL ARRANGEMENTS

2.1. Building

The series of six experiments was carried out in Building No. 81 which is the original airship hangar to house the airship R.101 at what is now the Royal Aircraft Establishment, Cardington. This building is 247.5 m (812 ft) long, 83 m (273 ft) wide and about 50 m (165 ft) high to the catwalk just below the roof. The area used for the experiments was at one end of the hangar and gave a free access of air to the fire. The height of the roof compared with that of the racking was such that the hot gases and smoke from the fire rose freely as a plume. In this respect the experiments were not typical of the upper levels of racking in a storage where the roof is often only just above the level of the goods. If the racking is considered as the lower part of a very high racking, the effect of the high roof might not materially affect the application of the experimental results.

2.2. Racking

The arrangement of the racking is shown in Fig. 1 and Plate 1. It consisted essentially of two parallel racks, each 11.4 m (37.3 ft) high, separated by an aisle. Each rack was comprised of six levels of 1.7 m (6 ft) height. The longer rack was six "cells" in length, to give a total of 16.9 m (55.5 ft). The shorter rack was two "cells" in length, the total being 5.6 m (18.5 ft). The racks were set so that the two cells of the shorter rack faced the central two cells of the longer rack. The main structural elements of the racking were made from 127mm x 63.5 mm (5 in x 2.5 in) steel channel, the vertical frames being welded in the factory and the horizontal longitudinal members being bolted to these on site. Each pallet "cell" contained four pallets of dimensions 102 x 122 cm (40 x 48 in). They were the standard wooden 4-entry type to British Standard 2629 (Type B). Thus the longer rack contained a total of 6 x 6 x 4 = 144 pallets, and the shorter rack contained a total of 6 x 2 x 4 = 48 pallets, or 192 pallets in all. The pallets were housed on transverse runners extending 325 mm (12.7 in) beyond each side of the main structure. The salient dimensions of the racking were thus:

Height :	11.4 m	(37.3 ft)
Length :	16.9 m	(55.5 ft)
	5.6 m	(18.5 ft)
Width (frame only) :	1.4 m	(4.7 ft)
Spacing (rack to rack) :	2.1 m	(6.9 ft)
Spacing (pallet to pallet) :	1.4 m	(4.7 ft)

2.3. Stored goods

Most of the 192 pallet loads consisted of nine corrugated cardboard cartons, each 71 x 46 x 46 cm (28 x 18 x 18 in), loaded onto the pallet as shown in Plate 2. Each carton held three empty 22.7 l (5-gallon) steel drums, with the spaces between them loosely filled with wood wool. The method of filling was chosen as giving a good fire load in those parts of the cartons likely to be involved in fire while the core of the load was cheap and readily reusable. A few pallets contained other goods such as empty plastic containers in cardboard cartons. The loads in the main rack were labelled from one end, along the rack from A to M (omitting I) on one side, and back on the other side from N to Z (omitting O). The levels were numbered upwards from 1 to 6, to permit unambiguous identification of any pallet, when describing the progress of a fire.

2.4. Sprinkler system

Figure 2 shows the general arrangement of sprinklers in the longer rack, and Table 1 shows the particular arrangement used for each test. In the longer rack in which the fires were started, the sprinklers at each level were mounted on distribution pipes in two sections, each section protecting half the length of the rack and being fed from an individual riser at the adjacent end of the rack. The twelve individual risers were fed from a common supply and the pressures at the blind ends of the distribution pipes were displayed at twelve pressure gauges adjacent to the twelve control valves. The main supply pipe was 150 mm (6 in) bore, and the individual supply pipe and risers were 50 mm (2 in) bore. The distribution pipes tapered from 50 mm (2 in) bore to 25 mm (1 in) bore. In the short rack, all levels were fed from one main riser, and the pressure in this was monitored at the supply end. The function of this rack was to determine whether fire would spread to it across the aisle, and for the first four tests the sprinklers were kept at the same spacings on every level, i.e. 3.05 m (10 ft) horizontally, along the longitudinal centre line. In the first and fourth experiments, the fire did spread to this rack, and was not extinguished by the sprinklers, as it was in the main rack. The spacing was therefore reduced for the last two experiments, to 2.4 m (8 ft); with the sprinklers over the gaps between pallets as in the main rack. In all experiments, the sprinklers were 68°C (155°F) glass bulb types, mounted upright above the pipes, with a small metal shield 15 cm (6 in) above each, to prevent cooling by water from above (Plate 3). For the first four experiments conventional pattern 15 mm ($\frac{1}{2}$ in) sprinklers were used, and spray pattern 10 mm ($\frac{3}{8}$ in) sprinklers were used in the last two experiments. The rate of flow in the manifold was measured with an orifice plate and manometer, and a rough check on the total quantity of water used was made by measuring the depth of water in the supply tank before and after each experiment.

The pressures, as read at the pressure gauges, were controlled to give a pressure-flow characteristic such as would be used in a full size system in which the last four sprinklers to operate would give an average distribution density of 7.5 mm/min (0.15 gal/ft^2/min). The actual pressures used were those that would apply to the <u>first</u> sprinklers to operate in such a system. The average pressures at the sprinkler heads are shown in Table 2 and ranged from 4.8 bar (70 lbf/in^2) to 5.6 bar (80 lbf/in^2) giving densities of about 20 mm/min (0.4 gal/ft^2/min) for experiments 1 to 4 and about 15 mm/min (0.3 gal/ft^2/min) for experiments 5 and 6.

2.5. Instrumentation and detection equipment

Various types of fire detection system were installed, some in the racking, some on a metal frame above the longer racking and some at various positions outside the racking area. A full account of these, and of their performance, is given in Appendix A.

The progress of the fire was also monitored by a series of thermocouples. Thirty-six chromel-alumel thermocouples were used to record air temperatures within the racking adjacent to the sprinklers, and a further nine were used to record temperatures in the air above the rack as shown in Fig. 3. Three thermocouples recorded air temperatures within the shorter rack.

Six more thermocouples measured the temperature of the structural steel of the racking, and four radiometers were mounted on the shorter rack at the top of the first, second, fourth and sixth levels to give a measure of the radiant intensity falling on the exposed face of the rack, from the fire in the longer rack. In the first four experiments, these radiometers were between columns F and G of the shorter rack, but they gave negligible readings. In the last two experiments they were positioned between columns G and H, directly opposite the vertical line of spread of the fire.

All the thermocouples and radiometers were connected to a data logger which scanned each point every 30 seconds.

Most of the sprinklers in the main rack were fitted with a wire which formed part of a monitored electric circuit. When the sprinkler operated, the circuit was broken and a lamp was lighted to give the time of operation of the sprinkler.

Time-lapse, monochrome still, colour still, and cine photographs were taken during each experiment, the close-ups giving the detailed progress of the fire and the distance shots showing the general progress and the distribution of smoke. Plate 4 shows the smoke distribution towards the end of experiment 3.

A summary of smoke observations is given in Appendix B.

3. EXPERIMENTAL PROCEDURE

Before each fire was lit, the air temperatures at ground level and ceiling level were measured, together with the humidity at ground level, inside the building. The wind speed and direction outside the building were obtained from the Meteorological Unit at Cardington. Local convection currents adjacent to the fire were measured at ground level in some of the experiments. (Appendix 2)

A Marconi Moisture Meter, Type 433A, with needle-contact probe, was used to measure the moisture content of a sample of twenty cardboard cartons. The meter gives a reading in terms of an "s-scale", which is converted to moisture as a percentage of dry weight by means of a calibration curve. The meter is supplied with a set of conversion scales for different types of wood, and it was found that a close approximation to the percentage of moisture content can be obtained by converting "s-scale" to English Oak scale, and then applying the formula:

Percentage moisture in cardboard = 0.81 (percentage on oak scale) + 0.69

The water level in the supply tank was measured, the pump was started, and the system was pressurized, before ignition, in each of the experiments.

The fire was lit with a match, at a tear in the side of a box, in the bottom layer on pallet H1, in the gap between G1 and H1, a few inches in from the aisle.

On the ignition signal, all clocks were started synchronously, together with the data logger. The progress of the fire was observed, and a commentary on this was recorded on tape. When it was judged that the sprinklers had effectively controlled the fire, final damping down, and removal of smouldering debris, was completed by firemen from RAF and Bedford Brigades.

In the last experiment, the sprinklers were turned off 27 min after ignition and the fire was left entirely alone for 18 min. The sprinklers were then turned on again for 5 min, and this completely extinguished the small fire which had built up, mainly in the top level, during this period.

4. EXPERIMENTAL RESULTS

The main experimental results are shown in Tables 2, 3, and 4. Graphs of air temperature rise within the rack, at various levels, are shown for each experiment, in Fig. 4. Figure 5 shows the flame height as a function of time for all six experiments, and Fig. 6 gives radiometer measurements during experiment 5.

Diagrams of the longer rack indicating the positions of the sprinklers which operated in each experiment, are shown in Figs 7-12.

Plates 5 & 6 show the development of the fire in experiment 2.

EXPERIMENT 1 - TABLE OF EVENTS

Time	Events
0.00	IGNITION
2.30	Flames 1 m high
3.10	Flames touching pallet on second level
3.31	First detector operated
4.15	Flames touching pallet on third level
5.10	Flames touching pallet on fourth level
5.20	FIRST SPRINKLER OPERATED
6.10	Flames touching pallet on fifth level
6.35	Flames reach top of rack - no horizontal spread, burning area less than 1 cell wide
7.30	Burning cardboard falling from main rack - some 'floating' onto small rack
8.40	Small rack, goods ignited on fourth level
9.30	Burning on third and fourth levels of small rack
10.30	Burning in small rack on levels 3-6
11.30	Flames 5 m high above small rack, very little burning in main rack
12.15	Only flaming in main rack in J6
13.30	Flaming in small rack subdued. Some flaming in J6 in main rack
14.40	No visible flaming in main rack
16.00	Only remaining burning in top layer of small rack
24.10	WATER OFF. No burning in main rack and no reignition
	Some burning in small rack extinguished by hose reel jets.

Number of sprinklers to operate in main rack	4
Number of sprinklers to operate in small rack	3
Total quantity of water used, main rack	11.79 m^3 at max rate of 706 dm^3/min
small rack	3.55 m^3
Total	15.34 m^3 (3374 gal)

EXPERIMENT 2 - TABLE OF EVENTS

Time	Events
0.00	IGNITION
3.00	Flames 1 m high
3.10	First detector operated
4.10	Flames touching bottom of second level pallet
4.50	Flames touching bottom of third level pallet
5.20	Flames touching bottom of fourth level pallet
6.30	FIRST SPRINKLER OPERATED - Flames to top of rack
6.45	Flaming subdued on first, second and third levels
7.00	Flames extinguished in first, second and third levels
8.40	Only remaining flaming on sixth level
10.30	Some flaming on third and fifth levels, remainder of stack extinguished.
22.30	WATER OFF - all flaming extinguished - no reignition
	The fire did not spread to small rack.

