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FIRE PROBLEMS OF PEDESTRIAN PRECINCTS. PART 2.
LARGE-SCALE EXPERIMENTS WITH A SHAFT VENT

by

A J M Heselden, H G H Wraight and P R Watts

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SUMMARY

The results of large scale experiments on the prevention of smoke travel along covered pedestrian malls by natural venting are presented and discussed.

Fires of 0.6, 1.1 or 3.2 MW output were set in a 'shop'giving on to a covered 'mall' or arcade about 17 m long, 6 m wide and 3 m high. Measurements of the temperature, layer depth, rate of flow and opacity of the smoke-laden hot gases were made in the mall with and without venting and with and without a ceiling screen in the mall and a fascia board in the front of the shop.

The experiments show that the spread of smoke along the mall can be prevented by the combined action of a venting system and roof screens - neither being effective alone.

Because substantial quantities of air mix with the smoke layer as it passes along the mall the venting system should have a larger capacity than would be required for fires in simple single-storey buildings. A number of small vents spaced well apart over the whole ceiling are likely to be much more effective than a single large vent of the same nominal venting capability.
KEYWORDS: Shopping mall, smoke, spread, vents, ventilation, escape means, screen

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1. INTRODUCTION

The hazards which could be created in a covered pedestrian mall of a town centre development by smoke logging from a fire have been indicated in previous reports[1,2,3], and Hinkley[4] has discussed methods by which these hazards may be overcome or reduced.

In the future it is likely that these centres will be fully enclosed and shop fronts will be open but even a glazed front would not necessarily hold back hot smoke from a fire for more than a brief interval. Without a very high capacity and specially heat-protected system for extracting hot smoke from the shop it would not generally be possible to prevent large quantities of smoke passing into the mall so that means must be sought for restricting the travel of smoke in the mall. The most promising method for this makes use of the fact that the smoky gases are at first hot or warm and therefore form a well defined layer under the ceiling. By extracting gas from this layer at a rate at least as great as the rate of flow into the layer and by installing ceiling screens, the travel of smoke along the mall could be prevented.

The advantages of this system are mainly that smoke is extracted before too much air has mixed into it so that the capacity of the extract system is a minimum, and before the smoke has cooled so much that it could fall to ground level. The extraction may be by a high capacity mechanical system, or by natural venting, where the energy required to extract the gases derives from the fire itself, and the gases are driven through the vents by the buoyancy force created by the difference in density between the layer and the ambient air.

The present report describes experiments carried out with a vent in an experimental building[5] representing on a large scale a part of a pedestrian mall. Many town centre developments are multi-storey and accordingly the vent was installed in the form of a shaft or duct tall enough to reach through a whole storey.

The experiments have shown, broadly, that whilst suitably-sized vents can indeed remove smoke from layers, their operation is hindered by certain features peculiar to covered pedestrian malls so that design data derived for venting smoke from fires in single-storey factories[6] need modification before they can be made use of in this application.

2. EXPERIMENTAL DETAILS

2.1. Experimental building

The fires were burned at the rear of the fire compartment (Figs 1 and 2) and the smoke passed via an open 'shop front' to the covered 'mall', closed at one end, where it flowed along and out of the open end, or through the vent. Conditions within the mall were monitored so that the improvements brought about by venting could be assessed.

The construction of the arcade has been described in an earlier report[5]. Plates 1 and 2 show the arcade under construction and when completed. For the tests described in this note a few modifications were made to the structure and instrumentation, noted below.

For all but tests 98(i), 98(ii), 125 and 127 a vertical screen or curtain 0.9 m deep of 5 mm hardboard was fitted, extending across the full width of the mall 3.2 m from the open end, 14.2 m from the closed end, and fitting closely to the ceiling and walls. (Figs 1 and 3).

A further screen, subsequently referred to as a 'fascia board' (Figs 1 and 2) was fitted across the upper part of the opening between the fire compartment and the mall for tests 104 to 108. It was constructed of 13 mm asbestos wood sheet fixed to a heavy-gauge angle-steel frame and was 3 m wide and 0.9 m deep.

A vent was fitted to the mall by making a rectangular opening 2.4 m by 0.6 m in the ceiling in the position shown in Figs 1-3, and extending this upwards as a vertical shaft 4.8 m high made of 13 mm asbestos wood. Its cross section was 2.4 m by 0.6 m throughout. The vent could be opened or closed by turning a pivoted flap in the shaft.

2.2. Instrumentation

Thermocouples, heat flux meters and radiometers were fitted as described earlier[5] except for the following alterations and additions.

Four 0.38 mm dia T_1/T_2 thermocouples were fitted in the vent shaft, two each at levels 0.75 and 3.75 m above the mall ceiling. At each level one was in the centre of the vent and one was half way between the centre and a longer side. The temperatures given in this note are excess temperatures over an ambient temperature of about 15°C.

The short-path smoke meters[5] were moved to positions 4.4 and 10.9 m from the closed end of the mall (see Fig.1). At each of these positions two were suspended from the ceiling so that the light beams ran horizontally across the mall at depths of 0.3 and 0.9 m. The path length of the light across the region exposed to smoky gases was 0.25 m and was centred on a line about 1.6 m from the centre line of the mall, i.e. about 1.4 m from the nearer side wall.

Remote reading electronic vane anemometer heads as used in earlier tests[5] were moved to positions vertically beneath the curtain (Tests 98–108) or to position K (Tests 125 to 129) and mounted halfway across the mall at heights of 0.5, 1.1, and 1.4 m above the ground, i.e. 2.6, 2.0 and 1.7 m below the ceiling.

Measurements of the CO_2 concentration were made in tests 125, 127, 128 and 129. These are described in Section 2.5.

The outputs from all the thermocouples, heat flux meters, radiometers and smoke meter photocells were passed into data-logging equipment located in a room adjacent to the arcade building. The instrument outputs were spread over 150 input channels of the data-logger which took 15 s to complete a scan. A few minutes before starting a test a calibration scan was carried out to get initial readings on all instruments. When a test was started the data-logger was set to commence scans at 30 s intervals, the first 30 s after ignition.

2.3. Fuels

The fuels used in the tests are summarised in Table 1. These consisted of kerosene fuel floated on water in two sizes of trays, and a wood crib similar to that used previously[5].

Table 1. Fuel arrangements for the tests

Fuel	Horizontal dimensions of tray or crib	Area	Perimeter	Rate of burning*	Rate of heat release	
	m	m^2	m	kg/s	k cal/s	MW
Kerosene (31 litres)	1.47 x 1.13	1.65	5.2	0.073	760	3.2
Kerosene (13 litres)	0.97 x 0.60	0.58	3.15	0.026	270	1.1
Wood crib (22 kg)	1.8 x 0.6	1.08	4.8	0.050	150	0.6

*Taken as the same as in previous tests where the fuel had been burned on a weighing platform. Reference 5 describes how the measurements of burning rate were made, but does not quote the value obtained.

2.4. Test conditions

The conditions for the tests are given in the first columns of Tables 3-5 with the test numbers. Except for test 98 conditions were unchanged throughout each test. Test 98 commenced with the vent open, this being closed at 3 min. For convenience the periods in test 98 before and after closing the vent have been designated as tests 98 (ii) and (i) respectively.

2.5. Measurement of flow rate of hot gases

It was naturally of considerable importance to obtain the rate of flow of the hot gas layer, containing the smoke, along the mall. In some cases the flows under the screen and fascia board, or up the vent, could be estimated using the relationships of reference 6, from the gas temperature, the dimensions of the building and the depth of the layer of the hot gas. In other cases this was not possible and an attempt was made to obtain the flow of the hot gas layer indirectly by measuring the air flow into the arcade under the layer. This should be almost the same as the hot gas flow leaving the mall.

The rate of flow of air into the arcade under the screen beween L and M was measured, using the anemometers described previously[5], but the readings were rather variable, partly perhaps because they were near to the arcade entrance and unduly influenced by exterior wind. The values found are thus subject to some uncertainty, reflected in the wide limits given in Table 5, but are nevertheless not too different from the sum of the flows leaving the arcade (up the vent and under the screen) even though these were obtained by calculation and are only accurate to the extent that the conditions lie within the range for which the theory is valid. For the flow under the screen and also from the fire compartment into the mall, plug flow has been assumed over a depth of layer taken as the depth to the point at which the temperature rise was $\frac{1}{4}$ of the peak temperature rise (Section 3.1) and this can only be an approximation to the more complicated integral required to evaluate the flow.

Some time after the bulk of the tests had been carried out, a more satisfactory method of measuring the flow rate of hot gases in the mall was devised, entailing the measurement of the carbon dioxide concentration in these gases (Appendix 1). This was carried out in tests 125, 127, 128 and 129, covering the four combinations: with/without screen and with the vent open/closed. These tests were conducted with large screens of hardboard covering the entrances to the three other compartments opening into the mall. Important information was gained from these tests concerning the degree of air entrainment at various positions along the length of the arcade.

3. RESULTS

3.1. Depth, temperature and flow pattern of smoke layer

The kerosene fires burned up rapidly, smoke passing into the arcade in about 10 s and reaching the screen in about 30 s (Table 2). The wood crib fires were slower to start. The temperature of the gas rose to a maximum value at about 4-5 min (kerosene fires) or 6-8 min (wood crib fires), and then fell as the burning rate decreased, (Fig.6). Temperature profiles at various times in a typical test (No.100) are plotted in Fig.7.

Except for test 98 the conditions were unchanged throughout each test and the readings given in Tables 3 to 5 were obtained at times corresponding to peak temperatures where conditions could be regarded as being in a 'steady state'. Test 98 commenced with the vent open; this was shut at 3 min. Readings were taken at $2\frac{1}{2}$ min (98ii), and again at 5 min (98i). Since 98ii was not allowed to reach peak temperature, in comparing readings of 98ii with other tests it must be remembered that the temperatures may be up to 50°C low (Fig.7). Layer depths should need no correction since they are nearly constant after 2½ min (Fig.7).

Table 2. Smoke travel times

Test No.	Time for smoke to enter mall (s)	Time for smoke to reach vent (s)	Time for smoke to reach screeen (s)
100	12	-	30
102	10	-	28
101	8	17	31
104	9.5	-	32
105	-	-	34
108	10	-	31
103	12	19	40
106	24	-	80
107	-	-	90

Table 3. Test conditions and layer depths

Fuel	Fascia board	Screen	Vent	Test No.	Time for readings quoted** (min)	Observed depth of smoke layer at J (m)	Depths of hot gas layer* below ceiling of arcade (m) at:- D≠	I	J	K	L	M
Kerosene (1.65 m^2 tray)	Without	Without	Closed	98i	5	–	1.7	1.2	1.0	1.1	0.9	1.05
				127	5	–	–	1.25	1.15	1.25	1.25	1.15
			Open	98ii	$2\frac{1}{2}$	–	1.65	1.0	0.85	0.7	0.7	0.8
				125	5	–	–	1.15	0.8	0.7	0.6	0.8
		With	Closed	100	5	1.8	1.8	1.55	1.55	1.75	1.7	0.9
				102	4	1.8	1.9	1.6	1.5	1.7	1.8	0.75
				128	5	–	–	1.45	1.55	1.8	1.8	1.1
			Open	101	$3\frac{1}{2}$	0.9	1.7	1.15	0.9	1.15	1.15	–
				129	5	–	–	1.20	0.95	1.15	1.2	–
	With	With	Closed	104	$4\frac{1}{2}$	1.65	2.15	1.5	1.5	1.7	1.65	1.0
				105	$4\frac{1}{2}$	1.65	2.1	1.5	1.45	1.55	1.6	0.4
			Open	108	5	1.05	2.05	1.05	1.1	1.15	1.2	–
Kerosene (0.58 m^2 tray)	Without	With	Open	103	4	0.75	1.45	0.95	0.9	1.0	1.0	0
Wood crib (0.6 x 1.8 m^2)	With	With	Closed	106	6	1.25	1.85	1.35	1.5	1.4	1.55	1.05
			Open	107	8	0.8	1.9	0.9	0.85	0.9	0.9	0

* Boundary of layer at any given position taken at a temperature rise of $\frac{1}{4}$ of the peak temperature rise at that position.

