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EXPERIMENTAL APPRAISAL OF AN AMERICAN SPRINKLER SYSTEM FOR THE PROTECTION OF GOODS IN HIGH-RACKED STORAGES

by

N W Bridge and R A Young

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FIRE
RESEARCH
STATION

50786

Fire Research Station
BOREHAMWOOD
Hertfordshire WD6 2BL

Tel: 01 953 6177

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SUMMARY

Six large-scale fire experiments are described, involving goods stored in a six-level rack, to simulate industrial conditions. For two tests, fourth level central and face sprinklers and sixth level central sprinklers were used. For four tests, a thick plywood barrier was put just above the fourth level and the fourth level central sprinklers were not used. The arrangements were derived from the NFPA Standard 231C - 1972 for Rack Storage of Materials.

In four tests the fire was lit in the first level. In two tests involving some polyurethane foam it was lit in the second level, (with the first level empty) simulating a system repeating every three levels. The rack is considered as the lowest portion of a much higher rack and so the effects of ceiling sprinklers are not discussed.

It is concluded that the barrier is an effective aid to stopping upward spread but the arrangement of sprinklers is not capable of extinguishing the fire quickly at the lower levels. Without the shelf, the fire spread to the top of the rack, except with the half load of goods on each pallet, which would rarely occur in practice.

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

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1. INTRODUCTION

Early work by the Joint Fire Research Organisation[1] and that by Factory Mutual Research Corporation in United States of America, on the sprinkler protection of goods in high racked storages, involved sprinklers operated either by glass bulbs or fusible links. The JFRO then developed a new high speed system, consisting of an arrangement of vertical zones of open sprinklers which are supplied with water on the operation of a special valve coupled to an electrical short circuiting line detector. This will be referred to as the JFRO system in the rest of the Note.

From their previous work, Factory Mutual in conjunction with the NFPA have instead made recommendations for several alternative arrangements of sprinklers. The sprinklers operate in the conventional way, but are distributed within the racking in ways dependent on the class of commodity stored, rack height, and in particular the presence or absence of full-width horizontal barriers in each rack, at various levels, for the full length of the rack. These arrangements differ from the systems of wet-pipe intermediate sprinklers recommended in the 29thEdition of the Fire Offices' Committee Rules for Automatic Sprinkler Installations[2].

This report describes six full-scale fire experiments, which were carried out using methods based as far as possible on those described in the NFPA Standard for Rack Storage of Materials, No 231C-1972.

The rack carried six levels of pallets, and it had a total height of 11.4 m (37 ft). Two categories of goods were used, at full and half-loadings on standard pallets, with three arrangements of sprinklers. Conventional sprinklers were used for three tests and spray sprinklers for the other three tests. Brief details are given in Table 1.

Line detectors of the JFRO System, dry intermediate-level sprinklers of the FOC System, and smoke detectors were installed to give comparative operating times under identical fire conditions.

2. EXPERIMENTAL ARRANGEMENTS

2.1. Building

All the experiments were carried out in a hanger 247.5 m (812 ft) long, 83 m (273 ft) wide, and 50 m (165 ft) high to the central catwalk, 4.5 m (15 ft) below the roof.

The area containing the racking is near one end of the hangar. The height of the roof is at least four times the height of the racking, and free access is given all round the racking. Thus there is virtually no restriction on the movement of either hot or cold smoke and gas from a fire, and no limit on the air supply to the fire except that due to the close packing of goods.

The building height does not permit the use of ceiling sprinklers, but the racking is considered as the lowest part of a much higher rack.

2.2. Racking

The fire experiments were carried out in one half of the large rack used for several previous series of tests[1,3]. The arrangement of this half is shown in Fig.1 and Plate 1. Rack height is 11.4 m (37 ft), divided into six levels of 1.8 m (6 ft) each. The length of the half rack is 8.5 m (28 ft) made up of three cells each holding four standard wooden 4-way entry pallets, of dimensions 1020x1220 mm (40x48 in) in a total width of 2.13 m (7 ft 2 in). Further details of the racking are given in ref.1

A shorter rack parallel with the main rack, and adjacent to its centre portion, was not used in any of these experiments except as a carrier for radiometers.

2.3. Stored goods

The loads on the seventy two pallets were varied in type and amount during the series. The first four experiments used the same type of goods, i.e empty 5 Imp gall (22 l) drums with wood wool, packed in cardboard cartons. This was considered to be equivalent to Class II/III goods in the NFPA classification. Details of these commodity classifications are given in Appendix 1. For experiments 1,3 & 4 each pallet contained 6 corrugated cardboard boxes 610 x 610 x 460 mm (24 x 24 x 18 in) each containing four drums packed around loosely with about 1 kg wood wool, and sealed at top and bottom with plastics tape (Tesa tape).

For experiment 2, only 3 boxes per pallet were used, with the same contents as in experiment 1 giving a load height of 610 mm (24 in) instead of 1.22 m (48 in).

In the last two experiments some plastics material was used in each box to simulate as far as possible Class IV goods in the NFPA classification. Each pallet carried 14 cartons, 530 x 330 x 460 mm (21 x 13 x 18 ins) each containing 1 drum, some wood wool, and a block of polyurethane foam. The weight of foam in each box was about 200 (± 50) gm (8 ± 2 ozs) in the fifth test and about 800 g (30 ozs) in the sixth test. This gave about 2.8 Kg (6.2 lbs) and 11.2 Kg (24.5 lbs) of plastics on each pallet.

2.4 Sprinkler system

Fig 2 shows a plan and elevation of the sprinkler arrangement 'E' used for experiments 1 and 2 based on Figure 4152E of the NFPA Standard, for the lowest six levels of a very high rack.

The sprinklers were arranged in three rows at the fourth level, one row on each face and one in the centre. There was also a central row at the sixth level.

The sprinklers used were all 15 mm ($\frac{1}{2}$ in) conventional type for these two tests.

The arrangement used for the third and fourth experiments is shown in Fig.3, derived from the NFPA Standard Fig.4152G. The essential difference between this and the previous arrangement is the presence of a continuous barrier shelf at the top of the fourth level. This was constructed from six pieces of 17 mm ($\frac{3}{4}$ in) plywood, to cover the full length and width of the rack. It resists the upward propagation of the fire, and diverts the hot gases rising up the central flues, to the sides of the rack. Immediately under the barrier is the position of the two face mounted lines of sprinklers. The central line of sprinklers is omitted, and the number of sprinklers in each face mounted line is halved, compared with arrangement E.

For the third test, the sprinklers were 15 mm ($\frac{1}{2}$ in) conventional as before, but for the fourth test, the fourth level sprinklers were 15 mm ($\frac{1}{2}$ in) pendant spray type, and the sixth level sprinklers were 15 mm upright spray type.

The arrangement 'J', used for the last two experiments, and shown in Fig.4 (Standard Fig.4152J), is the same as arrangement 'G' except that the layout is repeated every three levels instead of every four levels to account for the higher hazard category (IV) of goods stored. To avoid major disturbance of the pipework etc, this was simulated by lighting the fire at the base of the second level in these two experiments. The first level was left empty.

The water pressure was maintained at 2 bar on gauges at a height of about 1 m (3 ft 4 ins) near the manifold, connected throughout each experiment to the remote end of each sprinkler line.

It should be noted that in all six experiments sprinkler 'd' was almost directly above the ignition point. Further experiments will be conducted with the sprinkler layout reversed so that no sprinkler is directly above the ignition point.

Sprinklers representing the FOC intermediate level sprinklers, but without water supply, were fitted at the tops of the first, second and third levels in the centre of the rack in the ignition flue, to act purely as detectors. Their operating times are given in the Tables of Results.

2.5 Instrumentation and Detection Equipment

A number of fast response chromel-alumel thermocouples were used to monitor air and steelwork temperatures within the racking. Their outputs were recorded on a UV chart recorder, together with the outputs from two radiometers which were measuring radiation across the aisle. The latter were fixed to the main structural members of the adjacent rack at the second and fourth levels, but extending out from the end of the rack so that the measuring heads were facing the ignition flue of the main rack at a distance of 1.5 m (5 ft).

All the sprinklers at the fourth level were fitted with wires forming part of a monitoring circuit. Operation of any sprinkler caused an open circuit which was used to light an indicator lamp. The time of operation could thus be noted, together with the position of the sprinkler concerned. Pressure gauges were connected to the end of each sprinkler line, and taken back to a position near the manifold, at about 1 m above ground level, so that the pressure could be controlled at 2b on the gauges, with the valves on the manifold as each sprinkler operated. The flow of water was continuously recorded by a pen recorder connected to a flowmeter of maximum capacity 2727 dm^3/min (600 gpm).

Monochrome and colour still photographs were taken of each fire.

The dry heads referred to in Section 2.4 were fitted with wires and weights so that operation of the head resulted in the weight dropping to the ground. The time of operation was noted by observers.

Two slightly different versions of the short circuiting line detector developed by British Insulated Callenders Cables under contract from JFRO were also installed, to give operating times of the JFRO system under identical fire conditions. One form uses a PVC outer sheath over the twisted pair of conductors, and the other form uses a polypropylene braided sheath. Both types operate at a nominal minimum temperature of 105°C.

One length of each type was installed at the top of the first level and a length of the second type at the second level for each of the first four tests. The same arrangement, but moved up one level, was used for the last two tests. Operating times are given in Table 3.

An ionisation type of smoke detector was installed at the top of the sixth level.

3. Experimental procedure

Before ignition, the air temperature and humidity at ground level were measured, and the moisture content of a random selection of 10 cardboard cartons was taken with a Protimeter using a needle contact probe. In all cases the moisture content was between 13% and 15%. (Group B scale)

The fire was lit with a match at a tear in the side of a box on the lowest level in each case, ie on the first level for the first four tests and on the second level for the last two tests. The tear was near the bottom of a box in pallet load C1 (see Fig.1) approximately half way between the aisle face and the central flue, and in the flue between loads C_1 and D_1.

On the ignition signal, the clocks, UV Recorder, and flowmeter recorder were started simultaneously. Progress of the fire was observed, and operating times of sprinklers and detectors were noted. The pump and manifold valves were controlled manually so that the gauge pressure was maintained as close as possible to 2 bar.

When it was judged that the fire was under the control of the sprinklers, final extinction and removal of smouldering debris was completed by Bedford Fire Brigade.