Number of sprinklers to operate in main rack	3
Maximum rate of flow	556 dm^3/min
Total volume of water used	4.12 m^3 (906 gal)

EXPERIMENT 3 - TABLE OF EVENTS

Time	Events
0.00	IGNITION
1.05	First detector operated
2.20	Flames touching bottom of third level pallet
2.25	FIRST SPRINKLER OPERATED
3.00	Flames arrested, not spreading above fourth level
10.00	All flaming extinguished
13.25	WATER OFF - no reignition
	The fire did not spread to the small rack

Number of sprinklers to operate in main rack	2
Maximum rate of flow	363 dm^3/min
Volume of water used	3.09 m^3 (858 gal)

EXPERIMENT 4 - TABLE OF EVENTS

Time	Events
0.00	IGNITION
1.30	Flames 1 m high
2.30	Flames touching bottom of second level pallet
2.30	First detector operated
3.10	Flames touching bottom of third level pallet
3.24	Flames touching bottom of fourth level pallet
5.05	Flames reach top of rack
5.11	FIRST SPRINKLER OPERATED
5.30	Flames subdued on fourth and fifth levels
6.00	Small rack ignited on second level by radiation
6.25	Small rack burning on second - fifth levels
6.40	Whole height of small rack burning
7.15	Only burning in main rack at first level. Water from sprinklers in small rack wetting boxes in main rack
8.45	Burning in top of small rack and bottom of main rack
10.20	Some flaming visible on third levels of small rack
24.30	WATER OFF. No flaming in either rack, smoke issuing from small rack.

Number of sprinklers to operate in main rack	5
Number of sprinklers to operate in small rack	5
Maximum rate of flow - large rack	879 dm^3/min
Maximum rate of flow - small rack	493 dm^3/min
Volume of water used - large rack	10.76 m^3
Volume of water used - small rack	5.92 m^3
Total volume of water used	16.68 m^3 (3669 gal)

EXPERIMENT 5 - TABLE OF EVENTS

Time	Events
0.00	IGNITION
1.10	Flames 1 m high
2.00	Flames touching bottom of second level pallet
2.00	First detector operated
3.15	Flames touching bottom of third level pallet
3.40	Flames touching bottom of fourth level pallet
4.20	Flames touching bottom of fifth level pallet
4.20	FIRST SPRINKLER OPERATED. Burning embers falling from main rack
5.30	Flaming subdued on levels 1-4. Flames 2 m above top of rack
7.45	Burning at all levels in main rack
9.35	Some small flames on third, fourth and sixth levels
12.00	No visible flaming. Some smoke issuing from fourth level
19.20	WATER OFF - no visible flaming - no reignition. Fire did not spread to small rack.

Number of sprinklers to operate in main rack	6
Maximum rate of flow	792 dm^3/min
Volume of water used	7.22 m^3 (1588 gal)

EXPERIMENT 6 - TABLE OF EVENTS

Table	Events
0.00	IGNITION
1.50	Flames 1 m high
2.15	First detector operated
3.10	Flames touching bottom of second level pallet
5.00	Flames touching bottom of third level pallet
6.00	Flames touching bottom of sixth level pallet
6.20	Flames reach top of racking
6.20	FIRST SPRINKLER OPERATED
8.30	Burning on first, second, third and sixth levels
9.00	Flames in top level of racking on far side
14.00	Only flaming on far side of top level
18.00	Only visible flaming in top level
25.00	Persistent small flames in top level
27.30	WATER OFF - a little flaming still in top level
45.30	WATER TURNED ON AGAIN
50.30	WATER TURNED OFF - all flaming extinguished - no reignition.

Number of sprinklers to operate	5
Maximum flow rate	670 dm^3/min
Volume used in first 27½ min	8.79 m^3
Volume used from 45-50 min	3.35 m^3
Total volume used	12.14 m^3 (2670 gal)

5. CONCLUSIONS

The foregoing series of experiments on racked, palleted goods has provided useful information on the potential value of a sprinkler system installed within the racks in this type of risk. It has shown that:

5.1. The fires in all the experiments were controlled adequately by the sprinklers. No damage was caused to the racking and it is unlikely that any major damage would have been caused to a typical warehouse enclosing the racking.

5.2. Despite the generally good control of the fire, the method of operating the sprinklers by the usual glass bulb was such that the fire could spread upwards through the stack. In all but one of the six experiments, it reached to the top of the stack, and in the remaining one it was checked at the fourth level. The possible effect of a ceiling and ceiling-mounted sprinklers on upward spread is discussed in Clause 6.1.

5.3. The sideways spread of fire was very limited, being less than the width of the cell of origin at all levels. The possible effect of ceiling sprinklers on sideways spread is also discussed in Clause 6.1.

5.4. The initial rate of growth of flame height was low, due to the need for the fire to propagate from a small source. After the initial growth, the fire accelerated rapidly, taking about the same time to grow from 1.5 to 9.0 m (5 to 30 ft) flame height as it had taken to grow from 0 to 1.5 m (0 to 5 ft). The short times involved meant that any effect of cardboard moisture content was relatively unimportant in the second stage.

5.5. A total of 25 sprinklers operated in the six experiments, the actual numbers in each experiment ranging from 2 to 6 (Table 4). In none of the experiments did a sprinkler operate at the first level. The sprinklers, with one exception, operated <u>after</u> the flame tips had passed them. This explains, to some degree, the inability of the sprinkler system to prevent the fire moving upwards throughout the stack (except in the case where a sprinkler operated about 4 m (13 feet) above the flames) and provides a good reason for the "ganging" of sprinklers.

5.6. The fire tended to propagate up the outer faces of the boxed goods. It did not move up the central, longitudinal "flue" formed by the vertical gap between the back-to-back pallet loads, although it propagated vertically in the transverse gaps adjacent to the point of origin. This is contrary to the experience in the experiments at J.F.R.O.[1], and may be due to the fact that the goods largely filled the vertical distance between pallet levels, whereas in the earlier experiments this height was only two-thirds filled. This difference in behaviour needs further study as it can affect the selection of the layout of the protective installation. The centrally-mounted sprinklers could not apply water directly to the outer faces of the boxes, which were wetted largely by run-off water from the steelwork and goods above. Nevertheless, the position of the sprinklers at the intersection of the longitudinal and transverse "flues" was the most effective for a centrally mounted array as it caused the vertical propagating surfaces within the rack to be thoroughly wetted down.

5.7. The experiments did not permit a judgment to be made on whether sprinklers should be provided at all, or alternate, levels; or whether one or two sprinklers should be provided for each pallet cell. Further studies would need to be made to give positive answers on these points.

5.8. The use of 10 mm ($\frac{3}{8}$ in) sprinklers reduced the average rate of flow by some 25 per cent, but there was no noticeable effect of this on the control of the fire.

5.9. During the course of the experiments, burning debris fell into the aisle between the stacks, and would have endangered the lives of firemen present in an actual incident. This impeded movement in the aisle and caused the fire to spread to the other, unignited, stack of goods in at least one experiment.

6. FURTHER POINTS FOR CONSIDERATION

6.1. Ceiling effect

These experiments were conducted without a ceiling immediately above the top of the racking. The possible effect on the experimental results of a ceiling equipped with an array of sprinklers, should be considered. Without such a ceiling, the fire spread to the top of the stack in 5 of the 6 experiments, and, in the exceptional case, the actual progress of the fire was only arrested when the sprinkler chanced to operate in advance of the flames.

With a ceiling close above the racking equipped with a sprinkler array, the ceiling sprinklers are likely to operate before the upper sprinklers in the racking, due to the formation of a hot gas layer. The rate of vertical fire spread is such that even the topmost layers of goods will be involved before the ceiling sprinklers operate. This is indicated by American experiments[4] and also by those at J.F.R.O.[2] although in the latter case the gap between racking and ceiling was rather large at 5 m (15 feet) and 141°C (286°F) sprinklers were used.

The hot gas layer will tend to increase lateral spread by preheating the topmost layer of goods, at least up to the time that the ceiling sprinklers operate. After this time, the control of the fire should be rapid with sprinklers operating within the rack.

6.2. Future work

If a really effective fire detection/control method is required, as envisaged in the Introduction to this paper, it is clear that fire must be detected and suppressed within the slow first stage of its growth, (see 5.4.). If the fire can pass unhindered to the second stage, it is clear that, while good general control can still be established, there is still far too great a chance of a "stalemate" situation where the water is struggling for control of a fire which is too widespread and too hidden for it to reach effectively. This latter situation can be productive of much smoke and water damage. A radically new solution to this problem which will detect and control the fire in its slow first stage of growth is needed, if these requirements specified in the Introduction to this paper are to be met. Such a solution is not within the province of this paper, but it is the intention to follow up several promising lines of enquiry in future work.

7. ACKNOWLEDGMENTS

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The sprinkler system used in the experiments was arranged, installed and operated by the staff of Mather and Platt Ltd.

Several manufacturers co-operated by installing and operating their detection

equipment during the experiments, and by supplying their results for reporting in this paper.

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APPENDIX A

THE PERFORMANCE OF FIRE DETECTORS IN HIGH-RACKED STORAGES

by

P. E. Burry

A1 Introduction

Although the primary purpose of the tests reported on in this note was to consider methods of fire control, a secondary purpose of the experiments was to consider early fire detection within high-racked storages. It was hoped that information would be obtained which would enable the performance of different types of fire detector to be evaluated, and which would thus allow the maximum benefit to be obtained from a fire detector installation.

A2 Experimental arrangements

Since the racking was intended to represent the lower portion of a much larger rack, it was clear that the provision of a ceiling immediately above the rack would be unrealistic. A horizontal sheet of expanded metal on which detectors could be mounted was supported above the highest layer of pallets; detectors mounted on this sheet would experience conditions similar to those which would be experienced by detectors in the middle of a higher rack. Provision was made for the expanded metal to be lifted away from the rack after the operation of the detectors, so that damage of the detectors by fire could be avoided.