**This was as far as possible the time for peak fire development, i.e. near-steady state conditions

≠ Position D in plane of fire compartment opening

Table 4. Temperature rises

Fuel	Fascia board	Screen	Vent	Test No.	Time for readings quoted (min)	Temperature rise at hottest part of layer (deg C)						Temperature rise in vent shaft (deg C)			
						D	I	J	K	L	M	Bottom Side	Bottom Centre	Top Side	Top Centre
Kerosene (1.65 m^2 tray)	Without	Without	Closed	98i	5	395	355	230	195	190	175	Not measured			
				127	5	–	360	220	185	170	170	0	0	0	0
			Open	98ii	2½	385	300	220	160	110	105	Not measured			
				125	5	–	345	215	160	125	115	90	60	90	90
		With	Closed	100	5	395	350	255	200	185	165	30	40	30	30
				102	4	420	365	270	210	190	170	30	30	10	10
				128	5	–	355	245	210	185	145	10	15	5	5
			Open	101	3½	420	340	250	185	135	25	150	70	140	135
				129	5	–	335	205	160	120	30	115	80	110	110
	With	With	Closed	104	4½	455	245	180	150	125	105	45	45	25	25
				105	4½	415	235	170	145	125	120	25	25	15	15
			Open	108	5	440	240	150	120	100	20	70	80	85	90
Kerosene (0.58 m^2 tray)	Without	With	Open	103	4	210	180	115	90	60	0	60	15	55	50
Wood crib (0.6 x 1.8 m^2)	With	With	Closed	106	6	210	110	85	70	60	40	10	10	5	5
			Open	107	8	180	115	60	40	30	0	30	35	35	35

Table 5. Calculated and measured gas flow rates

Fuel	Fascia board	Screen	Vent	Test No.	Time for readings quoted (min)	Gas flow (reduced to m^3/s at ambient temperature)				
						Air into mall under screen	Air into fire compartment	Gas from fire compartment	Up vent shaft	Under screen or to end of mall
Kerosene (1.65 m^2 tray)	Without	Without	Closed	98i	5	4.5 to 6.5[a]	c.2.1[a] c.1.0[e]	2.8[d][g]	-	-
				127	5	(5.3[h] (6.1[l]	3.3[i]	3.4[i]	-	5.3[j]
			Open	98ii	2½	-	c.1.0[e]	2.6[d][g]	-	-
				125	5	(8.4[k] (12.6[l]	2.6[i]	2.6[i]	3.9[c]	4.5[j]
		With	Closed	100	5	-	-		-	-
				102	4	5 to 7[b]	0.7[e]	(f)	<0.15[c]	4.5[d]
				128	5	(3.8[h] (4.8[l]	2.1[i]	2.1[i]	-	3.8[j]
			Open	101	3½	5 to 7[b]	1.0[e]	2.6[d][g]	4.3[c]	0.8[d]
				129	5	(6.6[k] (9.75[l]	2.4[i]	2.4[i]	4.05[c]	2.5[j]
	With	With	Closed	104	4½	3 to 5[b]	0.5[e]	1.2[d]	<0.18[c]	2.8[d]
				105	4½	-	-	-	-	-
			Open	108	5	4.5 to 6.5[b]	0.6[e]	0.9[d]	4.0[c]	0.8[d]
Kerosene (0.58 m^2 tray)	Without	With	Open	103	4	3 to 5[b]	0.8[e]	1.9[d][g]	3.4[c]	0.1[d]
Wood crib (0.6 x 1.8 m^2)	With	With	Closed	106	6	2.5 to 3.5[b]	0.7[e]	0.4[d]	<0.10[c]	2.1[d]
			Open	107	8	-	0.7[e]	0.5[d]	2.9[c]	0[d]

Cont'd ....

Table 5 (cont'd)

(a) Measured by anemometers in previous tests under nominally identical conditions.

(b) Measured by anemometers at screen.

(c) Calculated from measured temperatures using equation (15) (p.13) of reference 6.

(d) Calculated from temperature and depth of layer measurements using equation (18) (p.14) of reference 6.

(e) Calculated from entrainment of air into part of flame below the hot gas layer in the fire compartment[9].

(f) Equation (18) of reference 6 cannot be expected to apply, even approximately, since there is insufficient change in level of the layer as it passes out of the opening.

(g) Equation (18) of reference 6 expected to over-estimate flow since the change in level of the layer is less than the depth of the layer passing through the opening of the fire compartment.

(h) Air flow at L derived from CO_2 concentration at L.

(i) From CO_2 concentration in gases leaving fire compartment.

(j) Flow of smoke-laden gases past cross-section at L.

(k) Air flow at L derived from CO_2 concentration at L and calculated flow up vent.

(l) Measured by anemometers at K.

In order to be able to compare one test with another the layer depth at a given position has been taken as the depth to the point at which the temperature was $\frac{1}{4}$ of the peak temperature. This, though having the advantage of precision of definition, is an arbitrary method but gives on average about the same layer depth as was judged by eye in these experiments; this can be seen by comparing the observed layer depths which those derived from this definition (Table 3). The point is in a region where temperature changes strongly with height and is thus not very sensitive to the precise definition.

In Figs 8 to 10 are shown typical temperature profiles for the thermocouple columns at positions I, J, K and L (see Figs 1-3), taken at peak burning rate or in a period of maximum steady burning. Position M was beyond the screen and too much influenced by draughts around the mall entrance to give useful profiles. The layer depths derived from the profiles and also those obtained at position D (in the plane of the fire compartment opening) as well as position M are given in Table 3.

Figures 11 and 12 show the layer depths, plotted in an elevation of the fire compartment and arcade with an exaggerated vertical scale. The temperatures in the hottest part of the layer and in the vent shaft (at the time the temperature profiles were plotted) are given in Table 4.

The deeper layers, obtained with the vent closed, appeared to observers in the arcade to have a fairly flat and calm lower boundary. In contrast, with the vent open, the layer appeared to slope up somewhat towards the vent and to have a more disturbed base.

With the vent open it was noted that the base of the smoke layer was deformed by the flow up into the vent, as in Fig. 13, and air was obviously being drawn up into the vent shaft. This shows the drawback of trying to extract hot gases from a thin layer at one point at too high a velocity[4]. Methods for reducing this effect will be explored further.

Temperatures obtained in the centre of the vent were lower than those at the side, at the lowest position (Table 4), showing that a central tongue of cool gas extended a little way into the vent. However, towards the top of the shaft the gases are seen to be well mixed because the temperature was constant across the vent.

In tests 125, 127, 128 and 129 where CO_2 concentrations at various points were measured, the fronts of the three other compartments giving on to the mall were enclosed with sheets of hardboard fitting closely round the openings.

Since the layer depths and gas temperature obtained were very similar (Tables 3 and 4) to those for tests which were nominally identical except that the fronts of the compartments were completely open, it may be concluded that in the main body of the experiments the characteristics of the hot gas layer are not materially affected by these openings. Presumably this is because where the layer depth is greater than the height of the wall above the openings (0.6 m) a stagnant layer of gas rapidly builds up in each compartment so that bulk movement of gases in or out of the compartments quickly ceases.

To check that the gas flows presented in Section 3.2 are consistent with the temperature data, calculations were made of the expected fall in temperature of the gases along the mall due to their cooling and to the admixture of cold air, and reasonable agreement was obtained with the observed temperature drops (Appendix 2).

3.2. Gas flow and CO_2 concentration measurements

A brief comparison was made in Section 2.5 and Appendix I between flow measurements made by anemometers and those derived from measurements of the CO_2 concentration. The latter were shown to exhibit a much smoother variation with time than the former, which were greatly affected by external phenomena, such as wind incident upon the entrance to the mall. For example Fig.5 shows that the air flow derived from anemometer data fluctuates very considerably, by at least ± 25 per cent, the average air flows nevertheless in this case agreeing broadly with those obtained from the CO_2 concentrations. Readings of individual anemometers may fluctuate even more - the values in Fig.5 have been smoothed out by averaging over 4 anemometers.

The flow measurements derived from the CO_2 concentration measurements thus appear to be more reliable and this is confirmed by a very close correlation obtained between temperature and CO_2 concentration at the same point (Fig.14). This is entirely to be expected since both should depend on the burning rate of the kerosene and the mixing of air with the gases. In Fig.14 the scale of the temperature data has been adjusted to make the closeness of the correlation more apparent. Temperatures at D were not available for this test and it was necessary to employ temperature measurements on the arcade ceiling near D, but these in turn should depend closely on the temperature of the gases at D. It has already been mentioned in Section 3.1 that the measured temperatures are in reasonable agreement with measured gas flows and estimated heat losses.

The CO_2 concentrations measured at 5 min, close to the peak burning of the fire, are given in Fig.15 and the corresponding values for the gas flows in Fig.16. These show several noteworthy features. First, for tests 125 and 129, with an open vent, the CO_2 concentration falls substantially as the gas passes along the mall, implying a considerable mixing of air into the layer. This mixing occurs not only between the fire compartment opening D and I where considerable mixing of air might be expected as the gases rise up into the mall to join the layer there, but also between I and J where it might not be expected. A further large drop in the CO_2 concentration occurs between J and the gases within the vent - in test 125 roughly half of the flow up the vent was air which had mixed with the gases since they passed the cross-section containing J. No readings of CO_2 concentration were made in the vent in test 129 because a fault developed in the CO_2 meter but the temperature measurements show that for this test about $\frac{1}{3}$ of the flow up the vent was air mixed in since the gases passed J. (See Table 7). This slightly lower proportion is no doubt due to the greater thickness of the hot gas layer produced by the addition of the screen.

Table 7. Origin of gases flowing up vent

Test	Gas flow up vent (m^3/s reduced to ambient temperature)		
	Total	Gas passing cross-section at J	Air entrained after J
125	3.9	1.7 (43%)	2.2 (57%)
129	4.0_5	2.7 (67%)	1.3_5 (33%)

The dilution with air which has occurred between the gases leaving the fire compartment and passing up the vent is considerable - about 4 or 5 times.

Beyond the vent, at K and L, the volume flows have been calculated from the CO_2 concentrations taking into account the fact that some of the gases have passed up the vent. The advantages of the screen are again seen in the smaller gas flows beyond the vent, passing under the screen.

Figure 16 shows that for tests 127 and 128 (vent closed) the rate of entrainment of air up to J was lower than for tests 125 and 129 (vent open), and virtually no entrainment took place with the vent closed after J. This is very likely to be related to the calmer base of the layer with the vent closed.

3.3. Optical density of the smoke

The smoke meter readings were converted into values of optical density per metre path length. The readings of the monitor photocells varied appreciably during a test and the optical density for the smoke meter path length of 0.25 m was taken as $D = \log_{10} (R_o M_t / M_o R_t)$

where R_o = output of receiver photocell before start of test
M_o = output of monitor photocell before start of test
R_t = output of receiver photocell at any time t during test
M_t = output of monitor photocell at any time t during test.

The value of D for a 1 m path length is obtained by multiplying the value given by the smoke meter readings by 4. The values of optical density obtained at four positions are shown for 4 tests in Figs 17 to 20. The optical densities obtained in test 105 (vent closed) were very similar to those of the nominally identical test 104, and varied with time in a similar way. At position I/J the optical density at the upper smoke meter was about 20-30 per cent higher than that at the lower smoke meter (Fig.17) whilst at K/L the readings of upper and lower smoke meters were close together suggesting that near the peak burning of the fire, mixing within the smoke layer has occurred between positions I/J and K/L. This is confirmed by the temperature profiles (Fig.9). A similar pattern can be seen in the curves for Test 100, which yielded similar optical densities, the test conditions differing from 104 and 105 only in the absence of the fascia board.

Unfortunately the results of test 102, nominally identical to test 100, seem to be anomalous, since they give optical densities about $\frac{2}{3}$ of those of tests 100, 104 and 105. The reason for this is not known, but there might have been a lower smoke production caused by some effect on combustion due to different water levels in the trays and different evaporation rates of the water. Tests 100, 101, 102 (and 103) were carried out in this order on one day, and some evaporation of the cooling water might possibly have occurred during the day.