4. Experimental results

The main experimental results are shown in Tables 2, 3, 4 and 5 with full fire chronologies in Tables 6 – 11. Table 2 gives the operating times of all sprinklers which applied water to the fires. Their locations, designated a – t are shown in Figures 2, 3 and 4. It can be seen that in every case except the first, sprinkler 'd' which was the face sprinkler directly above the ignition point, was first to operate. The reason for sprinkler 'c' operating first in the first experiment may have been a slight draught.

The operating times of all other detectors are given in Table 3 but it should be noted that no particular significance can be attached to the operating times of dry sprinklers which operated after water was applied, since the presence of water spray greatly affects temperature conditions in the racking. However, as is shown in Table 4, in half the experiments, a 'dry' sprinkler operated before a 'wet' sprinkler, but in every case these were later to operate than either the BICC line detector, or the smoke detector.

The maximum recorded values of radiation intensity opposite the second and fourth levels are given in Table 5. In three cases the levels were high enough for long enough to give a high probability of ignition in the adjacent rack (see notes to Table 5) ref 5. Fig.5 shows graphs of radiation intensity at heights of 3.6 m (12 ft) (opposite the second level) and 7.3 m (24 ft) (opposite the fourth level) during the sixth experiment . A value of 2 W/cm^2 was exceededat the second level for approximately 1 minute, indicating that cardboard in the adjacent rack would have ignited by this means. Ignition by flying brands was also very likely.

Graphs of flame height above the ignition point, against time are shown in Figure 6, for all experiments. It is seen that although there is a wide variation in the initial rate of spread, all the curves are almost parallel between the 3.6 m (12 ft) and 5.4 m (18 ft) levels (the third pallet level). The slow average progress of the fire in experiment 2 is due to the half loading of the pallets.

More detailed graphs of flame height with operating times of sprinklers etc are shown for each experiment in Figures 7 – 12. The operating times of sprinklers, smoke detector and line detector are plotted at the height of the device within the rack. The smoke detector point is well above the flame height curve, whereas all aprinklers are below it (except for one case in experiment two, which occurred after the other sprinklers had controlled the fire). However the line detector operating point, at the lower end of the short vertical line, would, if the detector were actually operating a JFRO system, apply water to the fire at the top of at least the third level. This point is the top end of the short vertical line, and is above the flame height curve, (though rather close to it in the sixth experiment).

Figure 13 shows the air temperature rise within the racking at various levels, during the sixth experiment when larger quantities of polyurethane foam were used on each pallet. Due to the high thermal capacity of the main structural steel work, the air temperatures attained did not cause a significant rise in steel temperature, but steelwork of lighter construction could be damaged in a fire of similar intensity. Steelwork temperatures were not measured, but some pallet bearers, which are of lighter construction, were distorted sufficiently to make them unusable in an automated rack.

5. Discussion and conclusions

This series of experiments has afforded useful information on the potential value of three different arrangements of sprinklers for racked storages. It has shown that:

5.1 Arrangement 'E' (without the barrier) controlled the fire, but not before it had reached the top of the racking when the pallets were fully loaded. This is because the rate of spread is normally such that the fire is above a sprinkler before it operates.

When the pallets were only half filled, the rate of spread was much lower and the first sprinkler to operate was able to control the relatively small fire without it going into the top level. However these conditions are unlikely to be met with in practice.

There appears to be no particular advantage in this arrangement over the FOC intermediate sprinkler arrangement.

5.2 Arrangements 'G' and 'J' (with the barrier) were successful in preventing upward spread of the fire beyond the barrier, but at the expense of some extra sideways spread compared with the FOC or JFRO arrangements.

Though the fire did not spread above the barrier there was considerable charring of boxes in the fifth and sixth levels. These boxes were apparently prevented from igniting by being wetted just in time, by water carried by the thermal updraughts past the sprinklers, but random factors such as boxes opening, and flying brands, might well enable these levels to be ignited in practice.

In series of experimental fires in a fully compartmented storage[6], it was found that the fires usually progressed to the upper levels in the absence of sprinklers. Since in the present arrangement there is a sprinkler in every alternate flue, at the face, it seems likely that a fire in a flue between sprinklers has a high chance of progressing beyond the barrier.

5.3 It was necessary to allow the sprinklers to run for some time before control was considered to be adequate, but this allowed a large proportion of the fuel load to burn out. It seems unlikely that such good control would be obtained with many of the fire loads which occur in practise, since burn-out of fuel would not take place so soon.

5.4 The fire spread through to the back of the racking when the barrier was present, thereby increasing the chance of ignition of the adjacent rack on that side.

No radiation measurements were made on that side, but the fire intensity appeared to be at least as great as on the ignition side, on several occasions.

Burning through to the back did not occur in any of the tests using the FOC arrangement nor with the JFRO system.

5.5 The radiation levels measured in experiments 1, 3, and 6, at the second level, indicate a very high probability of adjacent rack ignition by this means. In each of these three tests the line detector operated while the radiation intensity was still at a low level for example at about 0.15 W/cm^2 in test 6, compared with a peak of 2.6 W/cm^2. Though the first sprinkler in test 6 also operated at a low level of radiation it was unable to prevent the level from rising rapidly. In test 1 the first sprinkler opened after the radiation level had passed its peak. Wetting of goods in the adjacent racks by face sprinklers is unlikely to be sufficiently uniform to prevent ignition by radiation, in all cases.

5.6 The quantities of water used in the experiments (given in the Fire Chronologies) taken as a whole, were within about 10% of those used with the FOC arrangements .

The quantities used for the JFRO system were about a third of those used for the tests in this report and for the FOC arrangements , even including polyurethane foam block fires.

5.7 A considerable amount of smoke, was produced, especially in the last two tests. A visual estimate of 5 - 10 million cubic feet of thick black smoke was made during the last test. Though this caused no inconvenience in a building of about 850,000 cu m (30 million cubic feet) with a ceiling at 55 m (180 ft), it would have caused severe smoke logging in most warehouses.

Roof venting would be necessary to help in clearing the hot smoke, but the cold smoke produced when the sprinklers operate would cause great difficulties of access for fire brigade personnel.

5.8 The line detector operated before any sprinkler, in every test, giving a significant time advantage to the JFRO system. The generally earlier operation of a smoke detector also gave some time advantage which would enable personnel to be alerted, the Fire Brigade called, and stacker cranes moved to predetermined safer positions.

5.9 No significant differences were noted between spray and conventional sprinklers in these experiments, though it may be that with spray sprinklers the fifth and sixth levels were wetted more than with conventional sprinklers due to the smaller drop size. It is difficult to judge any differences in wetting of the adjacent racks by face mounted sprinklers of each type.

ACKNOWLEDGMENTS

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2. Rules for Automatic Sprinkler Installations, 29th Edition.

3. NASH P, BRIDGE N W and YOUNG R A. Fire Research Note No. 944. The rapid extinction of fires in high-racked storages.

4. Standard for Rack Storage of Materials. NFPA No. 231C - 1972.

5. WRAIGHT H G H. Fire Research Note in preparation; The ignition of corrugated fibreboard (cardboard) by thermal radiation.

6. BRIDGE N W and YOUNG R A. Fire Research Note in preparation; The extinction of fires in compartmented storages.

APPENDIX 1

NFPA Standard 231C, Rack Storage of Materials (13/3/73 Revision)

Chapter 1. Classification of Storage

11. Commodity Classifications

111. The following guide for commodity classification applies specifically to rack storage and is not related to any other method of classification of materials.

1111. Class I Commodities are defined as non-combustible products on wood pallets or in ordinary paper cartons or wrappings on wood pallets, such as: metal parts; empty cans; non-combustible food stuffs or beverages; stoves; washers; dryers; metal cabinets. Such commodities may have a negligible amount of plastic trim, such as knobs or handles.

1112. Class II commodities are defined as Class I products in slatted wooden crates or solid wooden boxes, on wood pallets.

1113. Class III commodities are defined as wood, paper, natural fiber cloth, or products thereof, containing no more than a negligible amount of plastics in the product or in the packaging material, on wood pallets, such as: natural fiber clothing or textile products; wooden cabinets; furniture or wood products; bicycles; luggage (except plastic); combustible foods or cereal products; paper products; leather goods. Bicycles with plastic handles, pedals, seats, and tyres are an example of a commodity with no more than a negligible amount of plastic.

1114. Class IV commodities are defined as Class I, II, and/or III mixed with more than a relatively negligible amount of plastics used in the product or packaging material, on wood pallets, such as small appliances with plastic parts; typewriters, cameras or electronic parts in plastic packaging in cartons; plastic back tape; synthetic fabrics or clothing.

TABLE 1

General details of fire experiments

Experiment No.	Sprinkler Arrangement	Sprinkler type	Commodity Classification	Pallet Loading	Carton contents
1	E	Conventional	II/III	Full	Steel drums Woodwool
2	E	Conventional	II/III	Half	Steel drums Woodwool
3	G	Conventional	II/III	Full	Steel drums Woodwool
4	G	Spray	II/III	Full	Steel drums Woodwool
5	J	Spray	IV	Full	Steel drums Plastics foam Woodwool
6	J	Spray	IV	Full	Steel drums Plastics foam

TABLE 2

Operating times of sprinklers (NFPA derived system)

Sprinklers[3] / Experiment No.	Front face - 4th level						Centre 4th level			Rear face 4th level						Centre 6th level		
	a	b	c	d[1]	e	f	g	h	j	k	l	m	n	p	q	r	s	t
	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s	min s
1	-	-	2 52	3 12	3 52	-	-	3 04	-	-	-	-	3 17	3 17	-	-	3 15	6 57
2	-	-	-	4 28	-	-	-	-	-	-	-	-	-	-	-	-	7 23	-
3		-		4 10		19 14				-		12 30		5 40		-	-	-
4		-		4 30		-				-		25 00		-		-	-	-
5[2]		8 05		4 30		7 45				-		7 20		6 10		-	-	-
6[2]		3 19		2 20		3 20				-		3 15		3 45		-	-	-

Notes 1. This sprinkler was directly above the ignition point

2. In experiments 5 and 6, the sprinklers were at the third and fifth level of goods

3. See figures 2, 3 and 4 for sprinkler identification.

TABLE 3

Operating times of detectors and sprinklers (dry) in rack

Experiment No.	Intermediate sprinklers Level 1	Intermediate sprinklers Level 2	Intermediate sprinklers Level 3	Line Detector Level 1	Line Detector Level 2	Smoke Detector 6th Level
	min s	min s	min s	min s	min s	min s
1	3 52	2 53	2 45	1 45	2 00	1 20
2	5 55	5 51	3 52	1 53	3 13	2 18
3	4 25	3 55	4 05	2 55	3 45	1 55
4	4 43	4 40	4 45	3 28	2 25	1 25
5	4 45	5 00	5 10	4 10	4 25	4 10
6	2 39	2 23	2 35	2 07	2 08	1 45

TABLE 4

Comparison of initial operating times of sprinklers and detectors.