The types of detector mounted by JFRO and by detector manufacturers included:-

- a ionisation chamber smoke detectors
- b optical (forward scatter) smoke detectors
- c heat-sensitive detectors
- d infra-red detectors
- e smoke sampling detectors
- f laser-beam fire detectors

A2.1 Smoke detectors

Smoke detectors of both ionisation chamber and optical types were mounted on the expanded metal sheet. Since the lack of a true ceiling meant that there would be no mushrooming of the smoke plume, the detectors were mounted immediately above the fire. In practice this would require a higher density of detectors than normal, the required density being defined by the expected dimensions of the smoke plume.

One ionisation chamber detector was mounted 35 metres (115 ft) above the floor and another at 45 metres (148 ft) above the floor; both these detectors were supported by cable from the catwalk above the racking.

A2.2 Heat-sensitive detectors

Previous experience had shown little possibility of early detection by heat-sensitive detectors at the level of the top of the racking; however, the low cost of such detectors gives the possibility of mounting a larger number within the racking. A number of commercial heat-sensitive detectors were therefore mounted at different levels of the racking in the vicinity of the origin of the fire.

A2.3 Infra-red detectors

Three different types of commercial infra-red detector were mounted on or near to the racking. Since it is difficult to ensure that a detector can have a clear line of sight to any fire, no matter where the seat of the fire may be, the positions of the infra-red detectors in the early fires were so chosen as to avoid a direct line-of-sight. In later fires the infra-red detectors were mounted closer to the fire, and given locations with better views of the fire.

A2.4 Smoke-sampling detectors

A commercial smoke-sampling detector system was mounted within the rack, with the detection console approximately 15 m (50 ft) from the rack.

A2.5 Laser beam detector

For the earlier fires a laser beam detector was mounted so that its beam passed about 1 m (3 ft) above the top of the rack. In the last two experiments the beam ran across the top of the hangar, at a height of approximately 50 m from the ground.

A2.6 Instrumentation

Where commercial detectors were fitted, they were used with compatible commercial control units. Recording of the operation of commercial detectors was carried out by the manufacturers or suppliers.

Recording of the operation of some of the smoke detectors, the infra-red detectors, and the laser beam detector was carried out by JFRO.

A3 Experimental results

The operating times of detectors of each type are shown in Table 1 (Appendix A).

Due to a failure of the timing system, no significant data on the operation of the laser detector was obtained from Experiment 2.

A4 Conclusions

Since there were considerable variations in the speeds of development of the test fires, the times of operation of the detectors are best discussed in relationship to the times of sprinkler operation.

In general detector warning was obtained about two minutes before the first sprinkler operated. This small advantage is not, perhaps, surprising. The thermal detectors, which were distributed throughout the rack in a similar way to the sprinklers, have a sensitivity which is not much better than that of the sprinklers. The smoke detectors, which are much more sensitive than the thermal detectors, were mounted more than 10 m (33 ft) above the seat of the fire; their response was therefore delayed by the effects of smoke transport time and smoke dilution.

It appears that the small advantage obtained from practical fire detector installations will be of little use in giving early warning for manual firefighting; the upward spread after the fire reaches a detectable size will give a fire which rapidly becomes inaccessible to manual methods. Detector installations may, however, be useful in automatic fire control techniques such as:-

(a) Starting sprinkler system pumps before the operation of the first sprinkler, thus reducing the delay before water is available at the sprinkler nozzle.

(b) Operating roof vents to reduce smoke damage.

(c) Operating automatic fire extinguishers, either locally as in water sprays or in bulk methods such as inert gas flooding.

(d) Giving location of the fire.

The additional warning given by detectors may also be useful for evacuation of the building.

Table 1 (Appendix A)

Operating time of the earliest detector of each type

Detector	Test No.					
	1	2	3	4	5	6
Heat detector in rack	3m 58s	3m 10s	1m 16s	2m 30s	2m 0s	2m 15s
Ionisation smoke detector on top of rack	4m 30s	3m 10s	1m 5s	2m 45s	2m 30s	3m 0s
Optical smoke detector on top of rack	4m 5s	4m 10s	A	3m 26s	3m 15s	4m 15s
Infra-red flame detector	3m 29s	3m 31s	1m 37s	3m 6s	2m 10s	6m 2s
Laser beam detector 12m above fire	3m 31s	B	1m 10s	A	A	A
Laser beam detector 50m above fire	A	A	A	5m 0s	4m 10s	6m 0s

A: Not installed or not functioning

B: No record due to timing failure

APPENDIX B

OBSERVATIONS ON THE BEHAVIOUR OF THE SMOKE IN THE TESTS AND ITS RELEVANCE TO ROOF VENTING

by

P. L. Hinkley

Behaviour of smoke

When the fire started to spread before sprinklers opened, hot smoky gases formed a plume rising above the burning stack to the ceiling. When the sprinklers opened some of the smoky gases still rose as a plume but others flowed out of the sides of the stack through gaps between the individual pallet loads. These gases were generally cool and some of them were slightly (c. 1°C) below ambient temperature.

The smoky gases above ambient temperature rose upwards, cooling by mixing with the surrounding air, until they reached a level in the hangar where their temperature was less than the ambient temperature; they then spread outwards and formed a layer. Sometimes several layers formed at different heights. The smoky gases below ambient temperature flowed downwards and formed a layer above the floor. All the layers drifted with air currents in the hangar and, as time went on, they became more diffuse.

Implications for roof venting

Those gases which are hot enough to rise to the ceiling and form a layer beneath it, would in theory clear by the effect of their buoyancy if vents are opened in the roof. The closer the ceiling is to the top of the stack the higher the temperature of these gases would be and the greater their buoyancy; even so they would generally be so cool that the pressure due to stack effect would be small compared with the pressures generated by a light wind. Thus the flow would generally be dominated by wind effects and it is most important to design any venting system so that winds produce a suction effect at the vents.

The gases would seldom be at a sufficiently high temperature to actuate fusible links for opening roof vents so that some other means of controlling their opening, such as smoke detectors, would be necessary. The prior opening of roof vents would be unlikely to have any adverse effects on the opening of sprinklers within the stack.

The smoky gases at below ambient temperature would be more difficult to clear and generally they would have to be swept out by air currents within the building. Air currents would generally be increased by opening roof vents because of wind effects and the stack effect due to temperature differences caused by the building heating system and solar heating.

Table 1

Details of sprinkler arrangements for main rack

Experiment number	Sprinkler details	Protected levels	Sprinklers per cell
1	15 mm ($\frac{1}{2}$ in) conventional	All	2
2	" " "	2, 4 and 6	2
3	" " "	All	1 (1)
4	" " "	2, 4 and 6	1 (1)
5	10 mm ($\frac{3}{8}$ in) spray	All	2
6	" " "	All	1 (1)

Note: (1) When only 1 sprinkler per cell was used, these were staggered in their plan position to cover alternate vertical gaps between pallets.

Table 2

Average pressures and flow rates of sprinklers in main rack

Experiment number	Average flow per sprinkler		Average pressure at sprinkler heads	
	dm^3/min	gal/min	bar	lbf/in^2
1	177	37	4.8	70
2	185	39	5.4	77
3	181	38	5.1	74
4	176	37	4.9	70
5	132	29	5.4	77
6	134	29	5.5	80

Table 3 Details of results

Experiment number	Number of sprinklers to operate		First sprinkler to operate				Volume of water used				Moisture control percentage dry weight
	Main rack	Small rack	Time	Level	Flame height		Main rack		Small rack		
					m	ft	m^3	gal	m^3	gal	
1	4	3	5min 20s	2nd	5.8	19	11.8	2600	3.6	790	12
2	3	0	6min 30s	2nd	12.2(1)	40	4.1	900	nil		16
3	2	0	2min 25s	4th	4.6	15	3.1	860	nil		12(2)
4	5	5	5min 11s	4th	12.2(1)	40	10.8	2400	5.9	1300	11
5	6	0	4min 20s	2nd	7.0	23	7.2	1600	nil		-(3)
6	5	0	6min 20s	4th	11.0	36	12.1	2700	nil		9.5

Notes: (1) Flames above top of rack. (2) Average, centre dried out to approx. 8 per cent.

(3) No measurements made.

Table 4

Operating times of sprinklers and corresponding flame heights

Experiment number	Operating times of sprinklers		Level	Flame height above sprinkler at time of operation(1)	
	min	s		m	ft
1	5	20	2	1.8	6
	7	25	4	4.6	15
	7	35	5	2.7	9
	10	02	6	0.9	3
2	6	30	2	8.2	27
	6	30	4	4.6	15
	8	35	6	0.9	3
3	2	25	4	- 3.7	- 12
	2	35	2	1.8	6
4	5	11	4	4.6	15
	5	40	6	0.9	3
	5	50	2	8.2	27
	7	10	2	8.2	27
	12	45	2	8.2	27
5	4	20	2	3.0	10
	4	30	3	1.8	6
	4	30	4	0	0
	7	20	5	2.7	9
	7	30	6	0.9	3
	7	35	6	0.9	3
6	6	20	4	3.4	11
	6	25	3	5.2	17
	6	45	5	2.7	9
	7	25	6	0.9	3
	12	45	6	0.9	3

Note: (1) Flame height assumed to reach maximum of 12.2 m (40 ft)