The results for test 102, though anomalous, are similar for both heights of smoke meter.

The effect of opening the vent can be seen by comparing test 108 (Fig.20) with test 104 (Fig.17). The optical densities are much smaller at the lower position, near the bottom of the layer, and are smaller at position K/L, past the vent, as are the temperatures (Table 4) and CO_2 concentrations (Fig.15).

The optical densities per metre given by the wood crib fires were in the order of 1/10 of those for the kerosene fires.

4. DISCUSSION

4.1. Effects of screen

Although the experimental building is much shorter than those pedestrian malls which could yield a serious escape problem, it is long enough to be able to judge the efficacy of measures for extracting smoke before it can travel far.

The effect of the screen cannot be considered entirely separately from the effect of the vent since the action of one depends on the presence or absence of the other. The results clearly show that the presence of the screen makes the vent very much more effective in arresting or retarding smoke flow along a long mall and this cannot be too strongly emphasized.

First of all, when there was no screen, opening the vent caused the bottom of the layer to rise by not more than 0.2 m on average (compare tests 98i and 98ii, Fig.11*), so that the flow of smoky gas continuing along the mall was only slightly reduced with the vent in operation (Test 125, Fig.16).

However with a 0.9 m deep screen present the bottom of the layer rose by about 0.5 m, on average, when the vent was opened (compare tests 101 and 100, Fig.11) and the depth of the layer and the flow of gases passing under the screen were much reduced (test 129, Fig.16).

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*Figure 7 shows that if conditions are unchanged the layer depth is likely to increase by c.0.1 m between $2\frac{1}{2}$ and 5 min, so that if readings had been taken in both cases at 5 min the curves for tests 98i and 98ii would be closer together than shown in Fig.11.

Adding the screen with the vent open (compare tests 101 and 98ii, Fig.11) deepened slightly the layer between the fire compartment and the curtain, but substantially reduced the rate of passage of smoke-laden gases to the end of the mall (compare tests 129 and 125, Fig.16).

The effect of adding the screen without any venting was to depress the bottom of the layer by an amount nearly as large as the depth of the screen itself (compare tests 100 and 98i Fig.11), so that screens without vents would substantially increase smoke logging near the fire without preventing smoke travel along the mall. The screens do not slow up the spread of smoke by a worthwhile amount since it was noted in these tests that as soon as the smoke layer reached the screen it passed under it. The better smoke extraction and the lower gas flows beyond the vent have been noted in Section 3.2.

The smaller fires were more successfully vented – substantially none of the smoke generated by the wood crib (Test 107) passed under the screen. The bottom of the layer for the 0.58 m^2 kerosene fire was only about 0.1 m below the screen and comparatively little smoke passed under it.

The base of the layer was not flat near the screen. It curved down slightly from the screen possibly because the air flowing in had just passed an abrupt contraction of duct cross section. Thus the depth of the layer flowing under the screen was slightly less than the total depth at L minus the depth of the screen (Table 8). Although this would appear to enhance slightly the capability of a screen to hold back a smoke layer it is a small effect and probably best disregarded, i.e. the layer should be treated as though it were flat up to the screen. In any case if there were a sufficiently large movement of air through the mall, and this could happen with an external wind blowing through a mall open at both ends, the effect would presumably be destroyed at the screen downstream from the fire.

Table 8. Spillage of smoke layer under the screen near the arcade entrance

Test No.	Observed depth of smoke layer spilling under screen	Depth of hot gas layer at L below bottom of screen (m)
100	≈ 0.7 m	0.8
102	≈ 0.6 m	0.9
101	Irregular discontinuous spillage for a few seconds at a time to a depth of 0.3 m	0.25
104	) 0.6 m	0.75
105	)	0.7
108	0.1 m, but external wind disturbance	0.3
103	Very little, irregular, spillage	0.1
106	Up to 0.5 m, external wind disturbance	0.65
107	Some spillage, but wind disturbance	0

4.2. Effect of fascia board

Inserting the fascia board caused no increase in the time for smoke to enter the mall nor in the time for smoke to reach the curtain (Table 2). As soon as the smoke layer reached the front of the shop it passed down and under the fascia board, apparently because of its momentum and low buoyancy (it was still relatively cool), even though the space in the fire compartment above the bottom edge of the board was by no means full of smoke.

However, even though a fascia board cannot prevent or delay the passage of smoke from a shop into an arcade, it can help to prevent entry of smoke into shops not involved in fire, as discussed by Hinkley[4].

4.3. Size of vent and quantity of gases extracted

4.3.1. Comparison of vent performance with existing theory

The area of vent required to extract the smoke-laden gases produced by a fire of the same size as that in tests 98, 100, 102, 101, 104, 105, 108 and 125 to 129 (perimeter 5.2 m) in a simple single-storey building can be obtained from nomogram 3 in reference 11, taking the height of the building as the vertical distance between the tray of kerosene and the top of the vent shaft and the depth of the layer as the vertical distance between the lower edge of the screen and the top of the vent shaft. Friction within the shaft can be neglected and an effective discharge coefficient of 0.6 has been assumed for the combined effect of the ends of the shaft. The area found is 0.8 m^2, about half that of the existing vent shaft, 1.5 m^2, which, though it removed a large part of the fire's production of smoke-laden gases in tests 101, 129 and 108, yet did not prevent smoke escaping under the curtain. For the small kerosene tray the required vent area can be similarly obtained as 0.5 m^2, and in this test (No.103) the vent was just large enough to prevent any continuous flow of smoke under the sceen (small quantities of smoke passed under for short periods, probably after some disturbance to the layer due to external wind).

The smoke from the wood crib fire (No.107) was also prevented from passing continuously under the screen, even though this was a fire of nominally larger perimeter than the small kerosene tray, but the thermal output was low, about half that of the test with the smaller kerosene tray (103). The temperature rise in the mall at J and K, near the vent, was also about half that of test 103 so that if the heat losses were in the same proportion the mass of gas reaching the vent would have been roughly similar for both tests. In the following discussion attention has been concentrated on the kerosene fires since they represent a worse situation than the wood crib fires.

The discrepancy between predicted vent area and performance in practice arises because the more complicated and longer path traversed by the gases in the arcade before they reach the vent, and the relatively thin layer developed, lead to a greater mixing of air with the gases and consequently a larger volume of smoky gases to be dealt with by the vent than in the simpler situation of a fire in a single-storey factory.

Four main regions can be identified where air mixes into the gases from the fire:

(i) the flame and plume of hot gases above the fire
(ii) the passage of the hot gases into the mall from the fire compartment
(iii) the gases flowing along the mall
(iv) at the entry of the gases into the vent shaft.

These are discussed in the following sections.

4.3.2. Flame and plume above fire

Entrainment of air into an upward moving flame and plume of hot gases takes place at a high rate. The resulting quantity of smoke-laden gases is that implicit in the relationships derived for the venting of smoke from large fires in single-storey buildings[6] where the gases are assumed to form a nearly stagnant layer under the ceiling and further mixing can be neglected.

The gases rapidly fill the upper part of the fire compartment and overflow into the mall.

4.3.3. Passage of gases into the mall

In the present tests the layer in the mall was always higher than the layer in the fire compartment. Some entrainment of air into the gases occurs where these pass out from the fire compartment and rise up into the mall. The entrainment is particularly important for those tests with the fascia board (104, 105, 106, 107 and 108) where the height the gases had to rise as they entered the mall was greater. This can be seen very roughly by comparing the temperature rises at D (in the plane of the fire compartment opening) with those at I (first measuring point in the mall). For those tests without the fascia board the temperature drop between D and I was on average about 15% of the temperature rise at D, whilst with the fascia board the corresponding drop was about 45%.

4.3.4. Gases flowing along the mall

Substantial mixing of air takes place into the gases moving down the arcade. Figures 15 and 16 show how the CO_2 concentration decreases and the quantity of gases flowing along the mall (calculated from the CO_2 concentrations) increases with distance.

This mixing was unexpected because the Richardson number of this layer, a dimensionless number characterising flow conditions in a gravity - separated layer, is in almost all cases much larger than the value of 0.8 usually required[12] before mixing takes place (Table 9). At first sight it appears to conflict with the Glasgow railway tunnel experiments[3] where the temperature drop at distances from the fire of more than about 18 m could be accounted for entirely by heat loss, suggesting that little if any mixing of air into the layer was taking place.

Table 9. Richardson numbers for four tests

Test	Richardson number for hot gas layer at:			
	I	J	K	L
125	2.8	0.63	-	-
129	-	1.37	-	-
127	-	2.15	-	-
128	-	5.8	7.6	5.5

The explanation for these apparent anomalies seems to be that when the layer is first formed in the mall it is disturbed in such a way that air can mix into the layer as in the present tests. The disturbance persists for a little way down the mall but eventually, it is presumed, the layer becomes more stable and subsequently very little air is entrained into it, as in the Glasgow tunnel experiments. If the stable layer then travels a long distance - very much longer than the mall of the present experiments - it may cool so much that the Richardson number falls to a value at which mixing of air into the layer commences. The layer should then rapidly expand to fill the whole mall. Smoke tracer demonstrations by Hinkley[13] in a long model 0.46 m high and 0.53 m wide suggest that the disturbance causing the mixing in the newly-formed layer possibly persists for a distance of not more than 2 or 3 widths of the mall.

For test 128, between I and L, the increase in flow corresponds to a vertical entrainment velocity of air into the layer of 0.025 m/s, and a ratio of velocity of entrainment to average horizontal velocity in the layer, i.e. an entrainment constant, of 0.045. This is much less than that for vertical flames (about 0.1), but larger than Hinkley found[10] for the entrainment of air into flame travelling under a ceiling (0.008 to 0.015).

It is interesting to note that in studies of flames travelling under the ceilings of corridors Hinkley[10] found an effect explicable on a basis of enhanced mixing of air into a newly-formed layer, rather like that in the present experiments.

4.3.5. Entry of gases into vent shaft

Substantial mixing of air into the gases takes place as they enter the base of the vent shaft. This effect was noted earlier (Section 3.2) and arises because the vent shaft, acting as a chimney, draws gas from a comparatively thin layer at too high a rate, a situation which Hinkley[4] has pointed out will lead to cool air being drawn up into the vent (Fig. 13).

The magnitude of this effect can be obtained both from the CO_2 concentration and the temperature measurements (Fig. 15 and Table 4). These show that about half to a third of the gas flowing up the vent is air which has been entrained at, or close to, the base of the vent and the remainder is gas from the layer which has passed the cross section containing J (having already been diluted since leaving the fire compartment).

This effect reduces the effectiveness of the vent in removing smoky gases on two counts, firstly because the full capacity of the vent is not used (since only about half of the gas flowing up the vent is from the smoke layer near the base of the vent) and secondly because the gases in the vent are much cooler. In practice this will probably mean that the minimum dimension of extract openings should be much smaller than the expected depth of the layer, and that as far as possible, openings should be distributed over the whole ceiling. This is being investigated further with a small-scale model.

4.3.6. Necessary size of vent

We can now discuss the size of the vent required in quantitative terms. For tests 125 and 129 where the vent was open, the flow of gas leaving the fire compartment (2.4 to 2.7 m^3/s at ambient temperature) was about equal to what would have reached the layer in the mall if the flames could have risen directly up into it (2.3 to 2.8 m^3/s at ambient temperature, Table 10). Since the gases had to rise up from the fire compartment to reach the layer in the mall this means that even in the fire compartment there was more entrainment of air than expected.

By the time the gases had reached J, just before the vent, enough air had been entrained along the mall to double the flow (~ 5 m^3/s at ambient temperature). In order to remove all these gases, a vent capable of removing 10 m^3/s would be required if a similar proportion of air was drawn up at the base of the vent ($\sim$ 50%). Such a vent would have a cross-sectional area* of about 1.5 x 10/4 = 3.75 m^2 if it were the same height as the present vent. This is 4 to 5 times as large as the vent that would be required if it were immediately over the fire (0.8 m^2).