Experiment No.	Face Sprinkler (wet)		Intermediate Sprinklers (dry)		Line Detector		Smoke Detector	
	min s		min s		min s		min s	
1	2 52	3rd	2 53	4th	1 45	2nd	1 10	1st
2	4 28	4th	3 52	3rd	1 53	1st	2 18	2nd
3	4 10	4th	3 55	3rd	2 55	2nd	1 55	1st
4	4 30	3rd	4 40	4th	2 25	2nd	1 25	1st
5	4 30	3rd	4 45	4th	4 10	1st	4 10	1st
6	2 30	4th	2 23	3rd	2 07	2nd	1 45	1 st
For guidance only: Average operating time	3 50	4th	3 44	3rd	2 32	2nd	2 07	1 st

TABLE 5

Levels of radiation, 1.5 m (5 ft) from rack face

Experiment No.	Maximum Radiation Intensity, W/cm^2 2nd level	4th level	Time to reach Maximum intensity min s	Time of operation of first face sprinkler min s
1	> 10	0.3	2 45	2 52 (1)
2	0.1	0.1	Radiation level too low to cause ignition	
3	> 10	0.2	4 30	4 10 (2)
4	1.0	0.5	Radiation level too low to cause ignition	
5	1.0	0.3	Radiation level too low to cause ignition	
6	2.6	0.6	4 30	2 30 (2)

Notes (1) Sufficient radiation to ignite adjacent rack before operation of sprinkler

(2) Insufficient radiation level to ignite adjacent rack before sprinkler operation, but sufficient at maximum intensity to ignite adjacent rack in the absence of wetting by the sprinklers.

TABLE 6

Table of events - Experiment 1

Time		Event
min	s	
0	00	Ignition
1	10	Flames to top of 1st level
1	20	Smoke detector operated
1	45	Line detector operated
1	50	Flames to top 2nd level
2	10	Flames to top 3rd level
2	35	Flames to top 4th level through to rear of rack at 3rd level
2	48	Flames to top 5th level
2	52	First sprinkler operated (c)
3	00	Flames to top of rack, spreading sideways in rack
3	04	2nd sprinkler operated (h)
3	12	3rd sprinkler operated (d)
3	15	4th sprinkler operated (s)
3	17	5th and 6th sprinklers operated (n, p)
3	45	Fire still spreading in upper levels, E6 well alight
3	52	7th sprinkler operated (e)
4	15	Fire moving on both sides of rack at 3rd and 4th levels
5	25	Fire spreading sideways on 5th level. Considerable smoke logging
6	57	8th sprinkler operated (t)
7	35	Considerable burning in rack, most severe in 5th level
20	00	Water to sprinklers turned off. Fire still burning in several places.

Fire damage 32 pallet loads

Water damage, additional 40 pallet loads

Maximum water flow rate of 745 dm^3/min (164 gal/min) from 8 sprinklers

Total volume water used by sprinklers 11,800 dm^3 (2600 gals)

TABLE 7

Table of Events - Experiment 2

Time		Event
min	s	
0	00	Ignition
	35	Flames 1 m height
1	10	Smoke to top of rack
1	53	Line detector operated
1	55	Flames to top of 1st level
2	18	Smoke detector operated
2	45	Pallets in 2nd level alight
3	10	Flames to top 2nd level
3	35	Flames to top 3rd level
4	26	Flames to top 4th level
4	28	First sprinkler operated (d)
5	25	Fifth level alight, flames through the rear of rack, 3rd and 4th levels
5	40	Flames to top 5th level
7	23	2nd sprinkler operated (s)
11	45	Considerable smoke logging at ground level, no fire spread to 6th level
12	45	Water off.

Fire damage to 18 pallet loads

Water damage to additional 12 pallet loads

Maximum water flow rate of 220 dm^3/min (48 gal/min) from 2 sprinklers

Total volume of water used by sprinklers 1800 dm^3, (400 gals).

TABLE 8

Table of Events - Experiment 3

Time		Event
min	s	
0	00	Ignition
1	25	Flames 1 m high
1	40	Flames to top 1st level
1	55	Smoke detector operated
2	55	Line detector operated
3	20	Flames to top 2nd level
3	45	Flames to top 3rd level
3	55	Flames to top 4th level
4	10	First sprinkler operated (d) flames spreading horizontally under barrier
4	30	Flames through to rear of rack at 3rd and 4th levels
5	40	2nd sprinkler operated (p)
8	00	Burning at all four levels, front and back of rack in centre pallets(C and D)
12	00	Sideways fire spread to pallets B and E at 3rd level
12	30	3rd sprinkler operated (m)
18	00	Fire spreading under barrier to F4
19	40	4th sprinkler operated (f)
23	00	Flaming in D2 and C1
24	15	Water off.

Fire damage to 26 pallet loads

Water damage to additional 22 pallet loads

Maximum water flow rate of 380 dm^3/min (84 gal/min) from 4 sprinklers

Total volume of water used by sprinklers 5000 dm^3 (1100 gals).

TABLE 9

Table of Events - Experiment 4

Time		Event
min	s	
0	00	Ignition
0	40	Flames 1 m high
1	25	Smoke detector operated
1	40	Flames to top 1st level
2	25	Line detector operated
3	50	Flames to top 2nd level
4	05	Flames to top 3rd level
4	20	Flames to top 4th level
4	30	First sprinkler operated (d)
6	30	All flaming on 4th level extinguished, considerable smoke
14	00	Water off - fire thought to be extinguished
17	00	Water on again, burning in pallets on 2nd level at rear of rack
20	00	Flaming spread upwards to 3rd level at rear
21	25	Flaming spread upwards to 4th level at rear
25	00	2nd sprinkler operated (m)
38	30	Water off

Fire damage to 16 pallet loads

Water damage to additional 10 pallet loads

Maximum water flow rate of 220 dm^3/min (48 gal/min) from 2 sprinklers

Total volume of water used by sprinklers, 5680 dm3 (1250 gals).

TABLE 10

Table of Events - Experiment 5

Time		Event
min	s	
0	00	Ignition (at base of 2nd rack level)
3	00	Flames 1 m high
3	40	Flames to top of 1st level of goods
4	10	Smoke and line detectors operated
4	15	Flames to top of 2nd level of goods
4	28	Flames to top of 3rd level of goods
4	30	First sprinkler operated (d)
5	00	Flaming full width of C D pallets under barrier
5	30	Flaming through to rear of rack at 2nd and 3rd level of goods Considerable smoke
6	10	Second sprinkler operated (p)
7	20	Third sprinkler operated (m) Flames 2 m above barrier on face, but cardboard not ignited
7	45	4th sprinkler operated (f)
8	05	5th sprinkler operated (b)
15	15	Flaming spread to 'A' pallets in first level of goods
31	45	Water off, flaming still in several places
		Fire damage to 28 pallets

Water damage to additional 20 pallets

Maximum water flow rate of 510 dm^3/min (112 gal/min) from 5 sprinklers

Total volume of water used by sprinklers 12 700 dm^3 (2800 gals).

TABLE 11

Table of Events - Experiment 6

Time (min)	Time (s)	Event
0	00	Ignition, (at base of 2nd rack level)
1	00	Smoke to top of rack
1	17	Flames to top of 1st level of goods
1	45	Smoke detector operated
2	05	Flames to top of 2nd level of goods
2	07	Line detector operated
2	15	Flames to top of 3rd level of goods, heating under barrier
2	30	First sprinkler operated (d)
3	00	Flaming through to rear of rack at all levels under barrier
3	15	2nd sprinkler operated (m)
3	19	3rd sprinkler operated (b)
3	20	4th sprinkler operated (f)
3	45	5th sprinkler operated (g)
4	00	Flaming 1 m high on face above barrier, but boxes not lit
5	10	Flaming spread from A - F pallets on 2nd level of goods
7	00	Considerable smoke at ground level
14	00	Flaming decreasing
21	45	Water off, flaming only in D2 and F4

Fire damage to 24 pallets

Water damage to further 34 pallets

Some charring on face of boxes on top level of rack, but boxes did not ignite.

Maximum water flow rate of 490 dm^3/min (108 gal/min) from 5 sprinklers

Total volume of water used by sprinklers 9100 dm^3 (2000 gals).