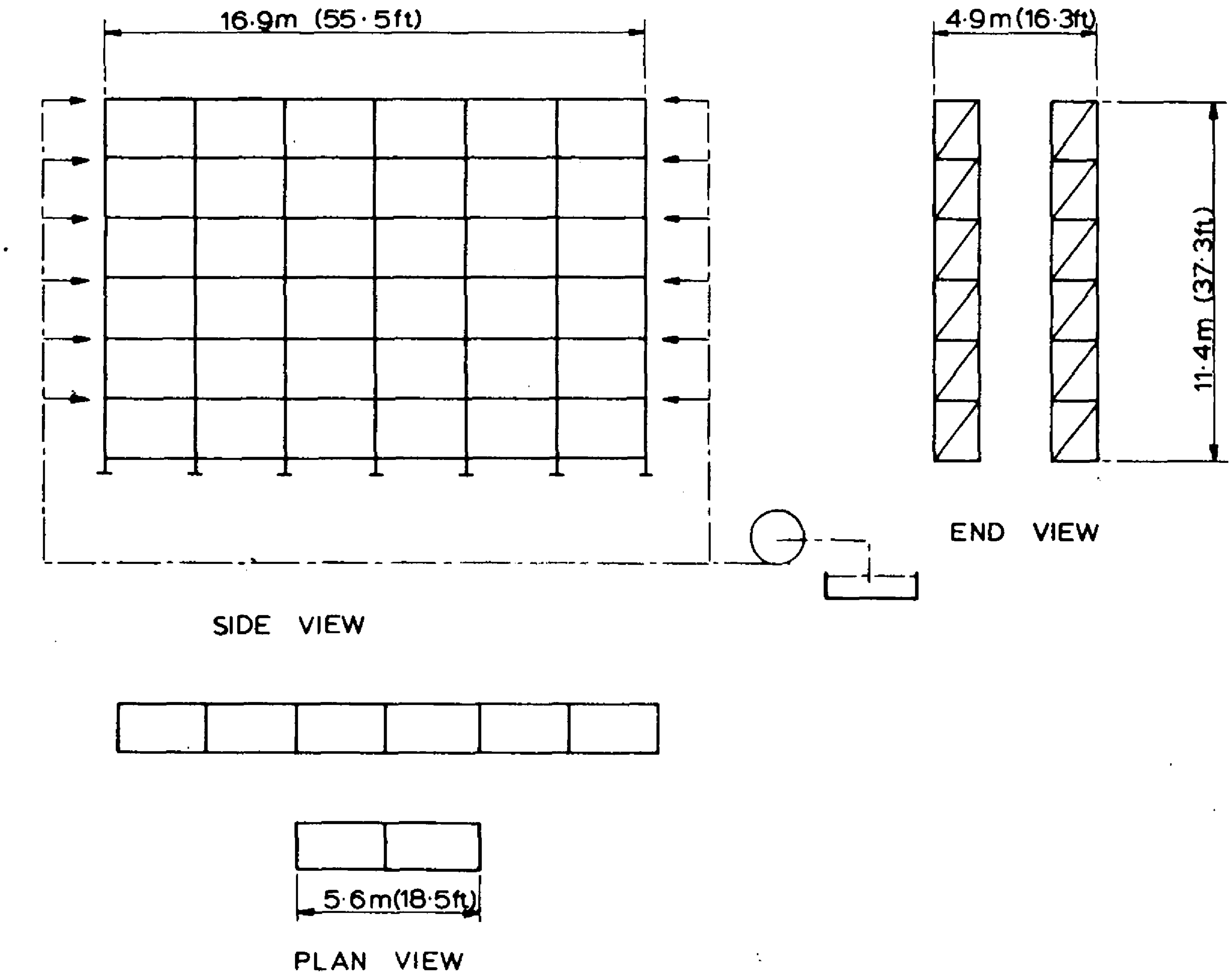


FIG. 1. GENERAL ARRANGEMENT OF THE RACKING

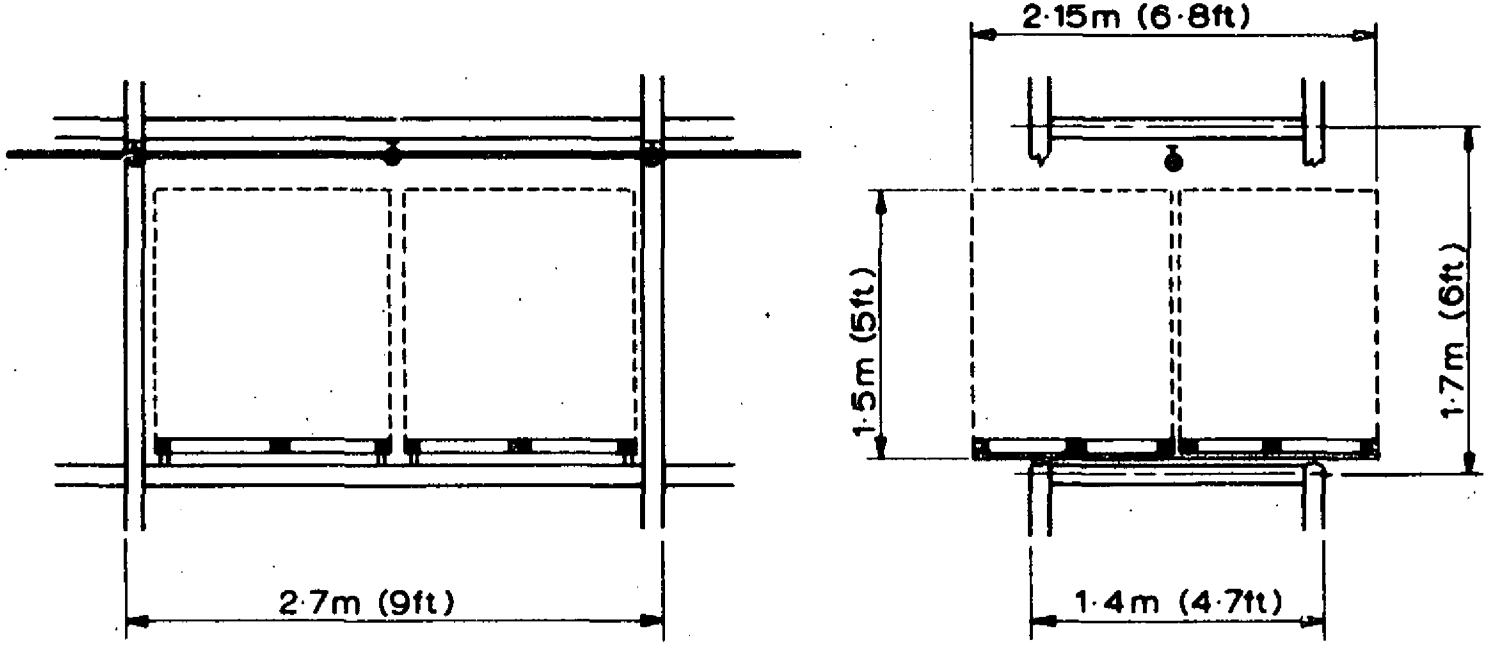


FIG. 2. SPRINKLER SYSTEM IN THE RACKING