This area could be reduced by a factor of 2, i.e. to 1.9 m^2, if a method could be found for extracting gas without drawing air up from underneath the layer, and experiments with a model[14] using gas at a temperature very close to that in these large scale experiments have shown that this could be achieved by using a number of much smaller openings of equal total area.

Table 10. Gas flow into layer calculated on the basis of entrainment into the flame*

Test	Vertical distance between tray and layer m	Gas flow into layer m^3/s (ambient temperature and pressure)
125	2.4	2.8
127	2.0	2.2
128	1.6	1.5
129	2.1	2.3

*This is the entrainment into a vertical sided flame of the same perimeter as the tray, over a height equal to the vertical distance between the tray and the bottom of the layer in the mall.

A further reduction in area would be possible if the gases could be extracted nearer the point at which they enter the mall.

*The vent described in the present experiments has an area of 1.5 m^2 and can pass $\sim$ 4 m^3 of gas (converted to ambient temperature).

For tests 127 and 128 the layer was deeper and appeared to an observer to be less turbulent and the rate of entrainment along the arcade was lower than with the vent open (Fig. 16). Thus a distributed vent system might produce a calmer layer with less entrainment and this would be an additional benefit.

5. CONCLUSIONS

5.1. Larger vents will be needed in covered pedestrian shopping malls to remove smoky gases originating from fires in the shops than are predicted from relationships derived for fires in simple single-storey buildings. This is because in this situation much more air mixes with the smoke layer and the amount of gases that a vent is called upon to remove is greater.

5.2. The mixing occurs (a) as the gases pass into the mall from the fire compartment (especially important when there is a deep fascia board), (b) as the gases pass along the mall and (c) as the gases enter the vent shaft. Mixing (b) may not persist beyond a length corresponding to a few widths of the mall. The mixing referred to in (c) could probably be overcome by an aerodynamically designed inlet or by replacing the one large vent by a number of smaller ones.

5.3. The temperature of the smoke-laden gas fell as it flowed along the mall partly because of the mixing of cool air into the layer and partly because of heat losses.

5.4. The action of the vent is very much improved by the presence of a screen beyond the vent. Without a vent the screen alone does not prevent smoke travel.

5.5. The fascia board in the opening of the fire compartment (representing a shop) does not slow down the passage of smoke into the mall, but would help to prevent entry of smoke from the mall into other shops.

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APPENDIX 1

Derivation of gas flow rates from measurements of concentration of carbon dioxide

From the rate of burning[5] and combustion products[7] of kerosene, measurements of carbon dioxide concentration in a cross-section in the hot gas layer enabled the rate of flow of gases through that cross-section to be derived.

Theory

From Spiers[7], 1 kg of kerosene yields, on complete combustion with 11.96 m^3 air (15°C, 760 mm Hg pressure):-

1.70 m^3 CO_2 at 15°C and 760 mm Hg
1.64 m^3 water vapour at 15°C and 760 mm Hg
9.46 m^3 N_2 at 15°C and 760 mm Hg

12.80 m^3 Total

We assume:

(i) No water vapour condenses in the mall
(ii) No CO is produced since there is a plentiful air supply to the fire
(iii) CO_2 concentrations are measured in a dried sample.

Let x kg kerosene be burned in V_I m^3 of air (15°C, 760 mm Hg), there being an excess of air for combustion. Let the % CO_2 concentration in a dried sample extracted from the stirred gases be $\overline{CO_2}$.

If the total new volume of the gases is V_T, at 15°C and 760 mm Hg, then it can be shown that:-

$$V_T = V_I + 0.84x \qquad (1)$$
$$V_T = x(170 + 1.64\ \overline{CO_2})/\overline{CO_2} \qquad (2)$$
also
$$V_I = x(170 + 0.80\ \overline{CO_2})/\overline{CO_2} \qquad (3)$$

Approximately:

$$V_T = V_I\ (1 + 0.005\ \overline{CO_2}) \qquad (4)$$

Thus the rate of burning of the kerosene is known, the rate of flow of gases through a cross-section of the mall containing the CO_2 sampling point can be obtained from (2) and the rate of mixture of air into the gases from (3).

Experimental

Gas samples were continuously withdrawn through steel tubes, $\frac{1}{2}$ m long and 6 mm in diameter inserted through the arcade ceiling to protrude vertically downwards 0.30 m below the ceiling at each point, I, J, K and L. One tube was also installed to extract samples from the centre of the vent shaft at a height of 3.75 m above the plane of the ceiling. At position D, a tube about 1 m long was inserted through the ceiling just outside the fire compartment to withdraw gas from a point 0.15 m below the upper edge of the opening of the fire compartment (ie the shop front). In each case the tubes were positioned at right angles to the direction of flow of the hot gases. Rubber tubing carried the gas samples to either of two infra-red type meters or to any one of four sets of vessels designed to trap 50 ml gas samples by closing a tap at the open end of each vessel; these were analysed using a gas chromatograph after the test. Since there were only six vessels in each set, only six samples were taken, at 1 min intervals during the period of maximum burning rate of the kerosine. In each of the six cases a period of one minute was allowed for the passage of gas through the system, since this was about the time required for a sample to reach the analysers from the sampling end of the tubes. Having filtered the soot from the gases by passing them through a flask of glass wool, they were dried by passing through a tube containing granular sodium sulphate crystals. In calculating the rate of flow of hot gases, the small contribution made by the water vapour was taken into account by the method shown in the appendix.

To examine whether samples, taken in this way, would be representative of the hot gases over a cross-section in the plane of measurement across the mall, two additional tests were conducted, each with six tubes protruding either 0.3 m or 0.6 m below the ceiling and at positions one sixth, one half or five sixths of the distance across the mall. These measurements were made at K so that comparisons could be made with values of air flow given by anemometer measurements, also made at K. These tests involved burning 23 litres of industrial methylated spirits (i.m.s.) in trays slightly larger in area (1.76 m^2) than those used for the kerosene tests. The vent was closed. The concentrations of carbon dioxide produced were about $\frac{1}{4}$ those obtained whilst burning kerosine*. The results of one of these tests is shown in Fig. 4. and a comparison of air velocities, calculated using both methods is shown in Fig. 5.

The measurements of CO_2 concentration are in reasonable agreement at the six points from which samples were extracted. It is thought that the error in gas flow measurements, taken from recordings of carbon dioxide concentration, is not more than $\pm$ 10%.

The agreement between the CO_2 concentrations at the various positions shows that the turbulence in the hot layer is sufficient to mix, fairly thoroughly, the hot gases and the entrained air.

Figure 5 demonstrates the level of agreement between the two methods of determination of flow rate, showing the overall similarity in spite of the large deviations in the instantaneous values. The values obtained from CO_2 readings were calculated by assuming two periods of constant burning rates, first, a high burning rate from 0 to $7\frac{1}{2}$ minutes and then a lower burning rate from $7\frac{1}{2}$ to 16 min. This is clearly an approximation, since the burning rate falls gradually after peak burning, and has led to an anomaly where the two regions join (Fig.5).

---

*I.m.s. in large trays can be expected to burn at a linear rate of about 2 mm/min[8], roughly half that of kerosene, producing about $\frac{2}{3}$ as much CO_2 per kg of fuel than kerosene, the densities of the two fuels being about the same[7]. Thus if the amounts of air mixing into the hot gas layer were the same as for comparable kerosene tests, the CO_2 content for the alcohol fire would be about $\frac{1}{2} \times \frac{2}{3} = \frac{1}{3}$ of that for the kerosene fire and this is close to the factor of $\frac{1}{4}$ actually found.

APPENDIX 2

Fall in gas temperature along the mall

To check that the gas flow data presented in Section 3.2 are consistent with the temperature data, calculations were made of the expected fall in temperature of the gases along the mall due to their cooling and to the admixture of cold air. Calculations showed that the surface of the insulating material used for the ceiling and walls heated up rapidly and in 5 min was close to the gas temperature. The net heat transfer to the ceiling and walls could therefore be neglected, and the only heat loss from the layer taken into account was downward radiation, assumed to be black body radiation from a body at the temperature of the hottest part of the layer.

In the calculations the gas temperature and flow past a cross-section at I were set at the measured values and the temperatures at J, K etc calculated.

Table 11 compares observed temperatures with those calculated on the following bases:

(a) assuming no further air mixes into the layer and the layer cools by heat loss

(b) assuming there is no further heat loss and the temperature of the layer falls along the mall because cool air mixes into the layer

(c) assuming that both cooling and mixing of air take place.

Table 11. Comparisons between observed and calculated temperatures of the layer

Test	Position	Observed temperature above ambient (degC)	Calculated temperature above ambient (degC)		
			Assuming no air mixing, only heat loss	Assuming no heat loss, only mixing	Assuming both heat loss and mixing
127	I	360	360*	360*	360*
	J	220	330	265	240
	K	185	315	255	225
	L	170	305	250	210
	M	170	295	245	200
128	I	355	355*	355*	355*
	J	245	315	245	220
	K	210	290	265	220
	L	185	275	230	175
	M	145	260	220	160
125	I	345	-	-	345
	J	215	-	-	220
129	I	335	-	-	335
	J	205	-	-	215

*Set equal to observed temperature

The temperatures calculated on the basis of both heat loss and mixing of air are in reasonable agreement with those observed, and this confirms the validity of the data. The assumption of 'mixing only' gives better agreement with observed temperatures than 'heat loss only' but neither assumption alone is satisfactory.

It has been assumed in these calculations that the entire layer is at the highest temperature recorded in the layer. This is not, of course, accurate, though it is more nearly correct for the flattened profiles at K and L with a screen (Fig.9), but it should be quite sufficient to enable trends to be obtained, particularly since the highest temperatures are recorded towards the top of the layer where the velocity is greatest (Fig.14 of Ref.10).