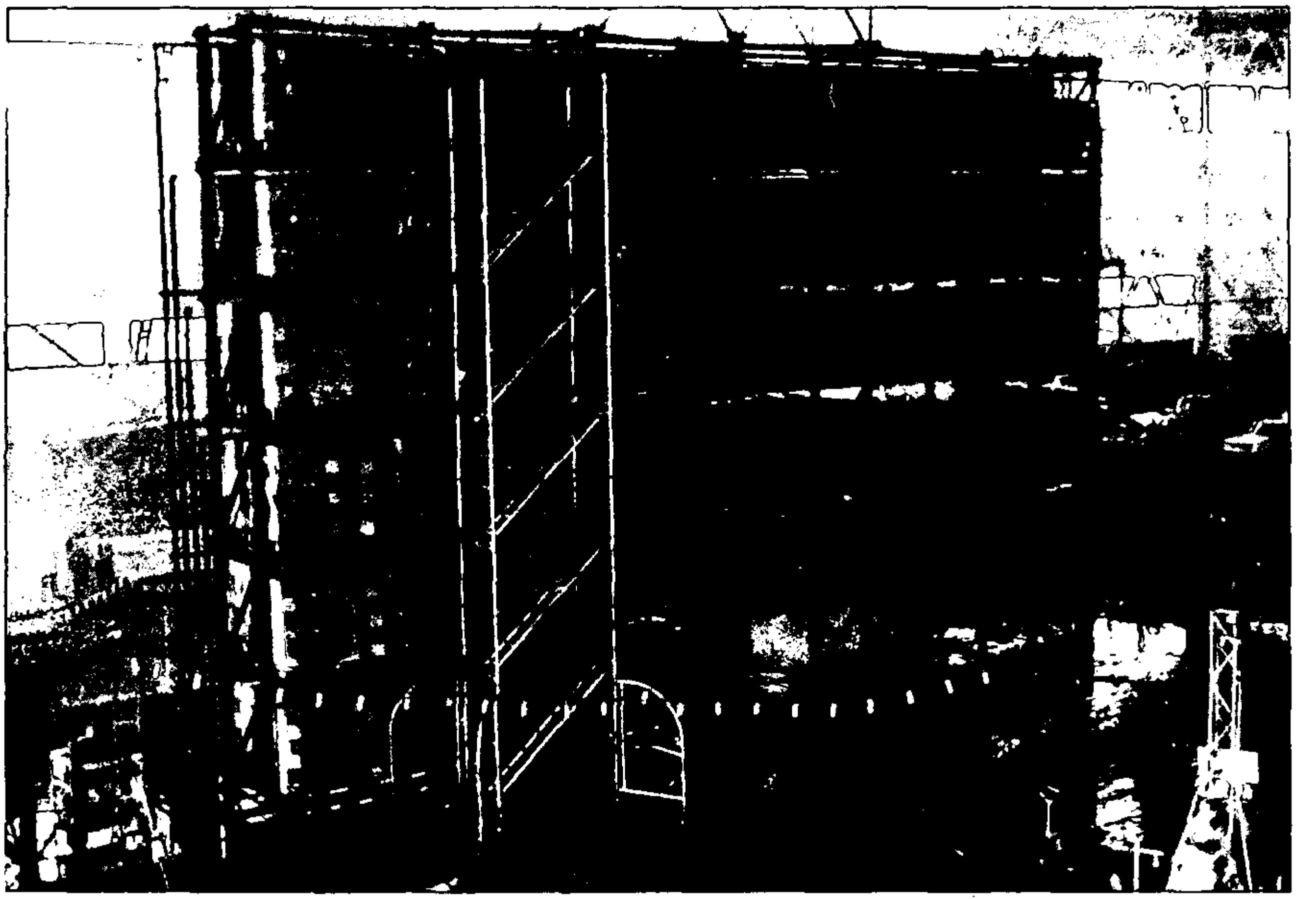
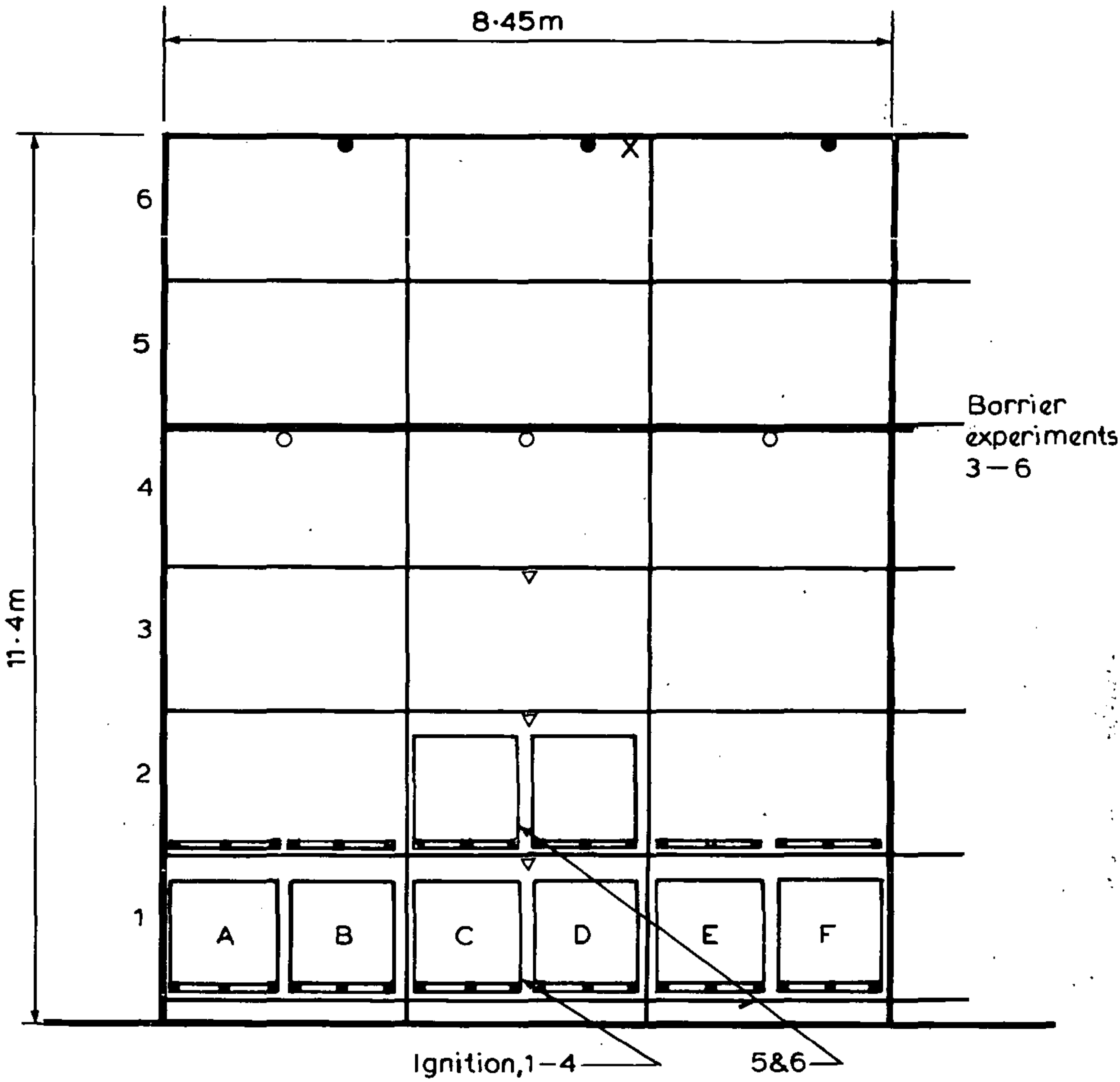
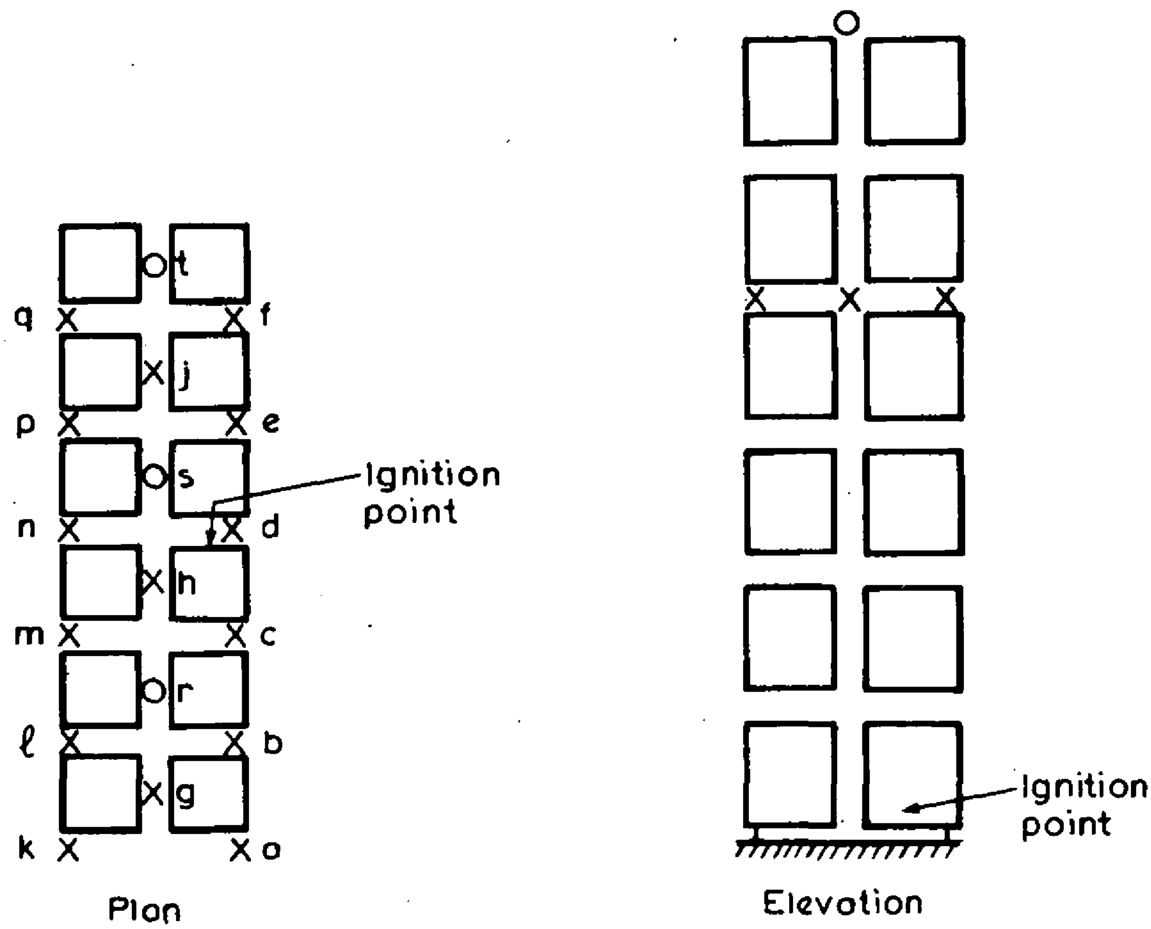


PLATE 1. GENERAL VIEW OF RACKING FROM REAR, EXPERIMENT 5.