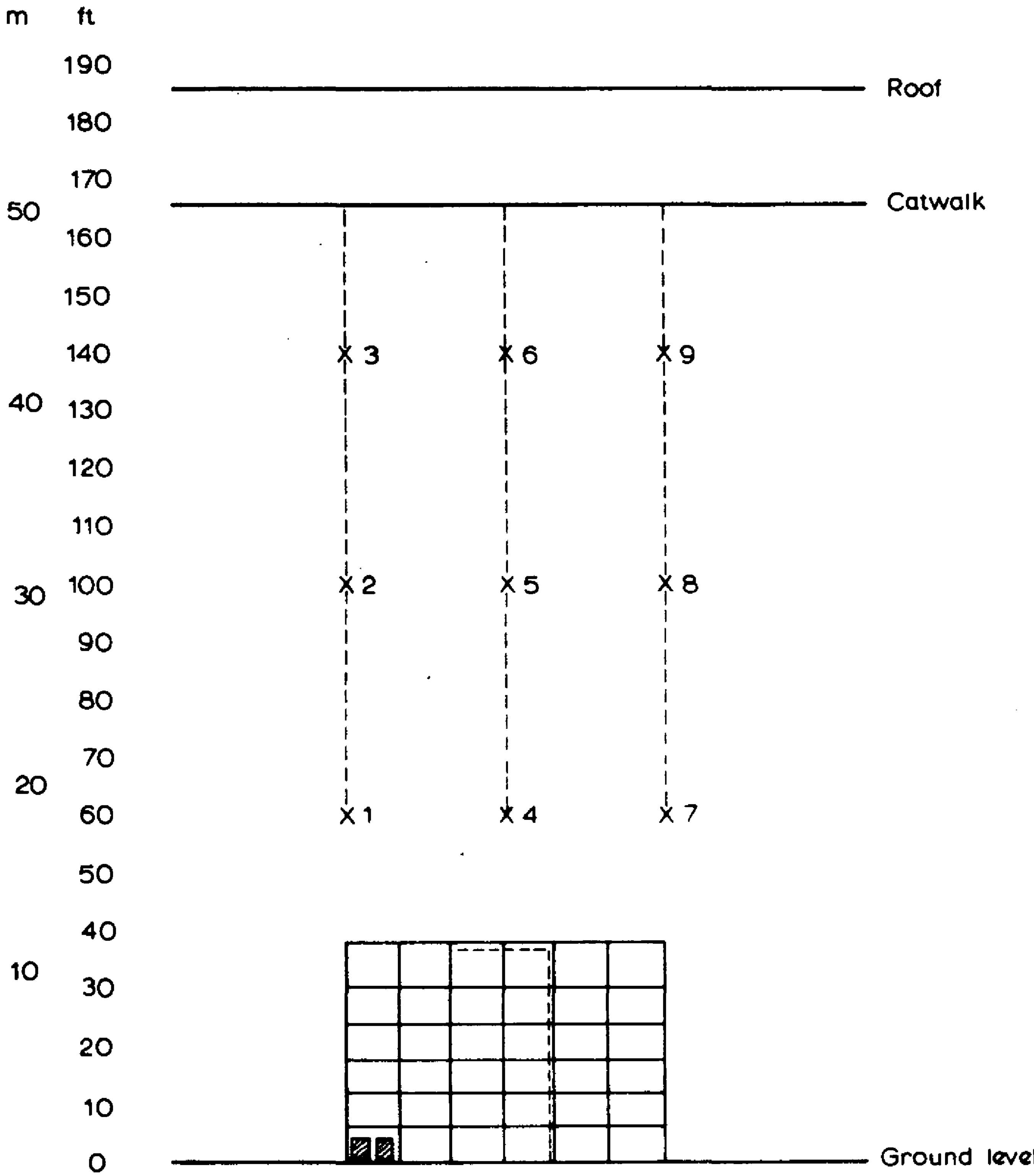


FIG. 3. THERMOCOUPLE POSITIONS ABOVE RACKING

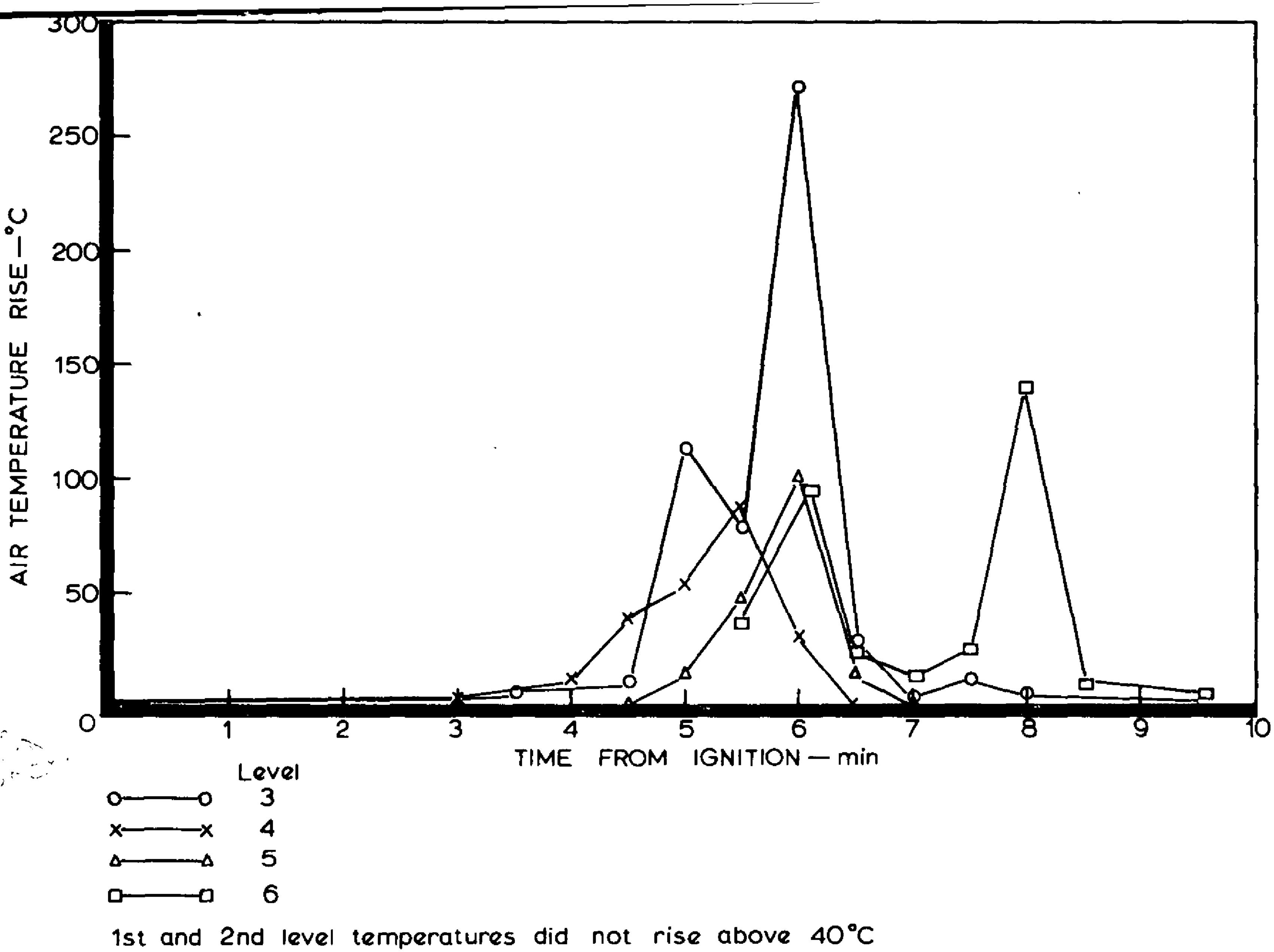


FIG. 4. AIR TEMPERATURE RISE WITHIN MAIN RACK ABOVE ORIGIN OF FIRE EXPERIMENT 2