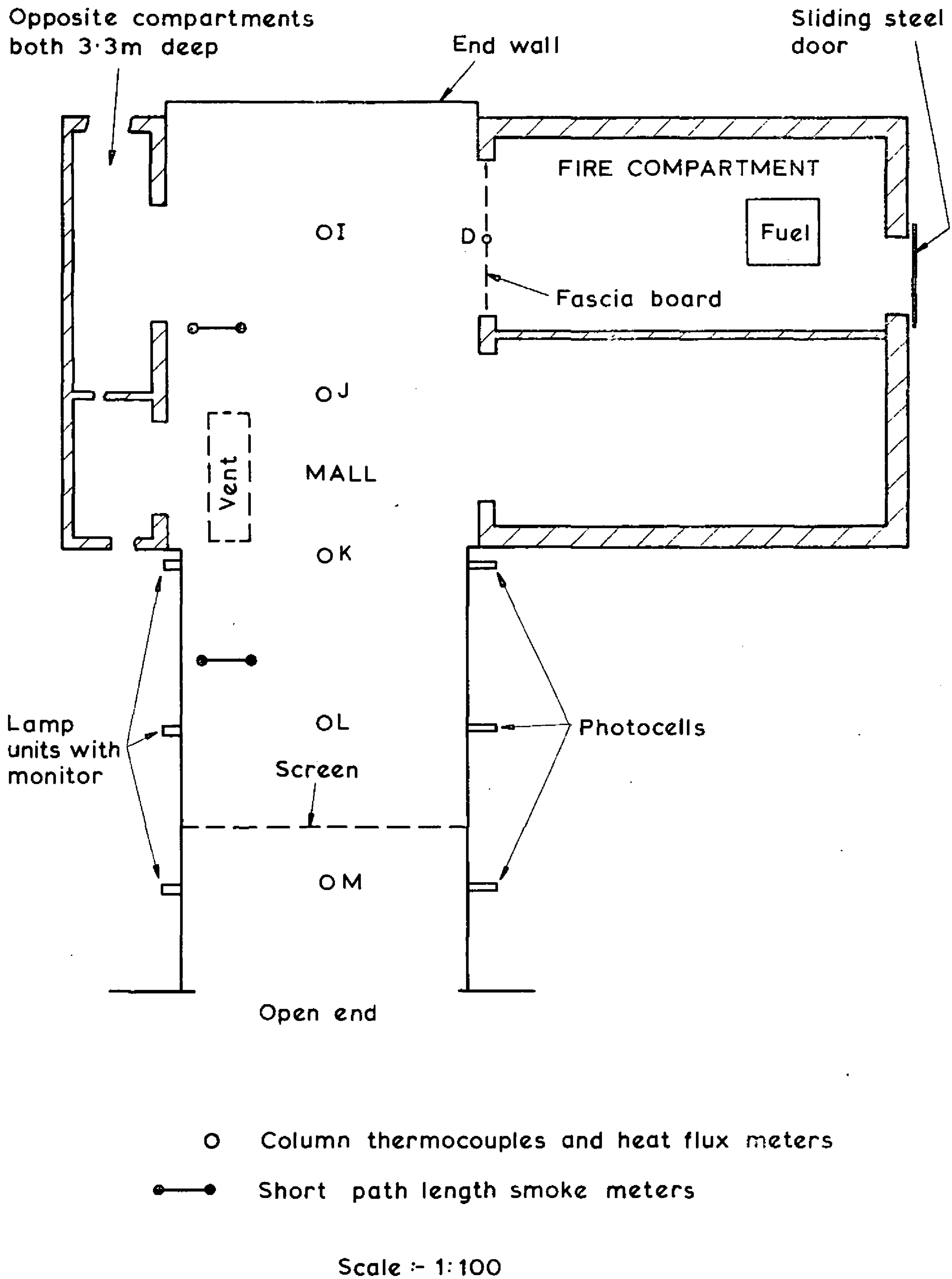
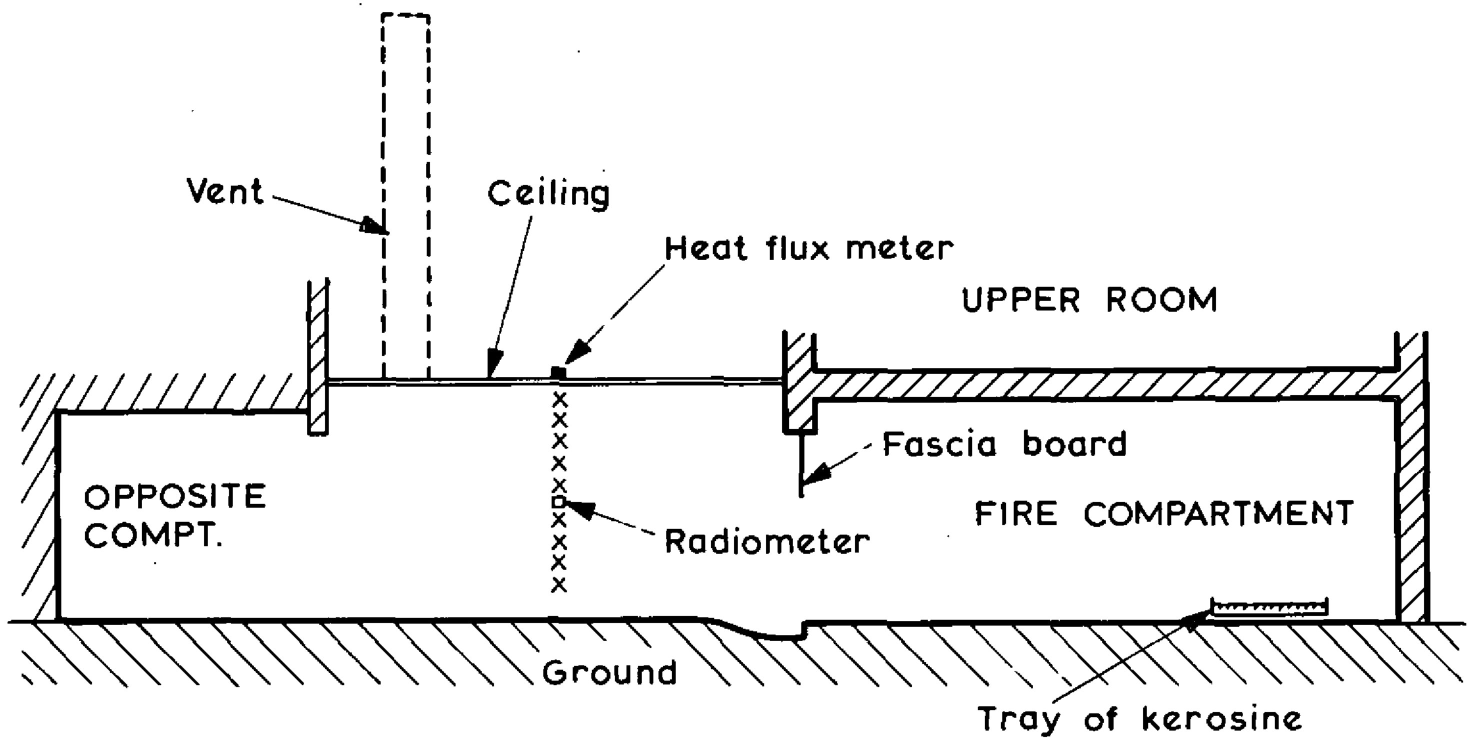


FIG.1 PLAN OF EXPERIMENTAL BUILDING



VERTICAL TRANSVERSE SECTION THROUGH
POSITION 'I'