○ Sprinklers, face
● Sprinklers, central axis
▽ Sprinklers, central axis dry
X Smoke detector

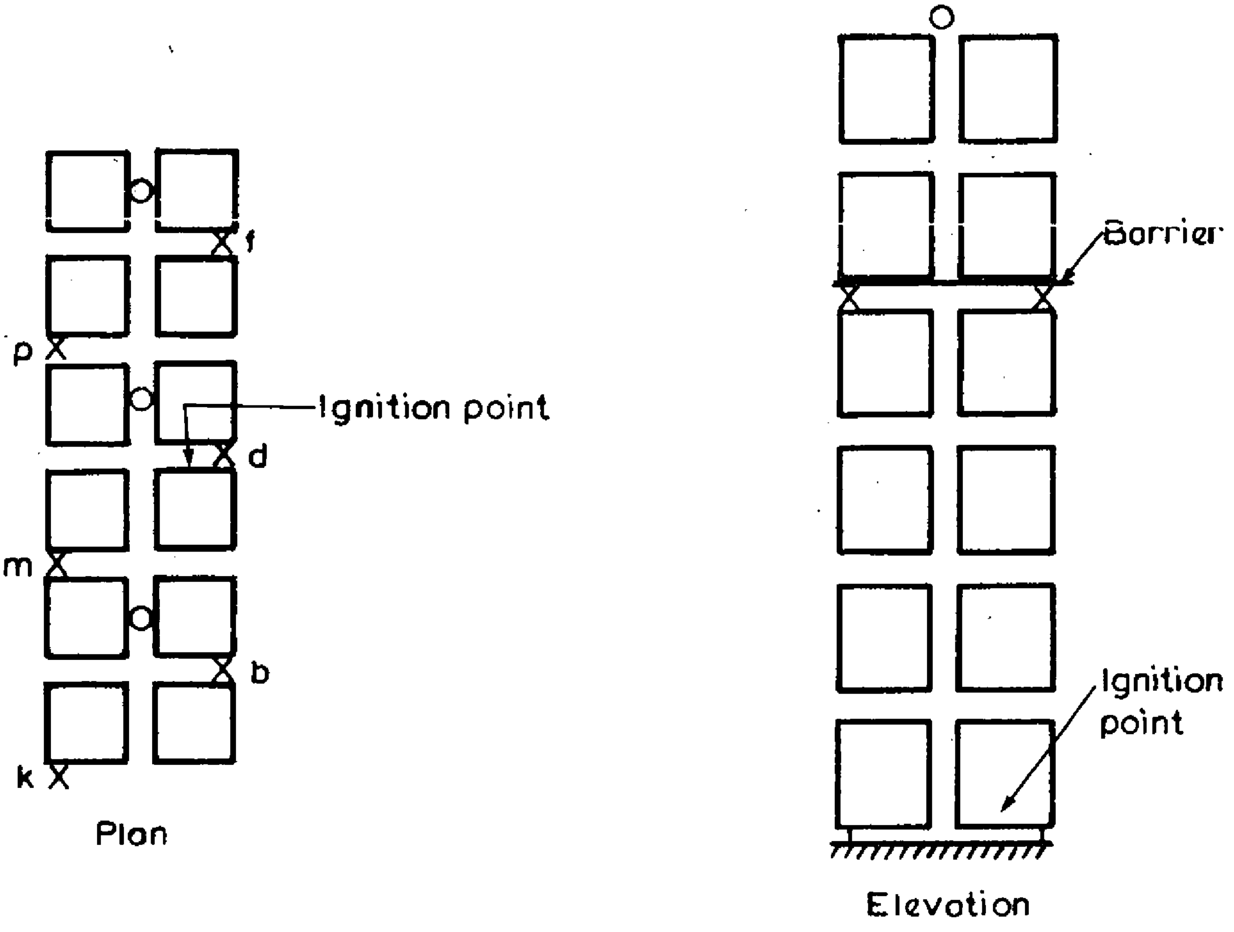
Figure1 General arrangement of racking, viewed from front face