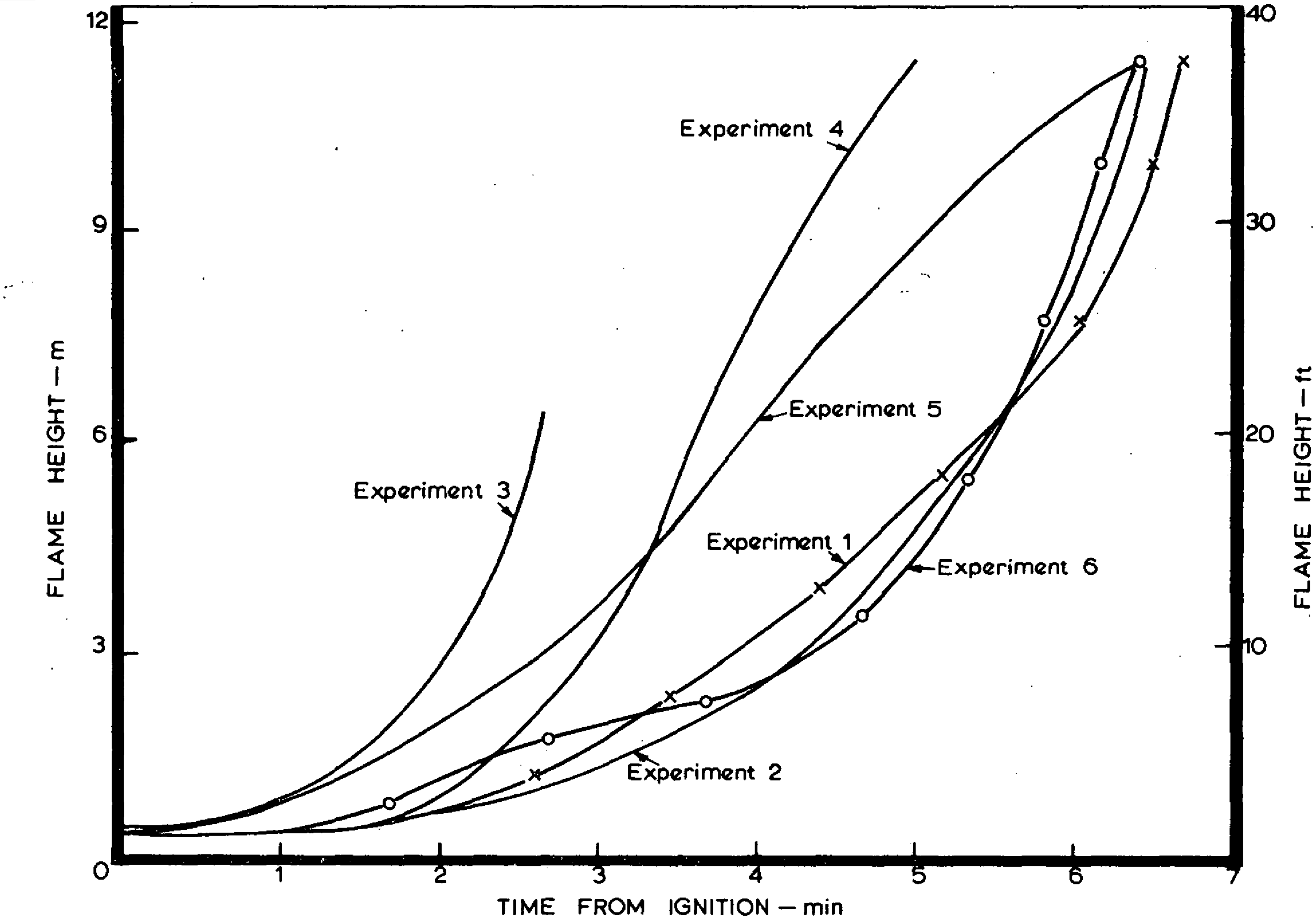


FIG. 5. INCREASE IN FLAME HEIGHT:- EXPERIMENTS 1-6

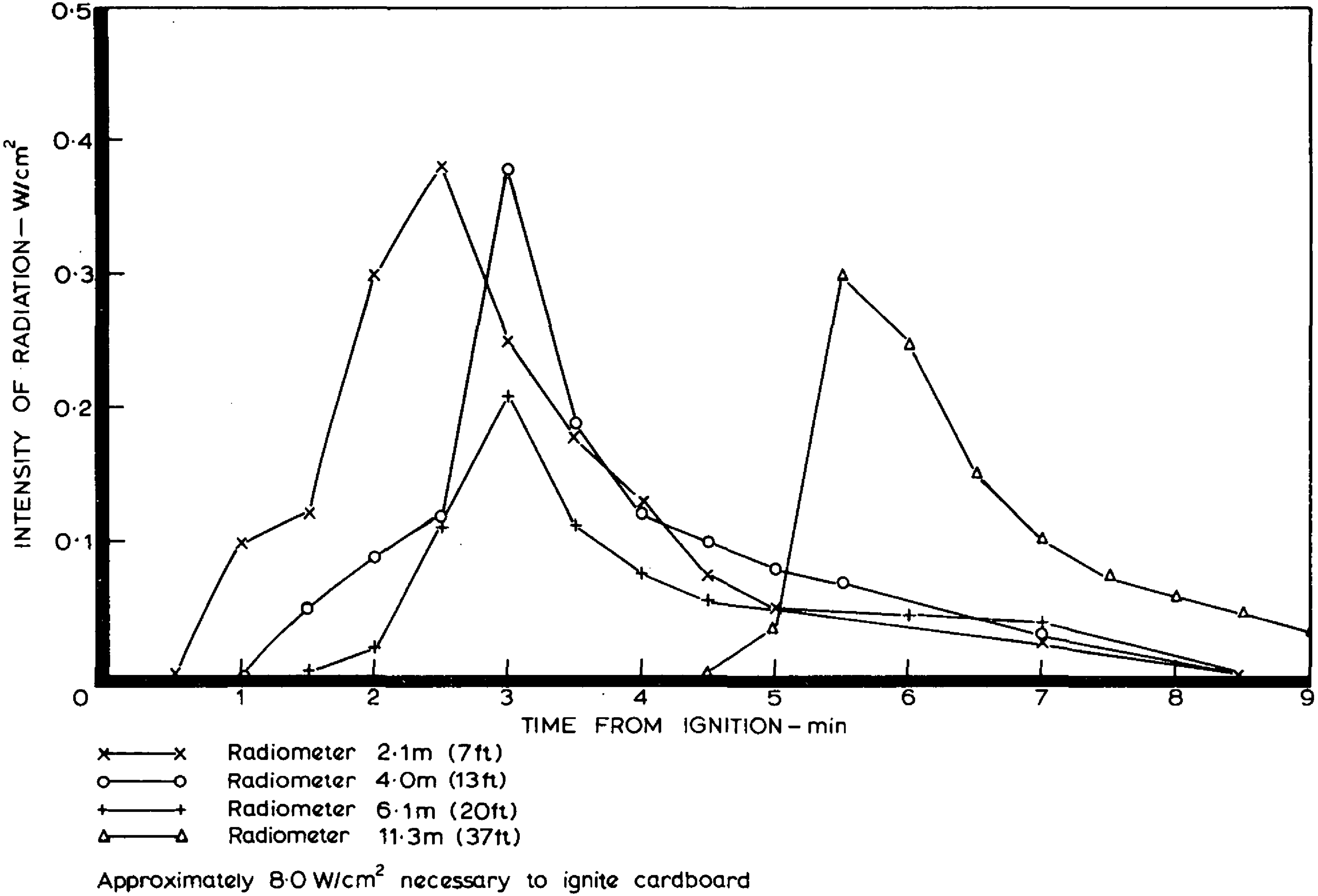
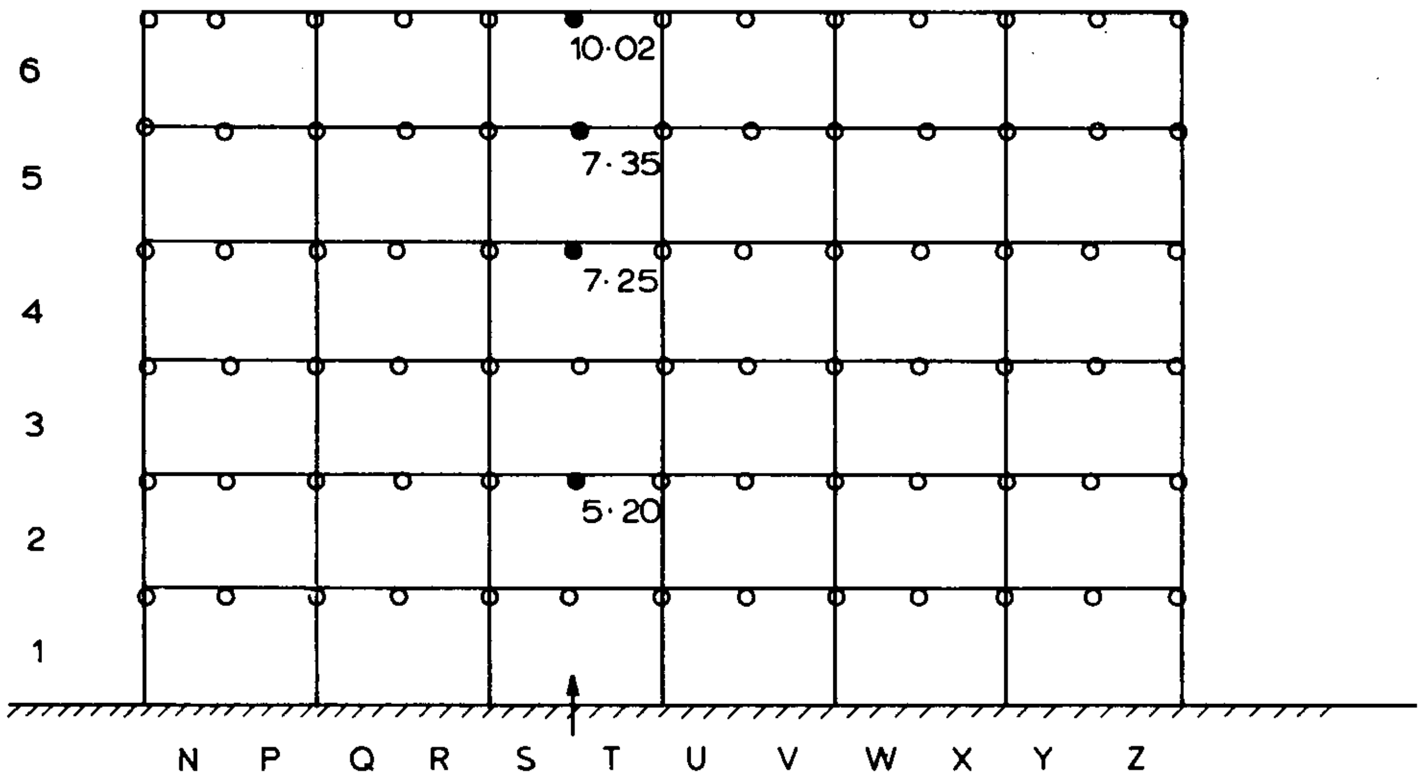