× Column thermocouples
Scale :- 1 : 100

FIG. 2 CROSS-SECTION OF EXPERIMENTAL BUILDING

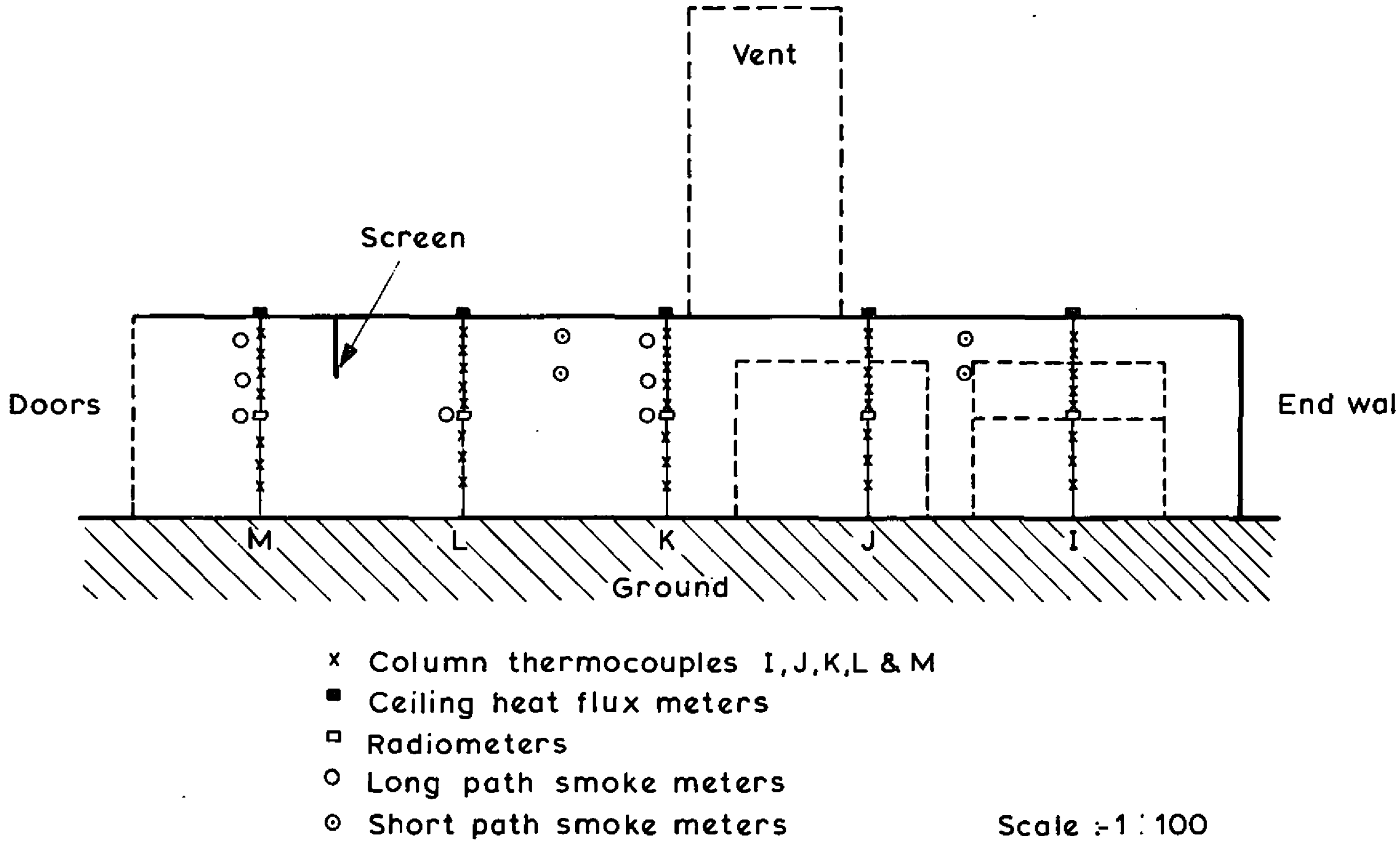


FIG. 3 VERTICAL LONGITUDINAL SECTION ALONG CENTRE LINE OF ARCADE

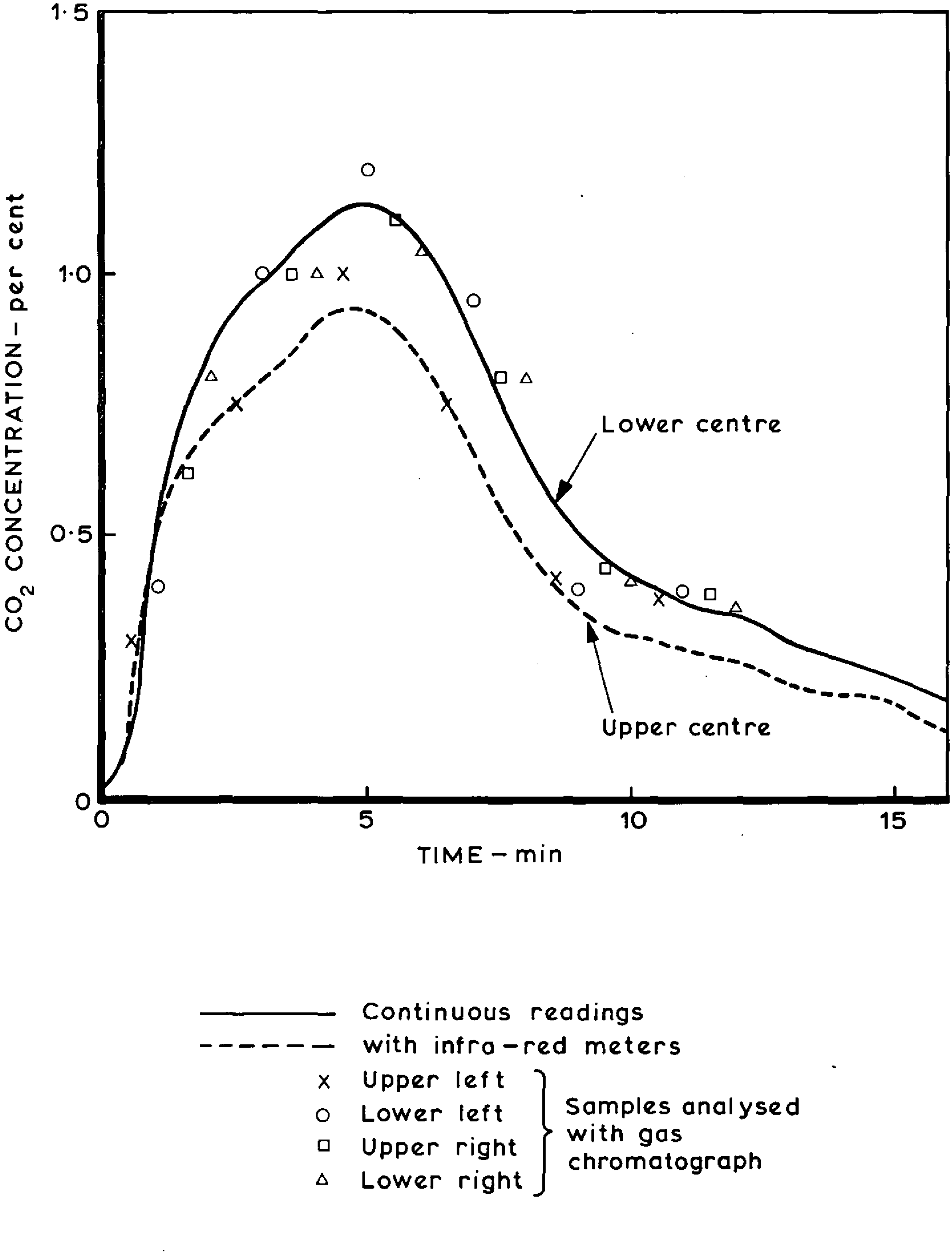


FIG. 4 HOMOGENEITY OF HOT GAS LAYER. CO_2 CONCENTRATIONS OVER A CROSS-SECTION OF THE MALL AT K

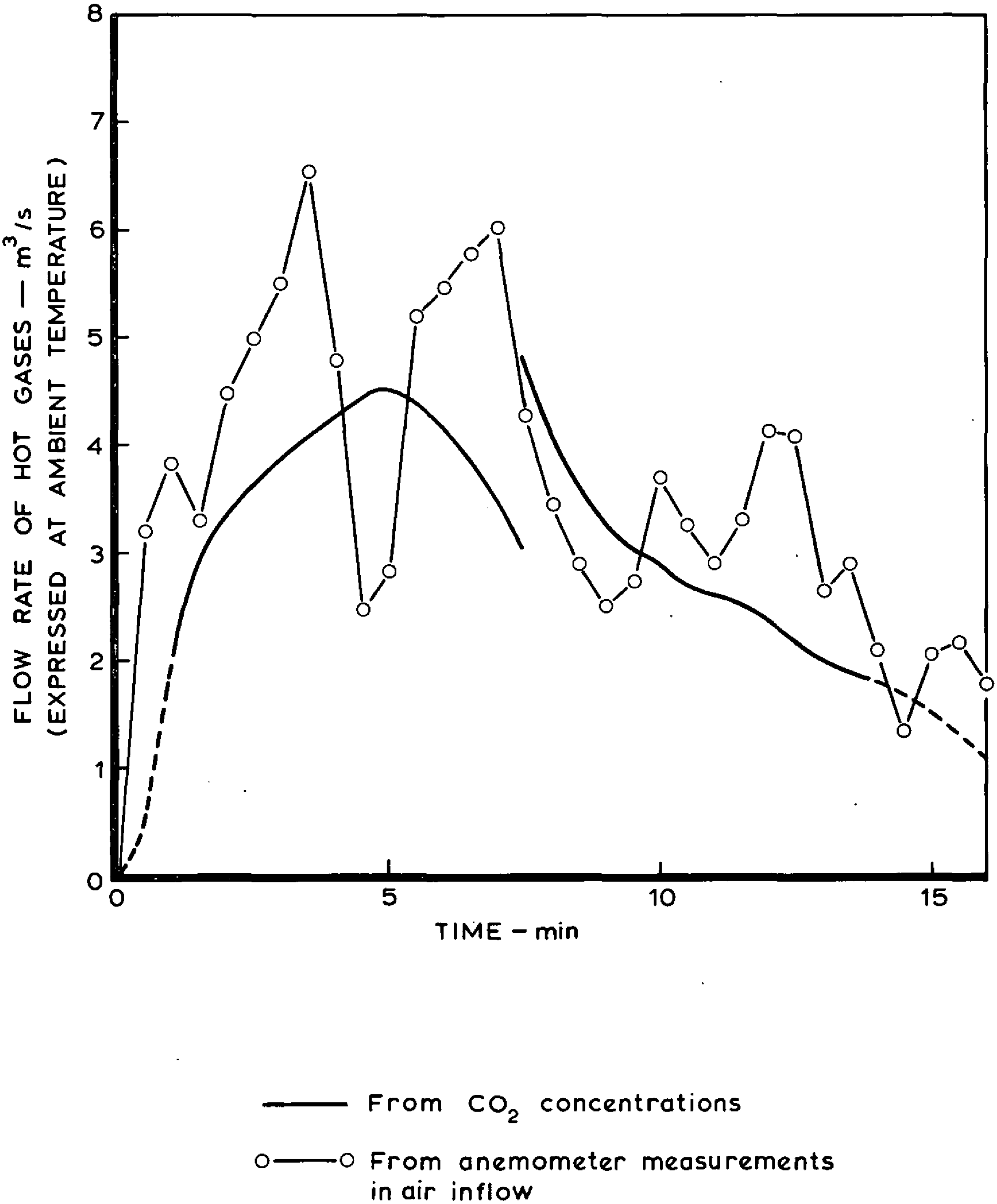
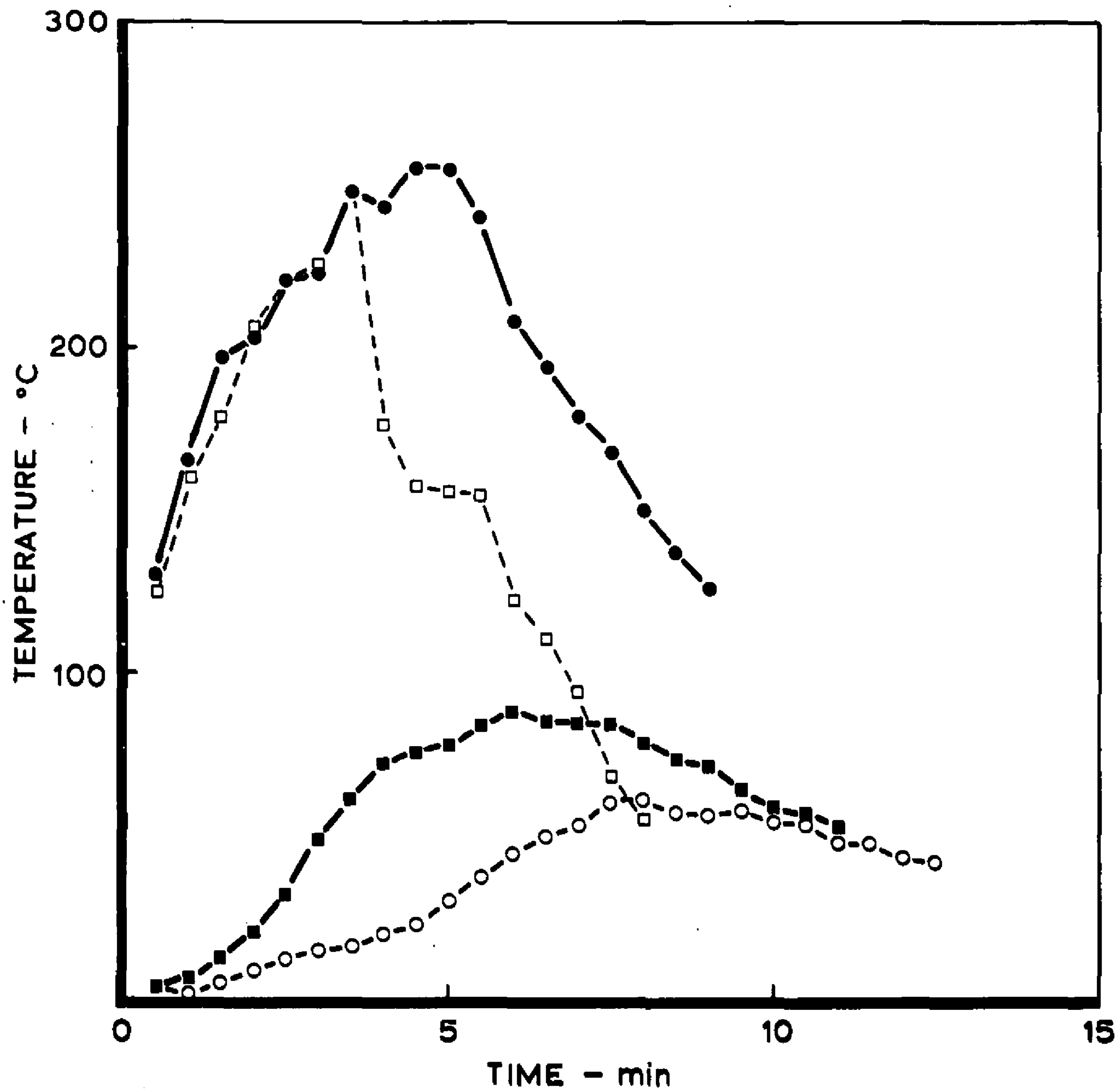


FIG. 5 COMPARISON OF METHODS OF MEASURING GAS FLOW



●——● Vent closed Kerosine tray (Test 100)
□- - -□ Vent open Kerosine tray (Test 101)
■——■ Vent closed Wood crib (Test 106)
○- - -○ Vent open Wood crib (Test 107)