O = 6th Level sprinklers

X = 4th Level sprinklers

Figure 2 Sprinkler arrangement E



O = 6th Level sprinklers

X = 4th Level sprinklers

Figure 3 Sprinkler arrangement G

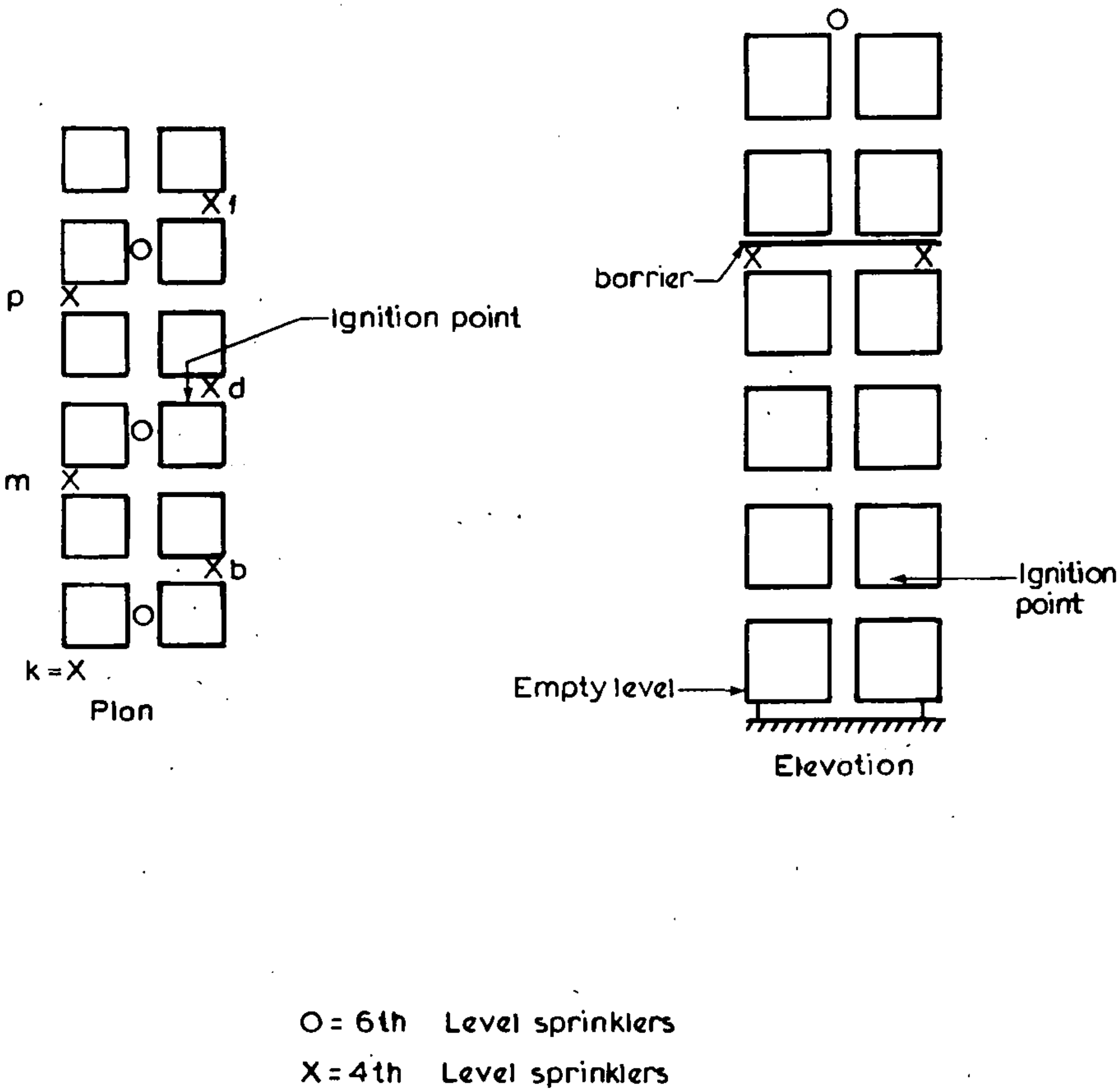


Figure 4 Sprinkler arrangement J
Modified ignition point

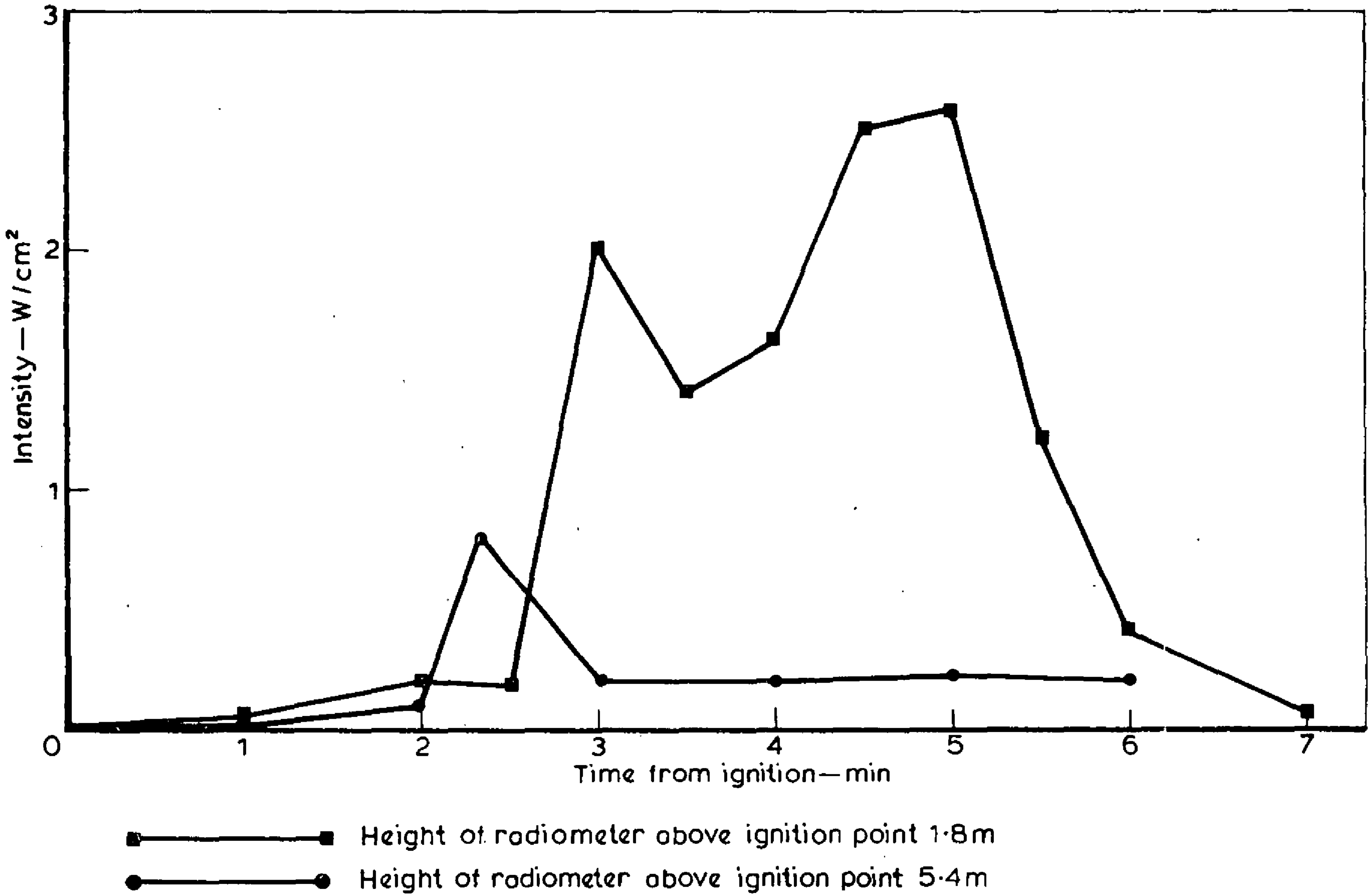


Figure 5 Radiation intensity 1·5m from rack face, experiment 6

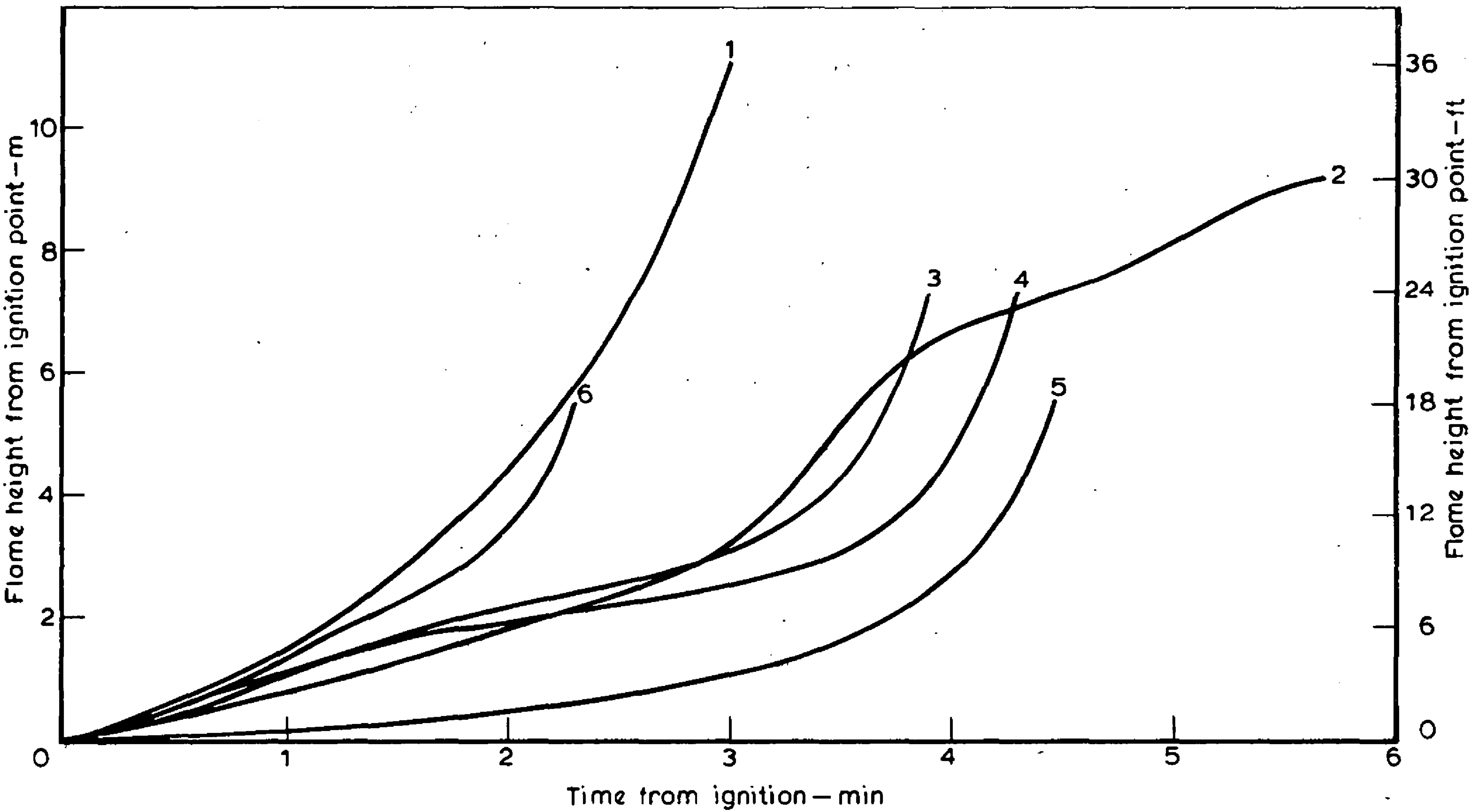


Figure 6 Vertical flame spread — experiments 1 – 6

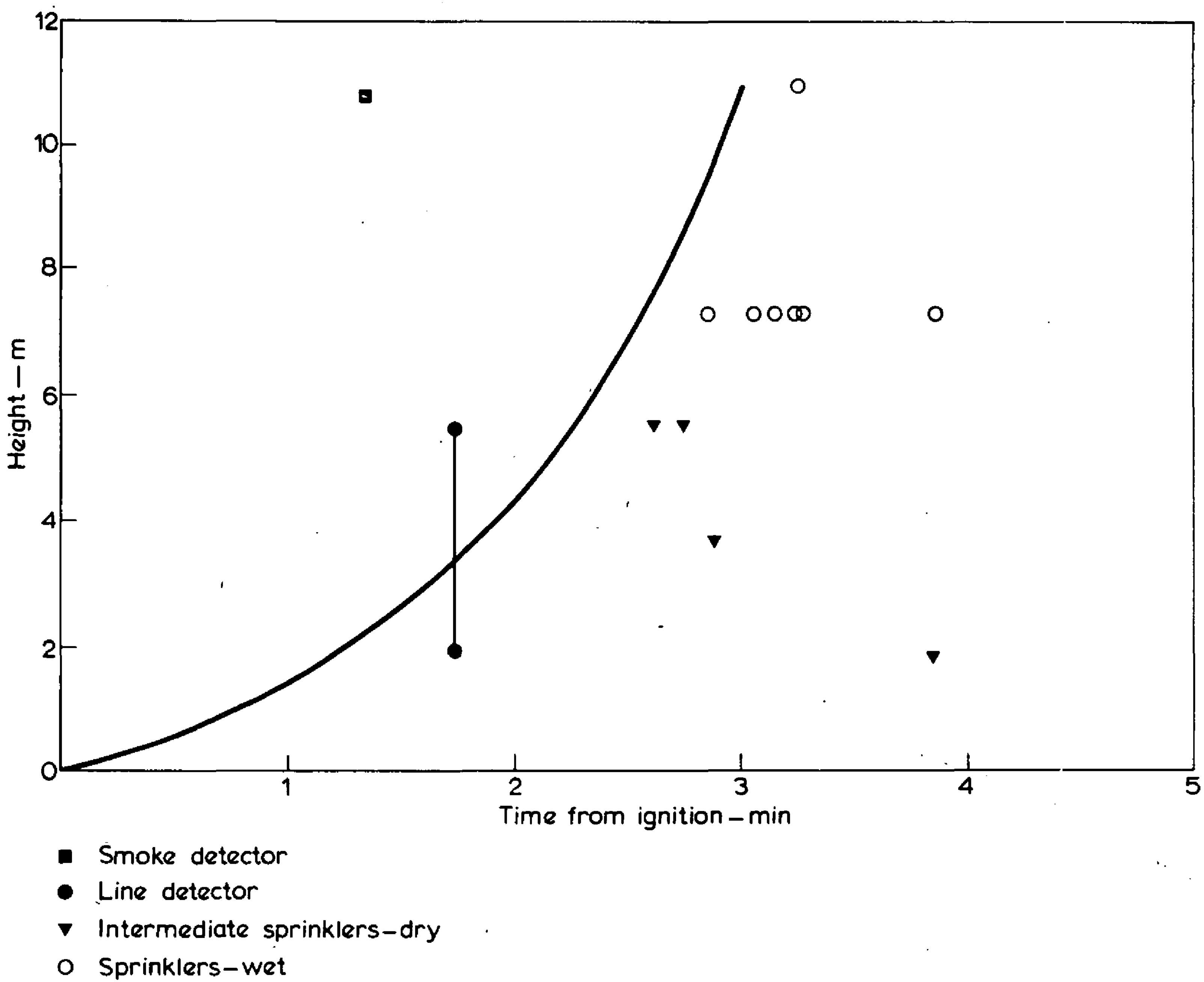


Figure 7 Relationship between flame height and sprinkler and detector operation – experiment 1

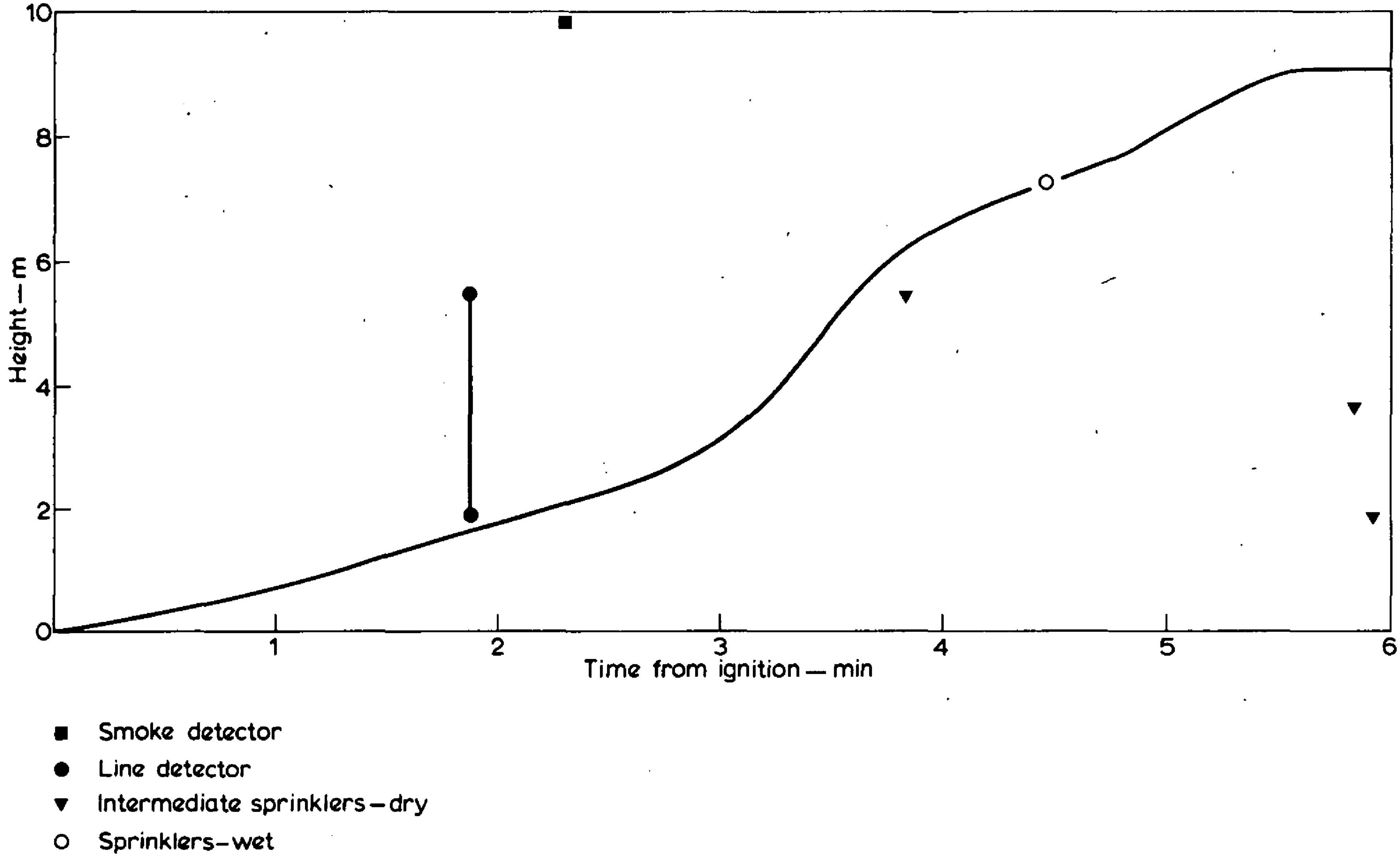


Figure 8 Relationship between flame height and sprinkler and detector operation — experiment 2