FIG. 6. RADIATION MEASUREMENTS :- EXPERIMENT 5



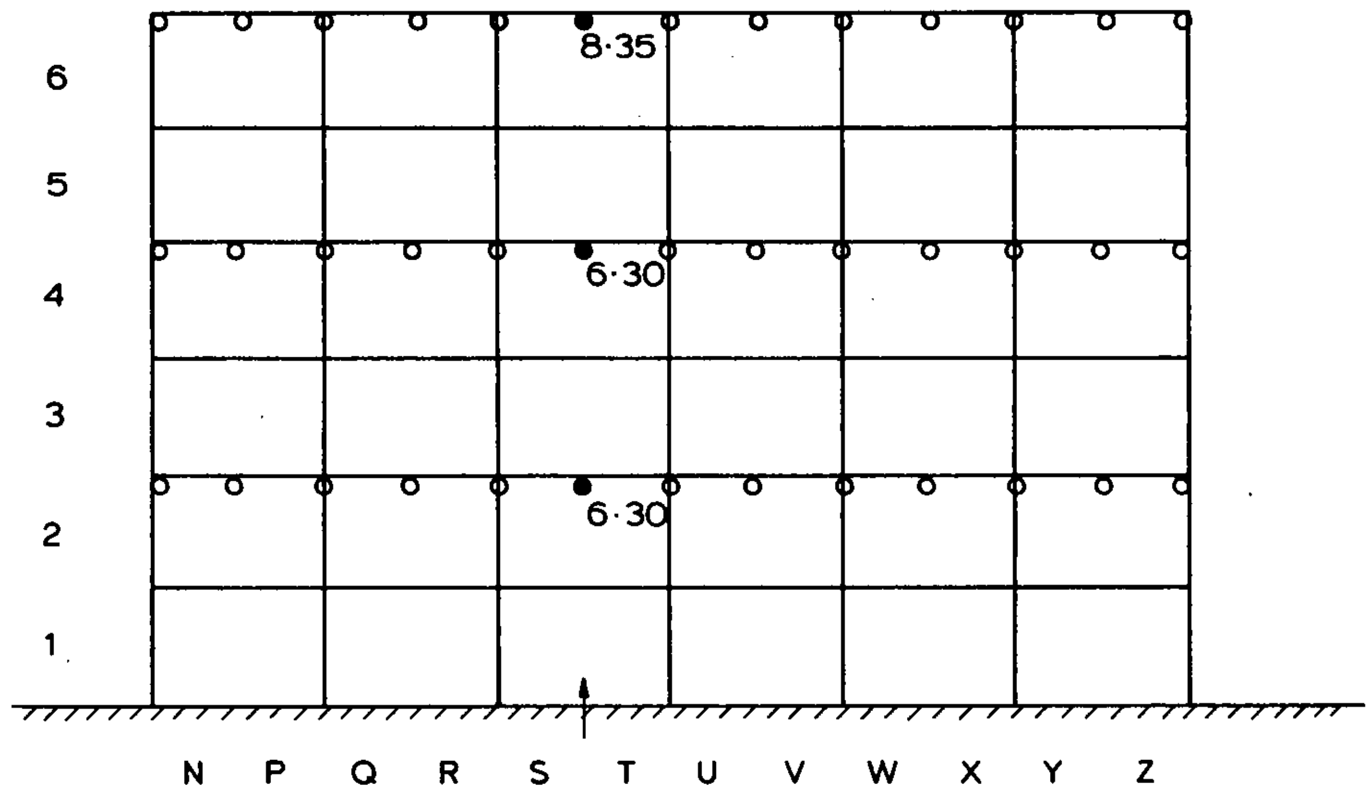
½" Sprinkler positions marked o

● Actuated sprinklers with times of operation

Total actuated 4

NORTH SIDE VIEW OF MAIN RACK

FIG. 7. POSITIONS OF SPRINKLERS IN EXPERIMENT 1



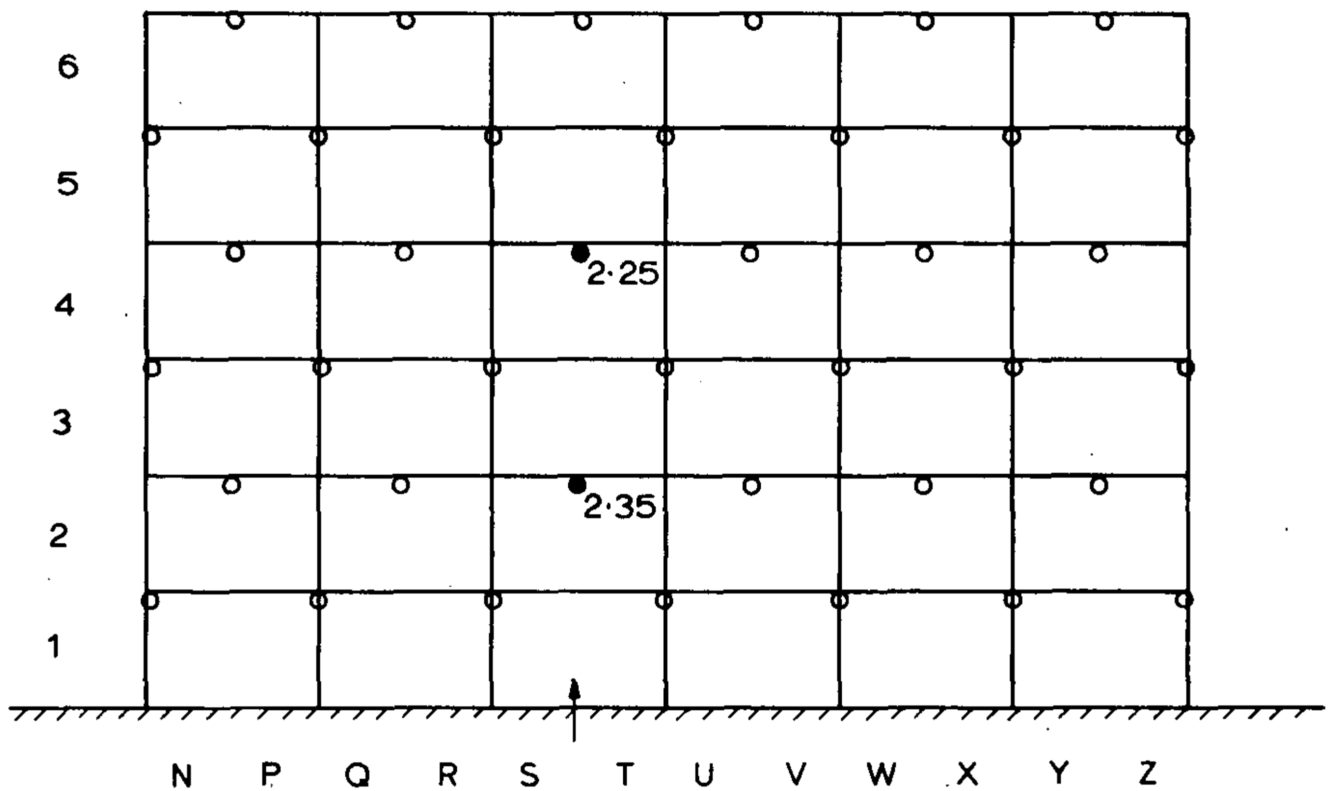
½" Sprinkler positions marked o

● Actuated sprinklers with times of operation

Total actuated 3

NORTH SIDE VIEW OF MAIN RACK

FIG. 8. POSITIONS OF SPRINKLERS IN EXPERIMENT 2



½" Sprinkler positions marked o

● Actuated sprinklers with times of operation

Total actuated 2

NORTH SIDE VIEW OF MAIN RACK

FIG. 9. POSITION OF SPRINKLERS IN EXPERIMENT 3

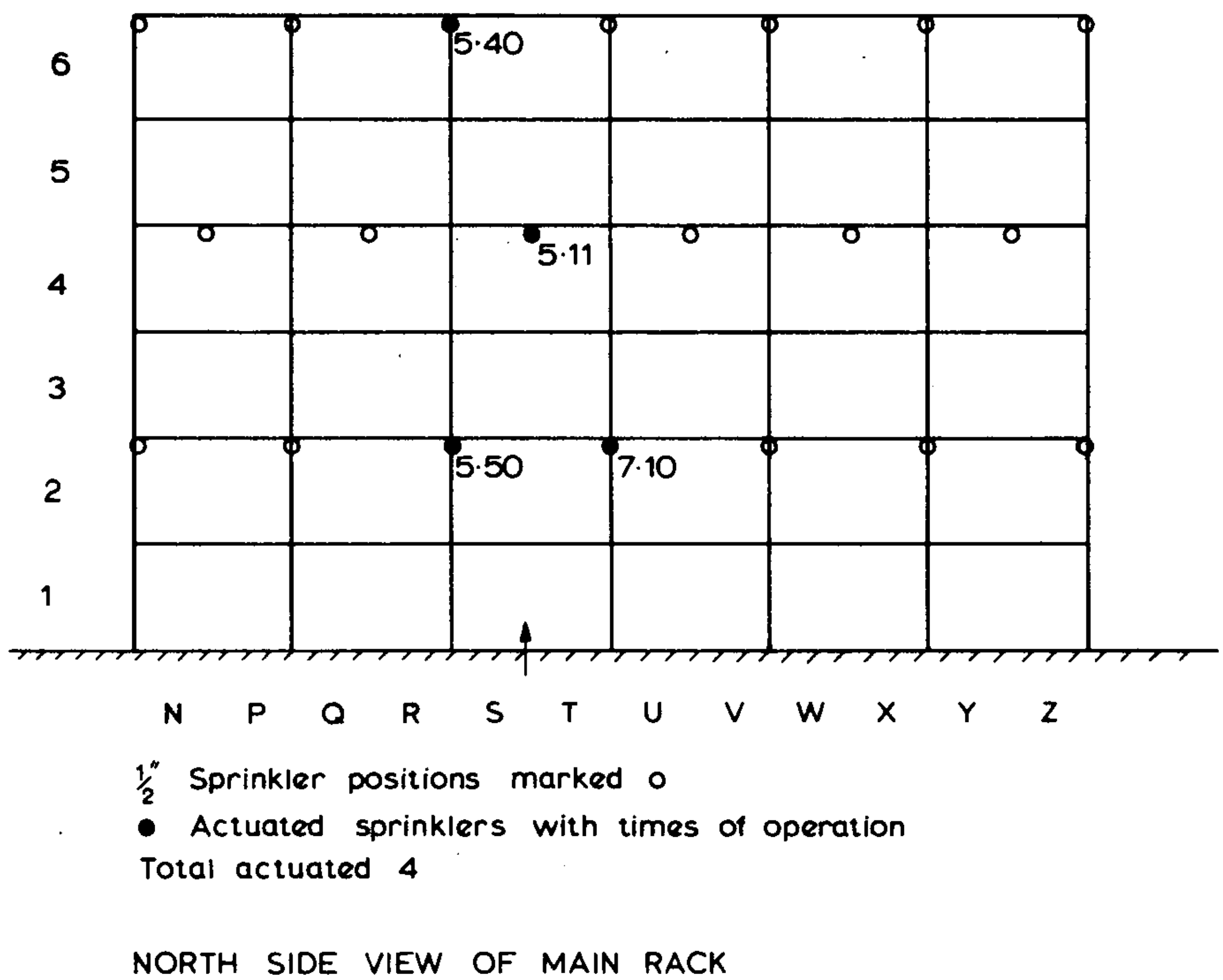
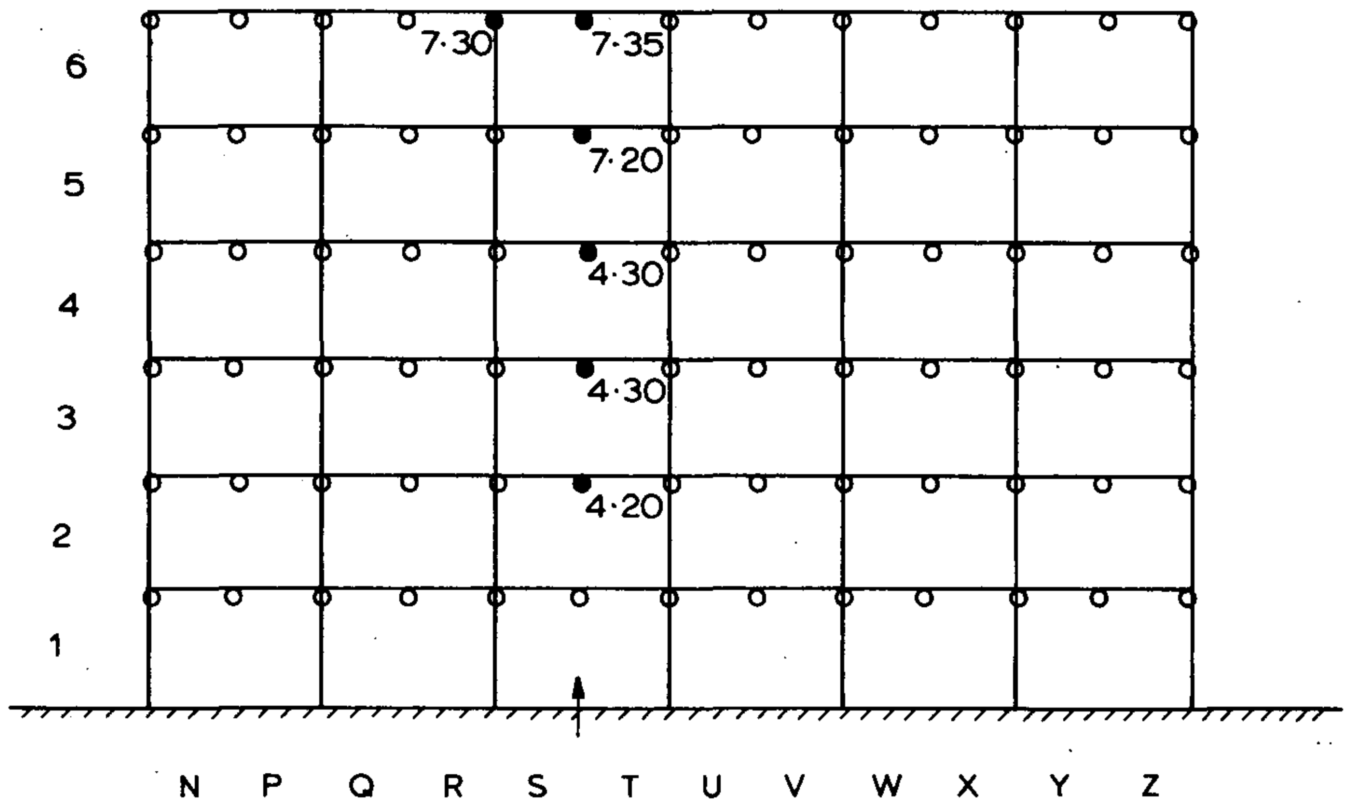