Measurements at top of column J

FIG.6 VARIATION OF TEMPERATURE WITH TIME FOR SOME TYPICAL TESTS

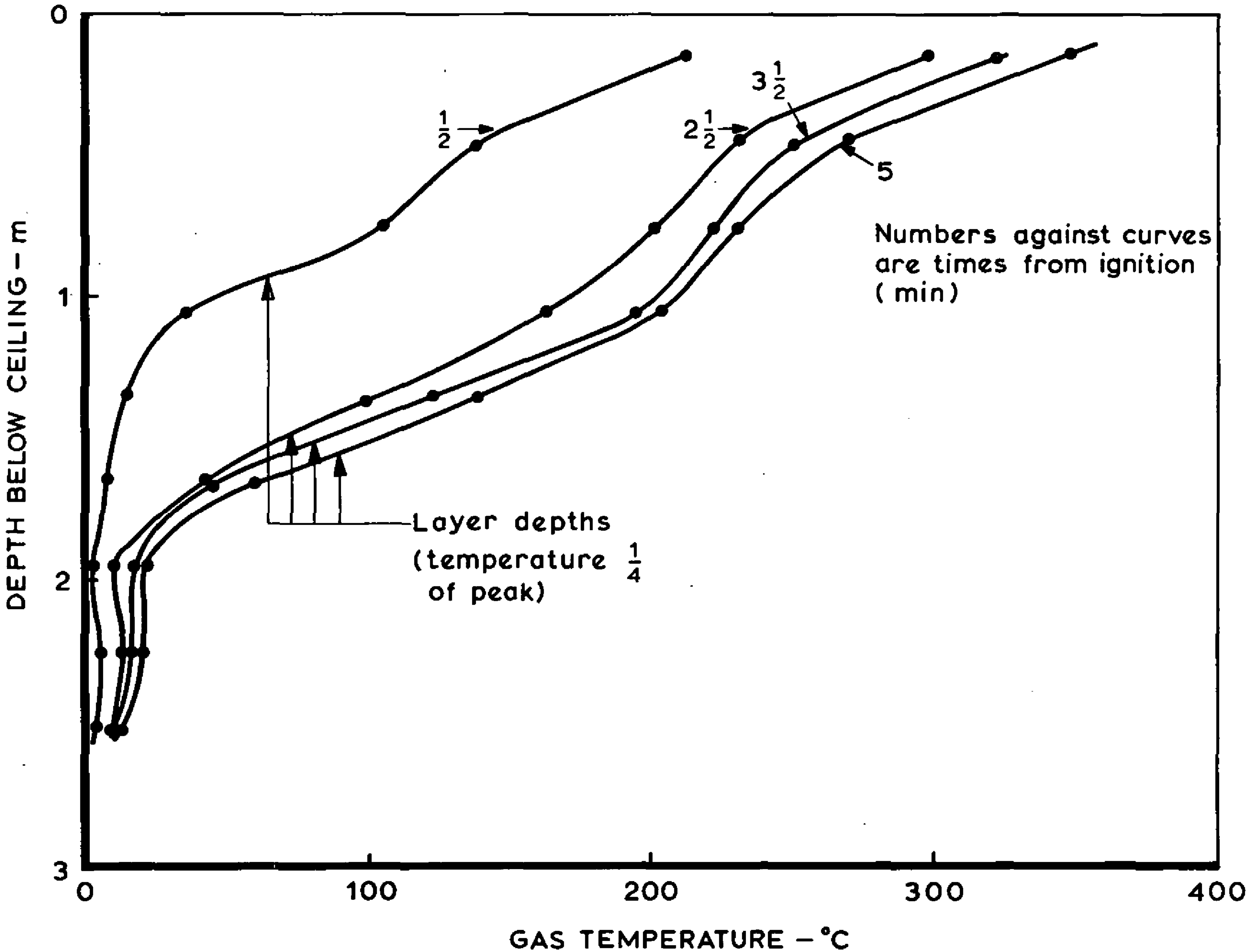


FIG.7 VERTICAL TEMPERATURE PROFILES FOR TYPICAL KEROSINE FIRE (TEST 100) AT POSITION I

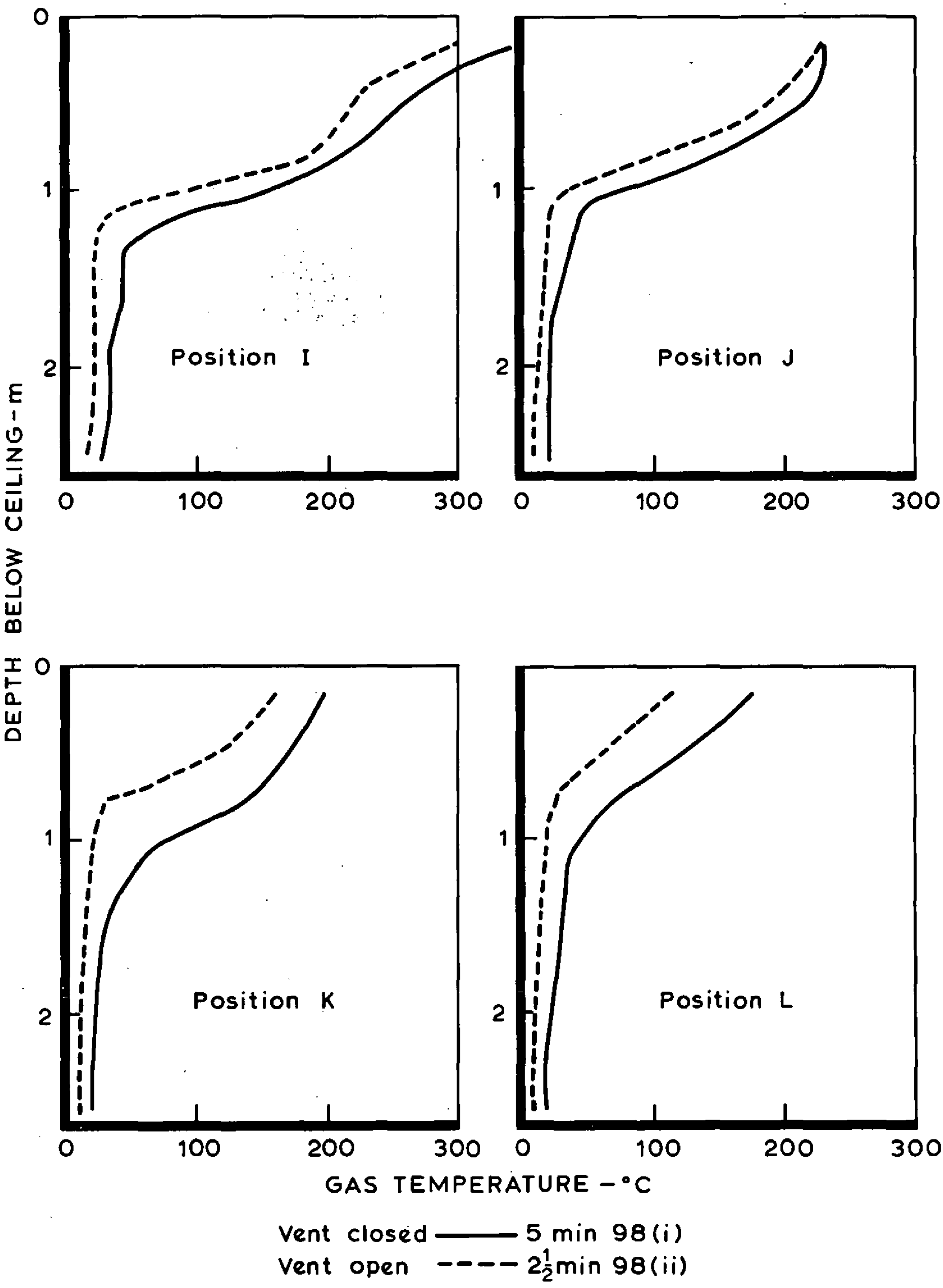


FIG. 8 VERTICAL TEMPERATURE PROFILES FOR TESTS 98(i) and (ii) (EFFECT OF OPENING VENT WITH NO SCREEN)

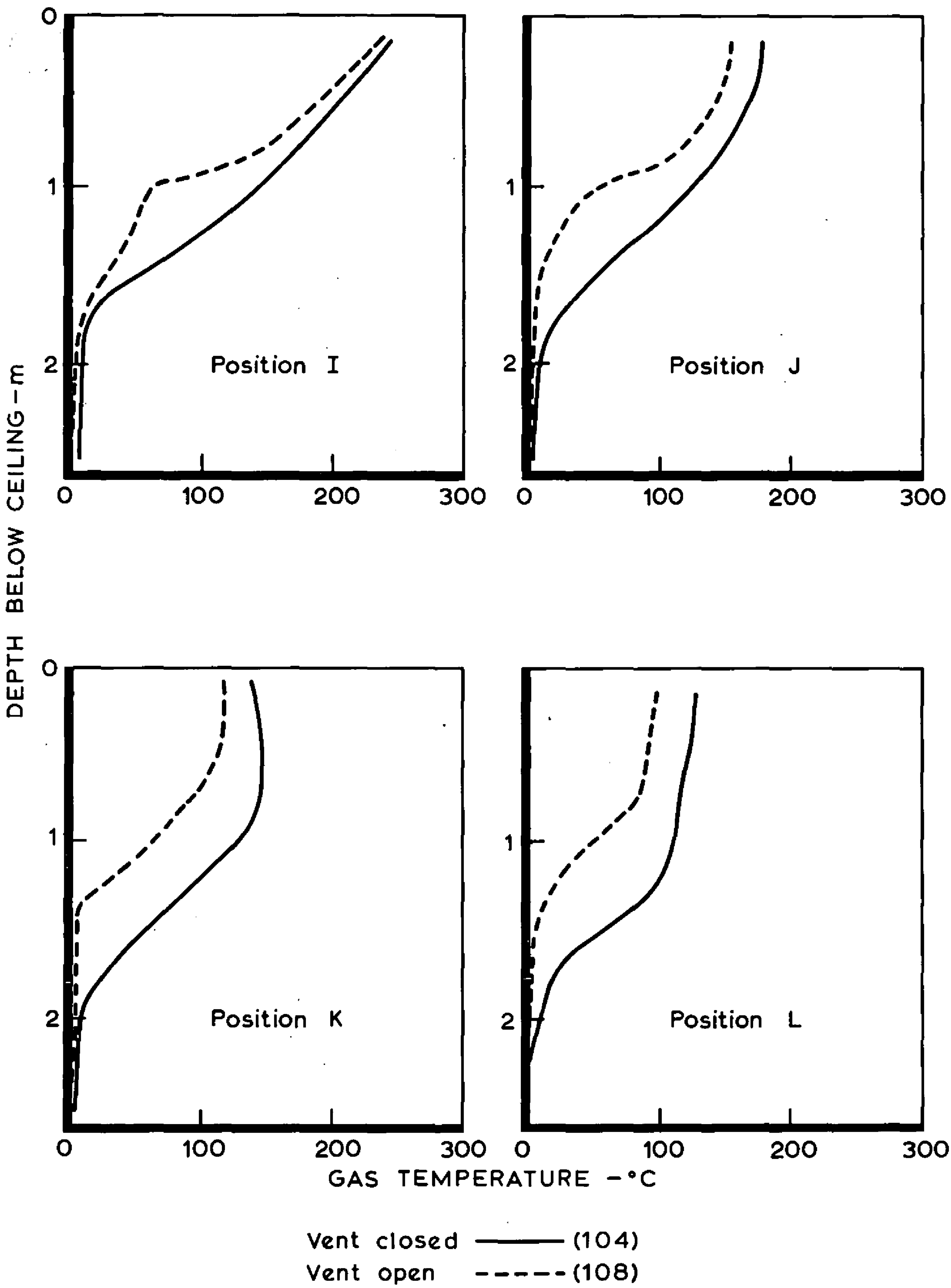


FIG. 9 VERTICAL TEMPERATURE PROFILES FOR TESTS 104 and 108 (EFFECT OF OPENING VENT, WITH A SCREEN)

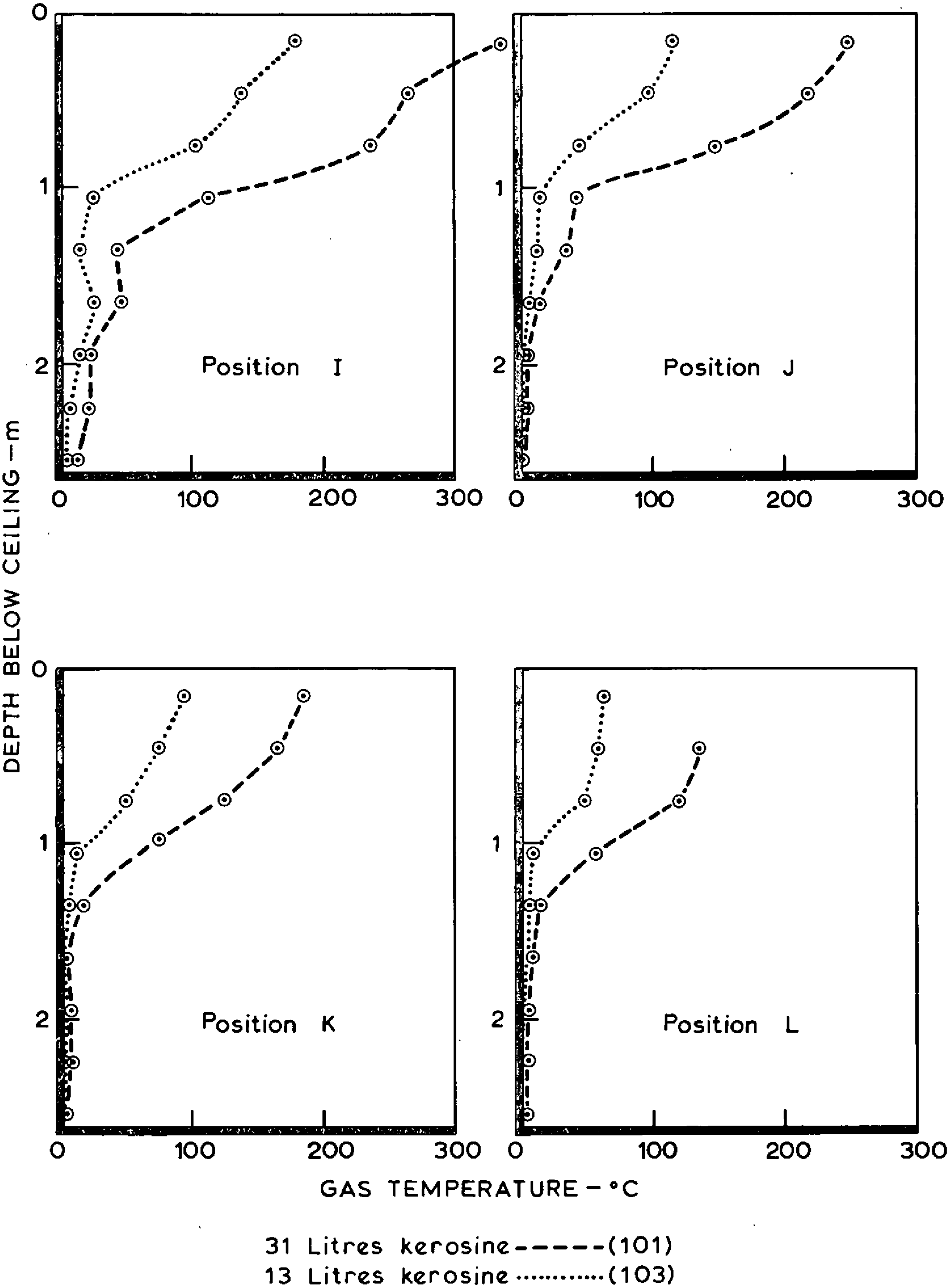


FIG.10 VERTICAL TEMPERATURE PROFILES FOR TESTS 101 and 103 (EFFECT OF SIZE OF FIRE)