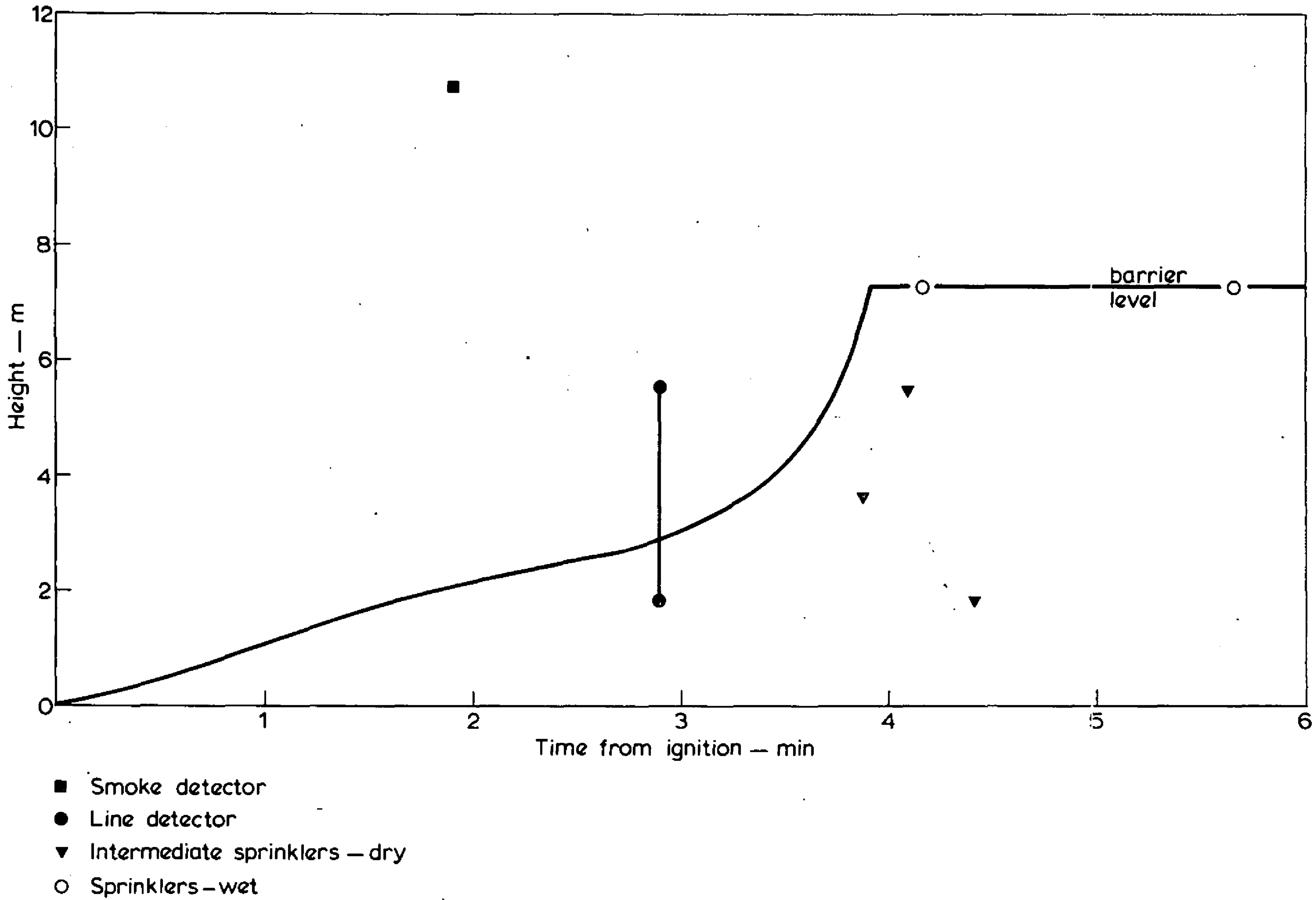


Figure 9 Relationship between flame height and sprinkler and detector operation — experiment 3

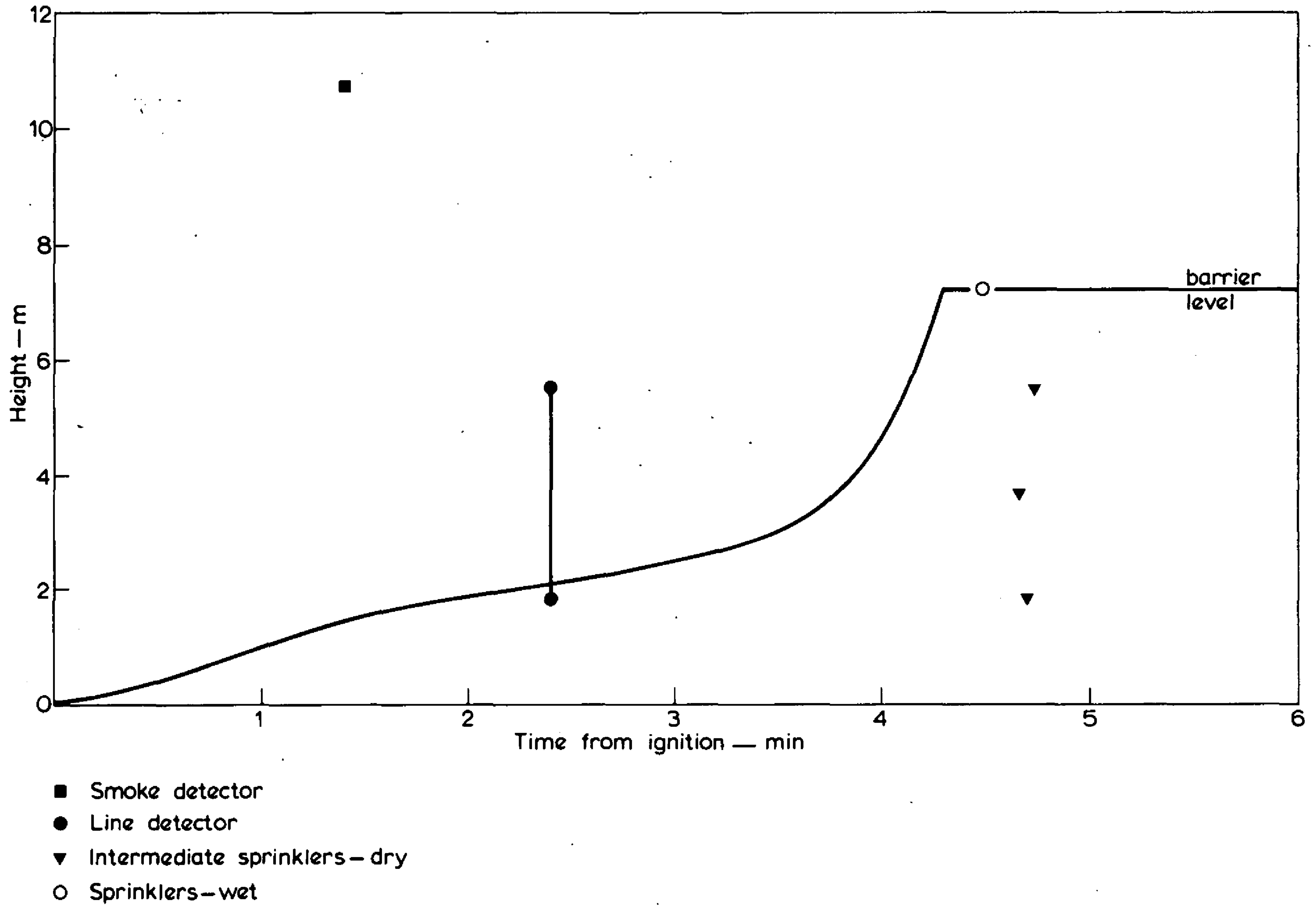
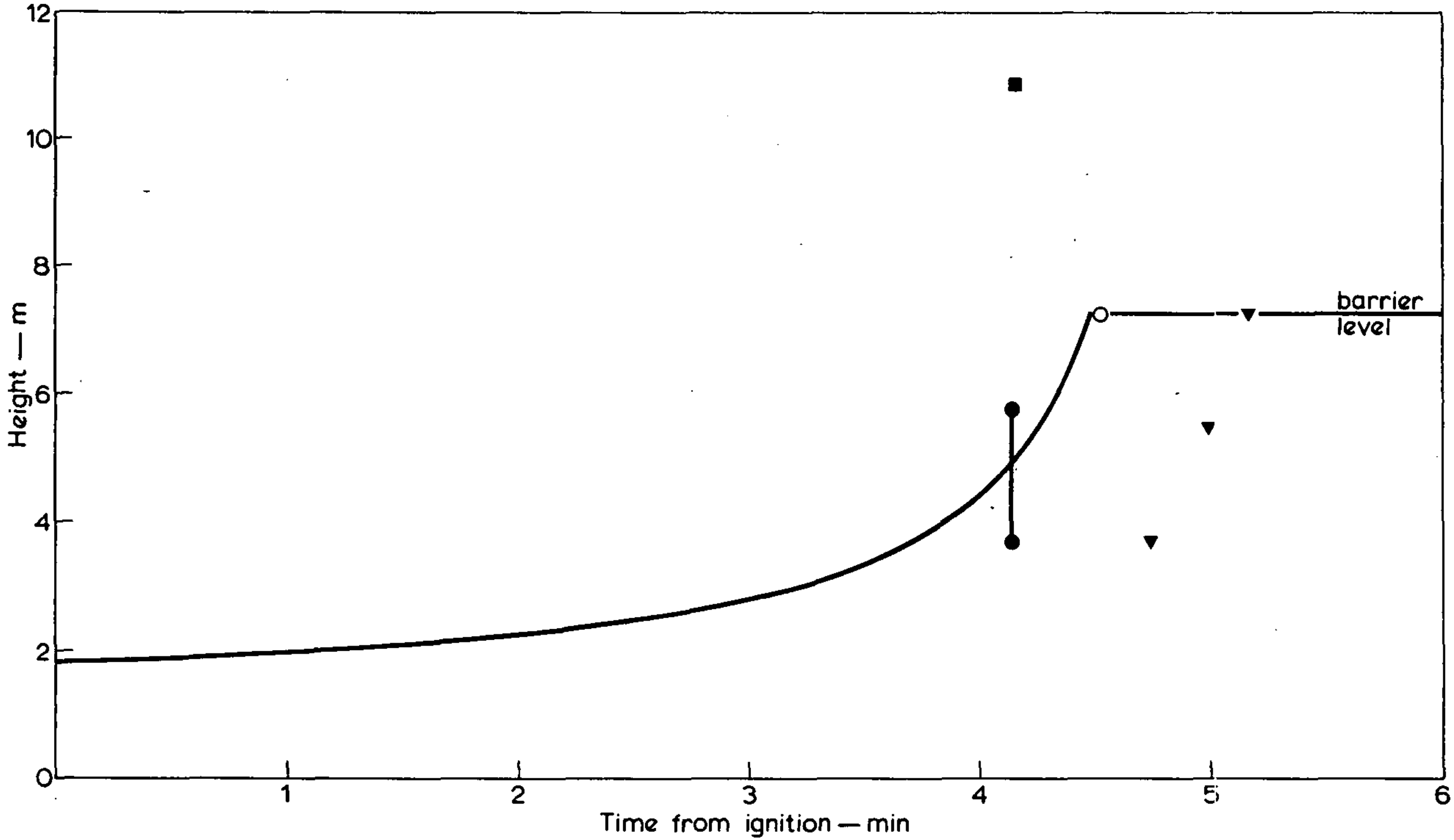