FIG. 10. POSITION OF SPRINKLERS IN EXPERIMENT 4



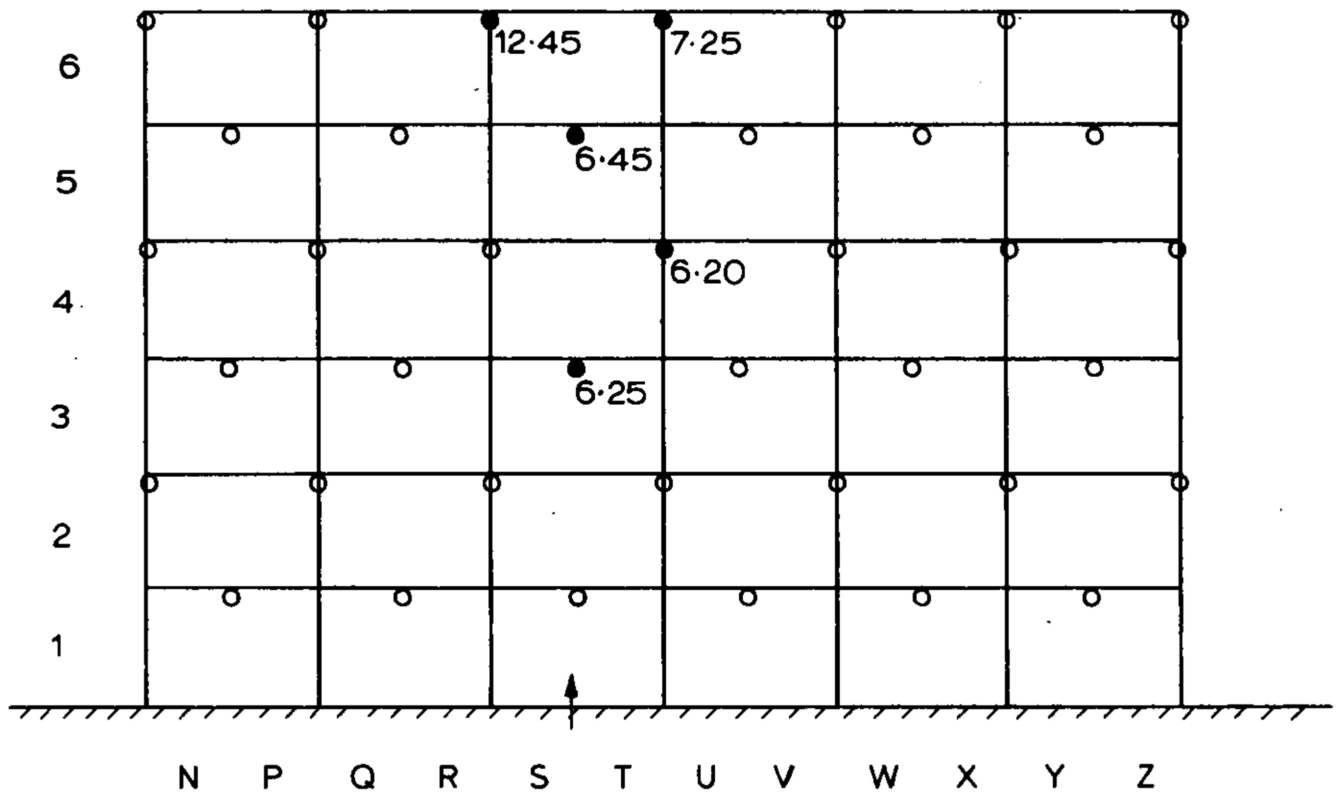
3/8" Sprinkler positions marked o

● Actuated sprinklers with times of operation

Total actuated 6

NORTH SIDE VIEW OF MAIN RACK

FIG. 11. POSITION OF SPRINKLERS IN EXPERIMENT 5



3/8" Sprinkler positions marked o

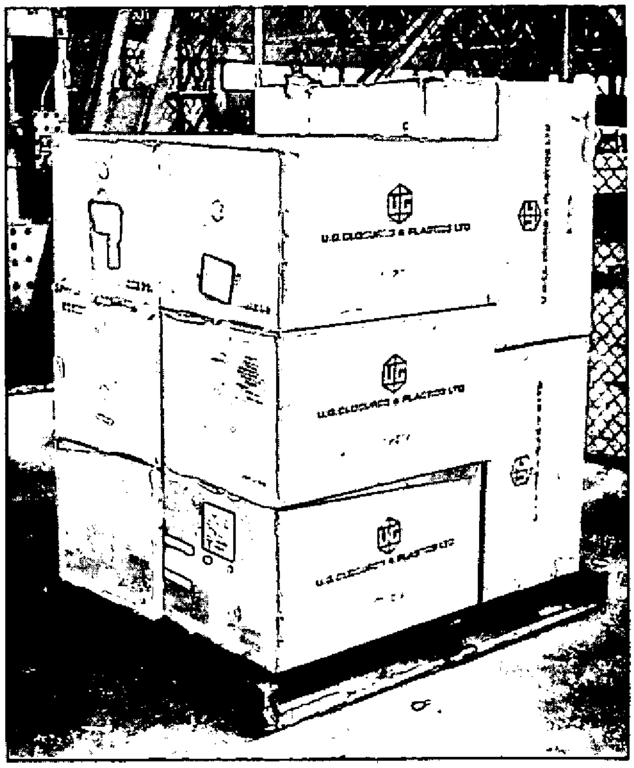
● Actuated sprinklers with times of operation

Total actuated 5

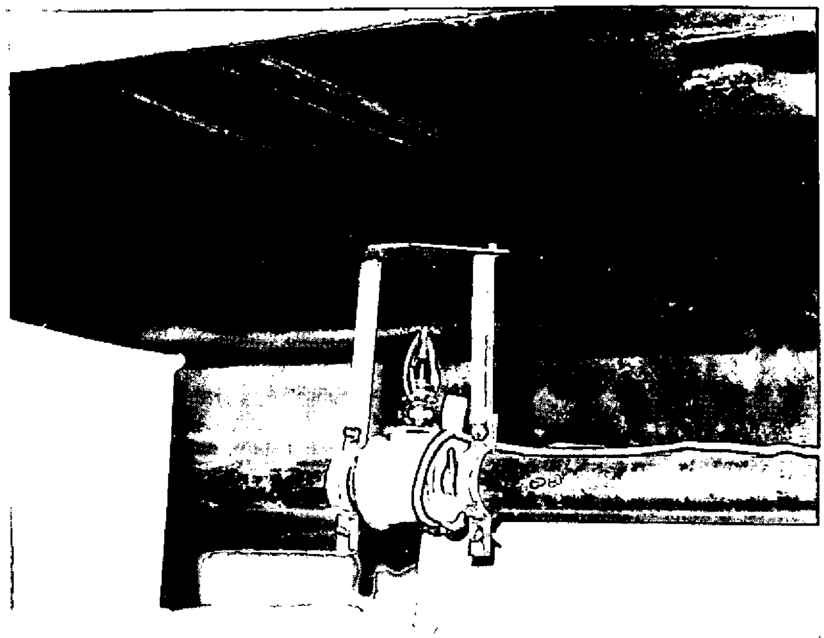
NORTH SIDE VIEW OF MAIN RACK

FIG. 12. POSITION OF SPRINKLERS IN EXPERIMENT 6

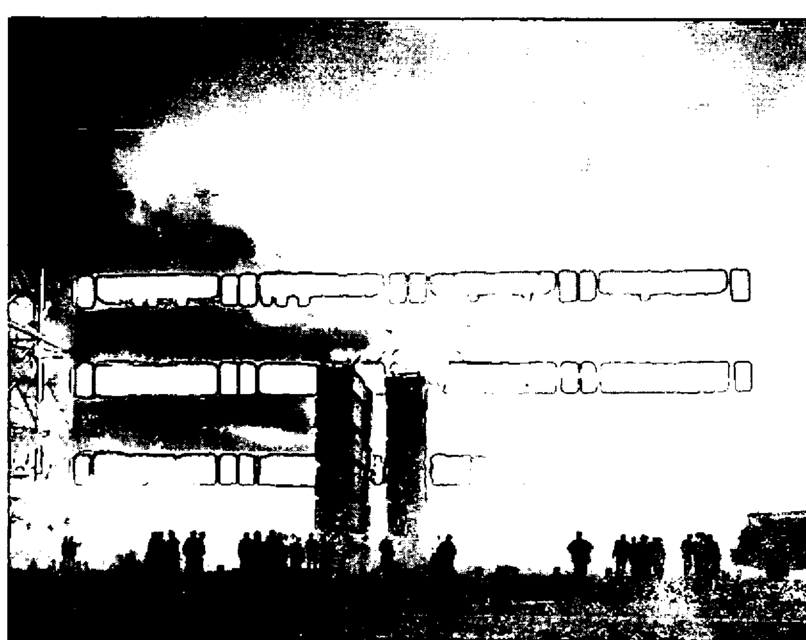
GENERAL VIEW OF RACKING
PLATE 1



DETAIL OF LOADED PALLET
PLATE 2



SPRINKLER FITTED WITH SHIELD AND THERMOCOUPLE
PLATE 3



HOT AND COLD SMOKE DEVELOPMENT AT
22 MINUTES, 1ST EXPERIMENT
PLATE 4

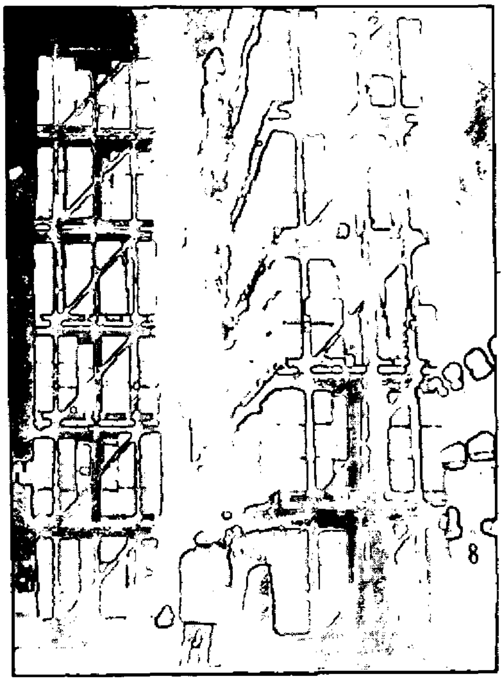
(a) 3 m 15 s after ignition

(b) 4 m 13 s after ignition

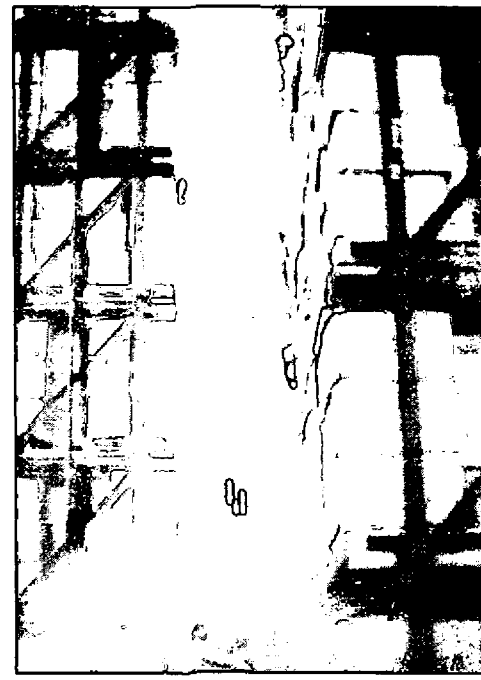
(c) 4 m 40 s after ignition

(d) 5 m 30 s after ignition

1ST EXPERIMENT
PLATE 5

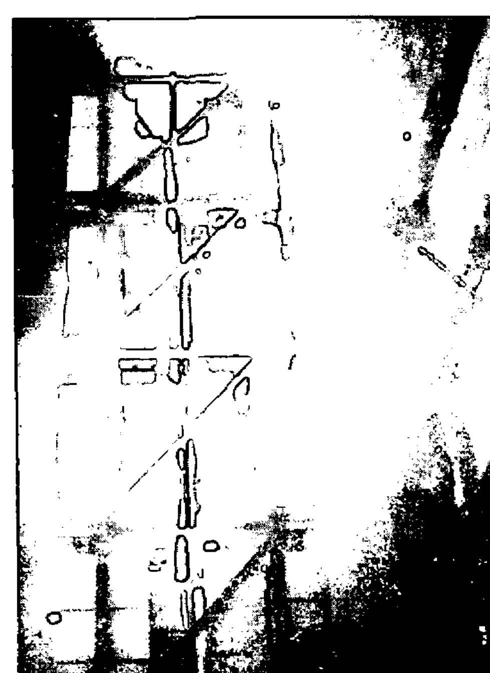


(a) 7 m 30 s after ignition



(b) 8 m 44 s after ignition

(c) 9 m 56 s after ignition



(d) 12 m 42 s after ignition

1 ST EXPERIMENT
PLATE 6