Figure 10 Relationship between flame height and sprinkler and detector operation – experiment 4



■ Smoke detector

● Line detector

▼ Intermediate sprinklers – dry

○ Sprinklers – wet

Figure 11 Relationship between flame height and sprinkler and detector operation — experiment 5

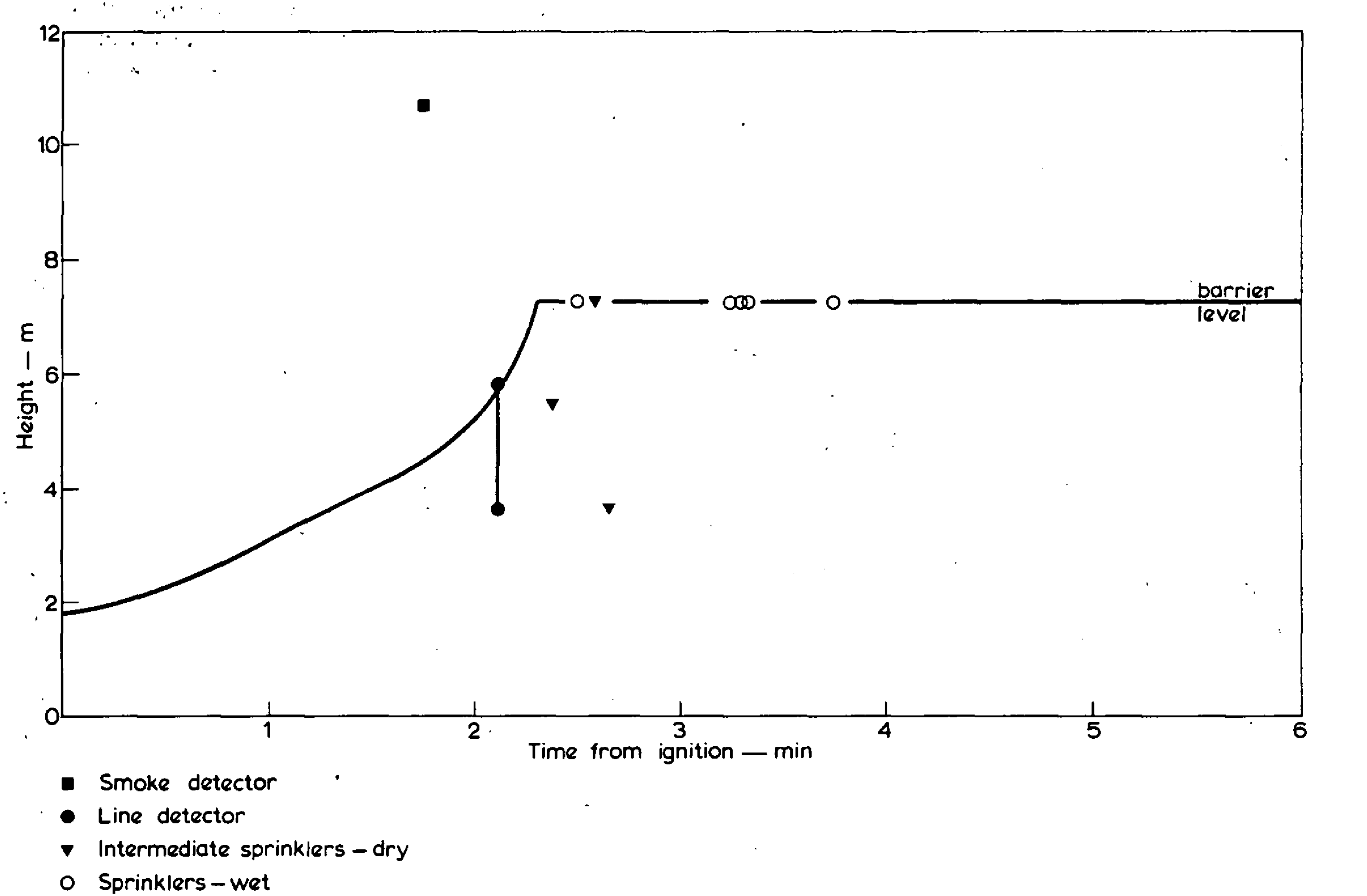


Figure 12 Relationship between flame height and sprinkler and detector operation – experiment 6

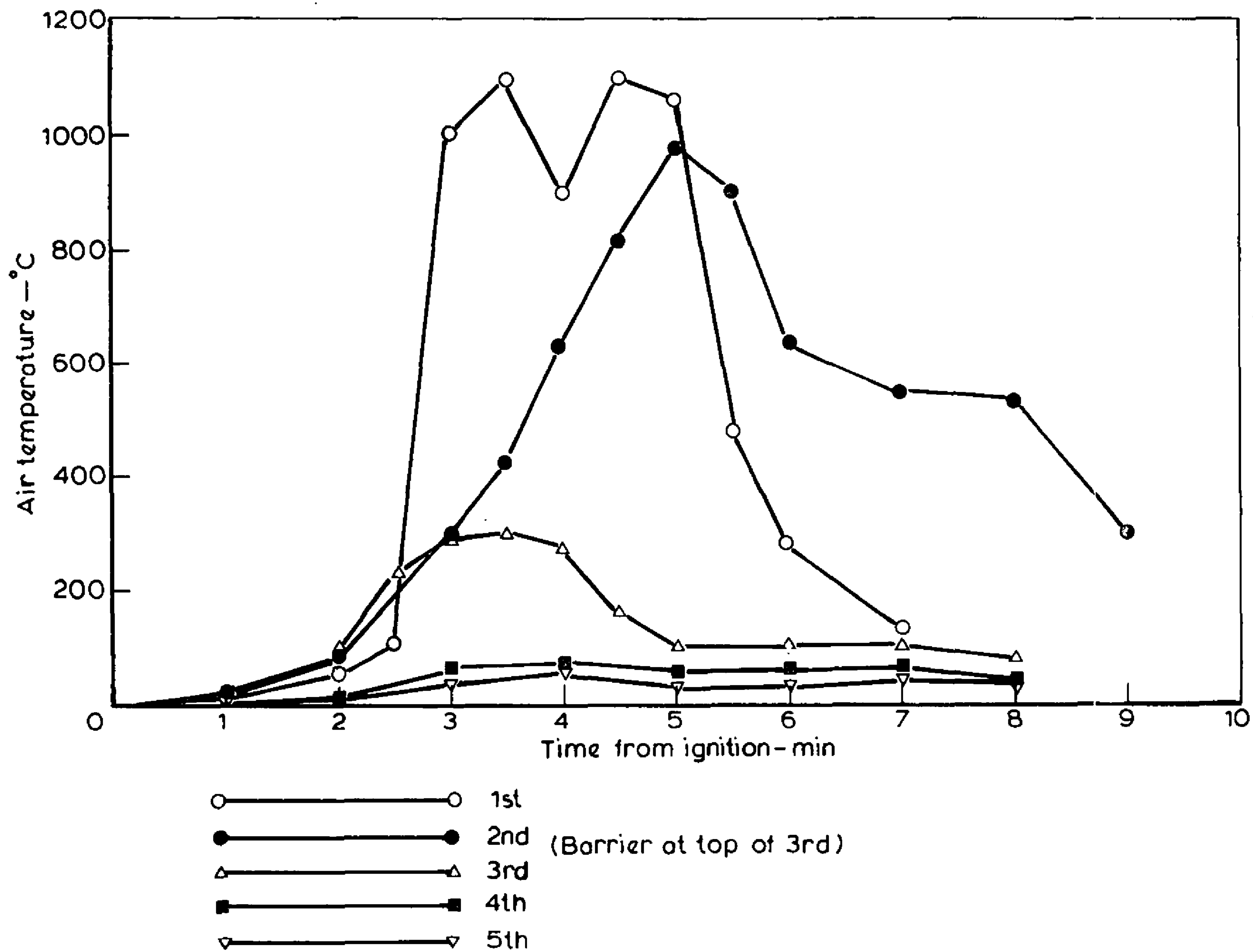


Figure 13 Air temperature rise within rack, experiment 6