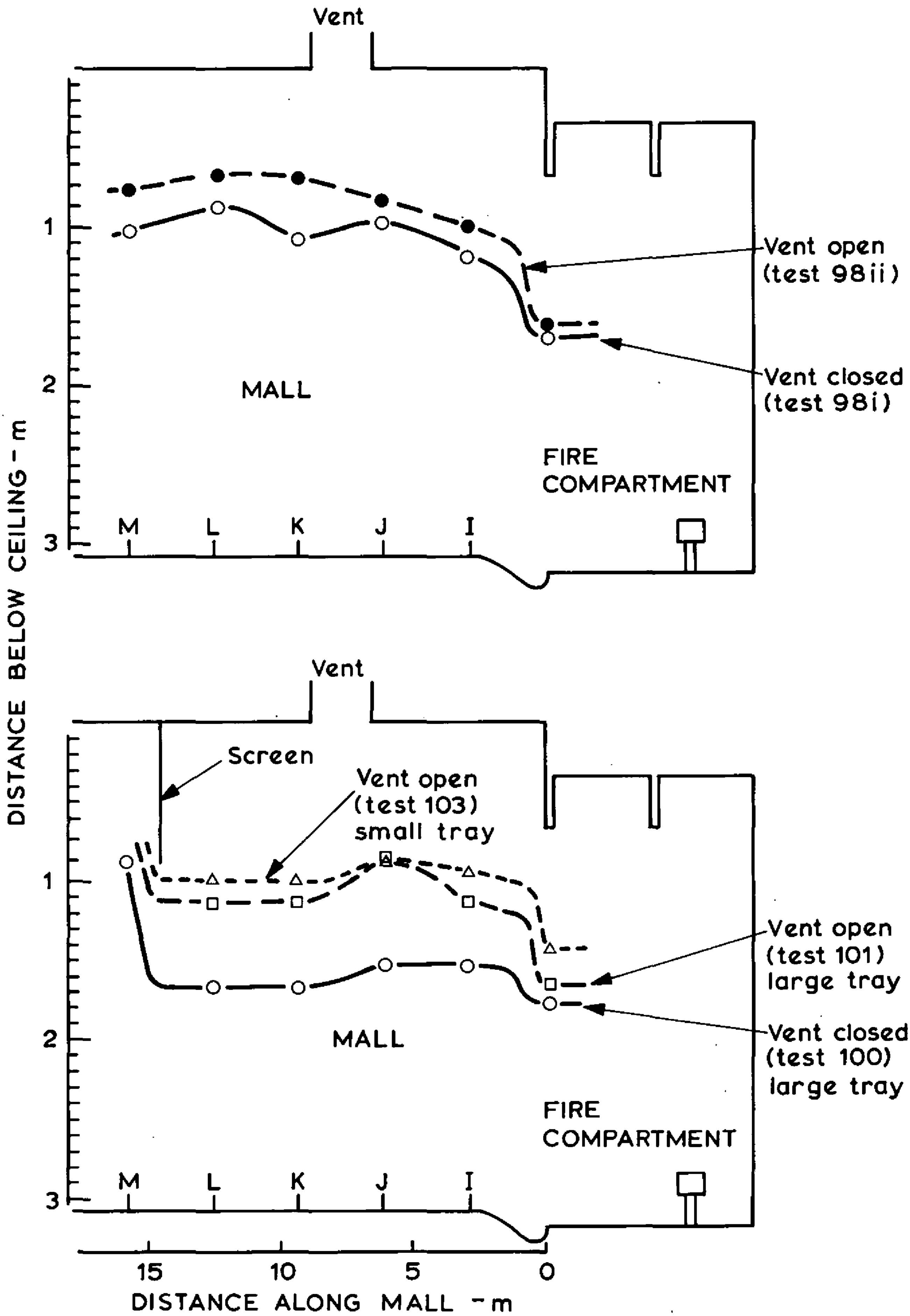


FIG.11 EFFECT OF VENT ON LAYER DEPTH, WITH AND WITHOUT SCREEN

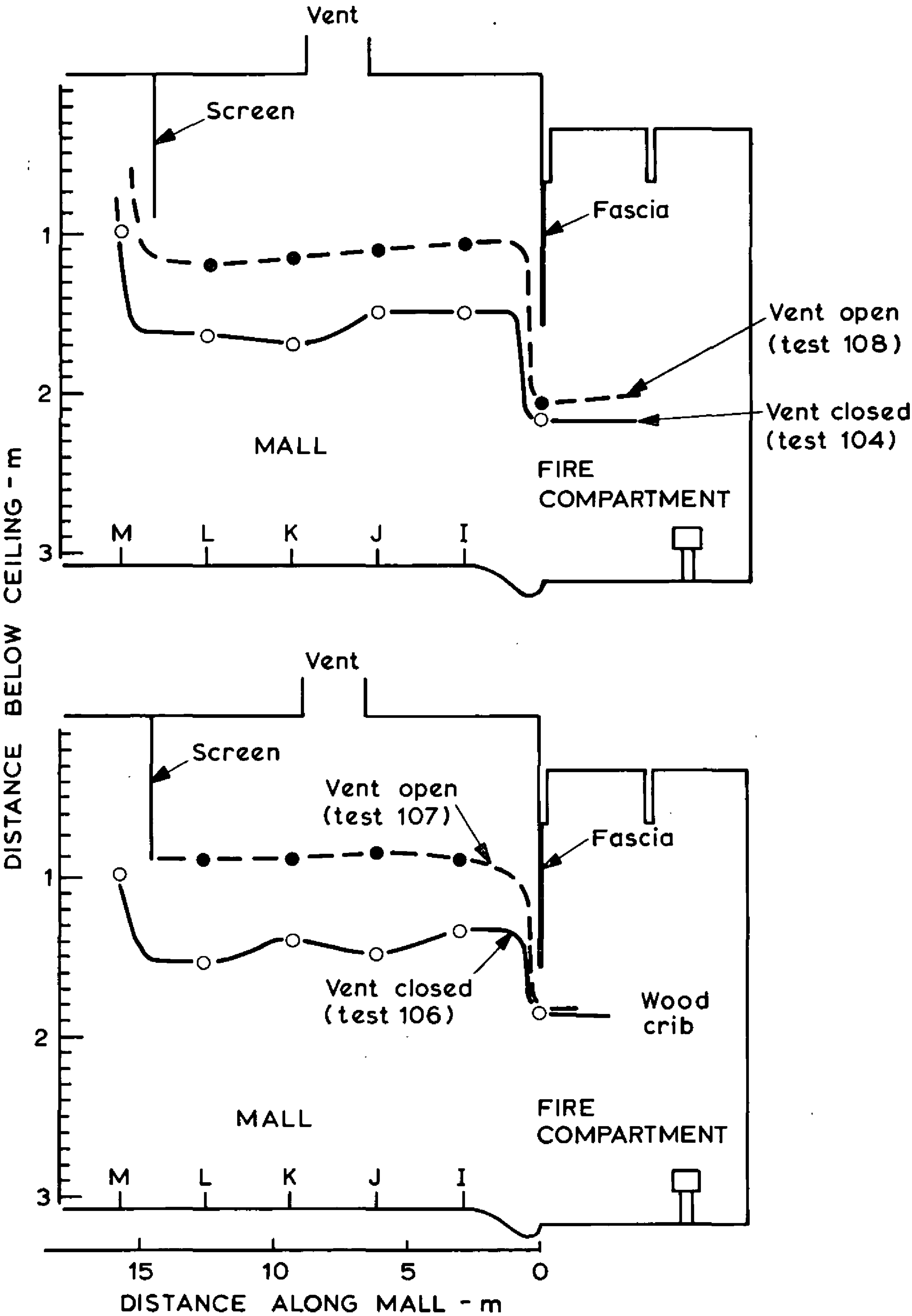


FIG. 12 EFFECT OF VENT ON LAYER DEPTH, WITH FASCIA BOARD

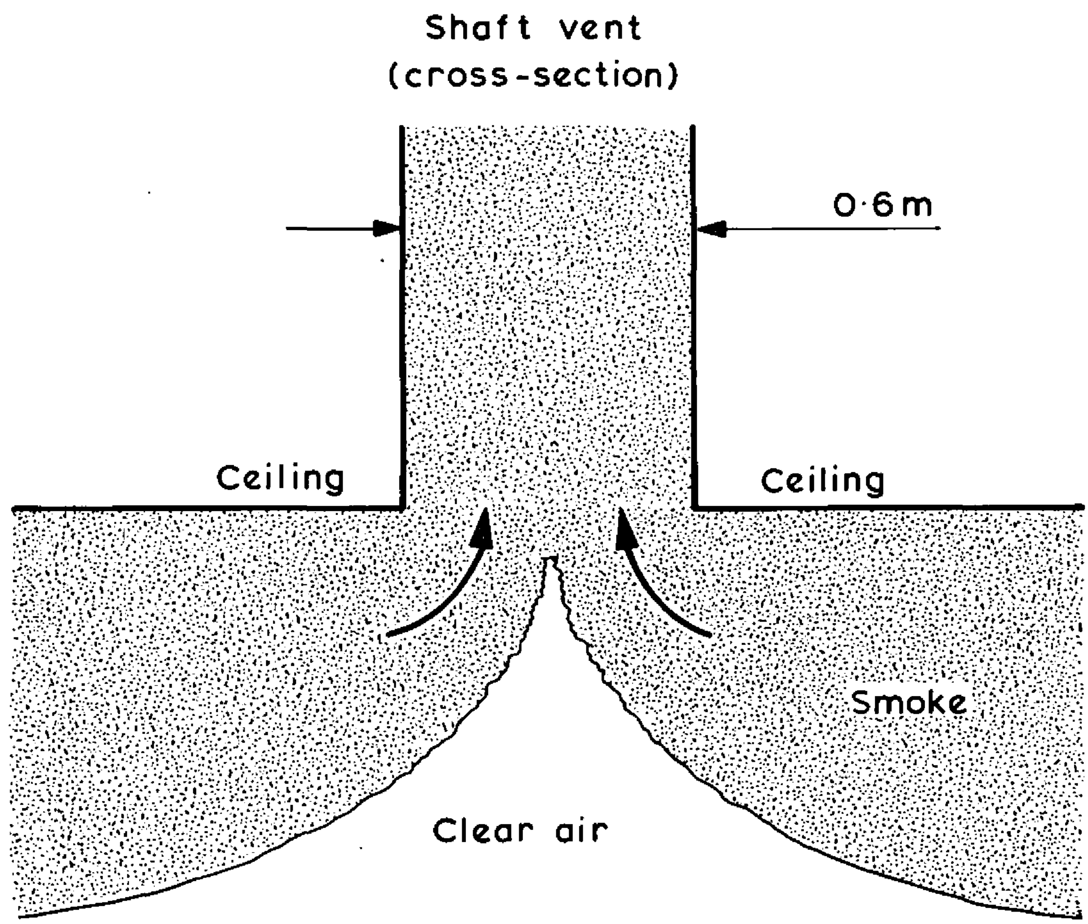
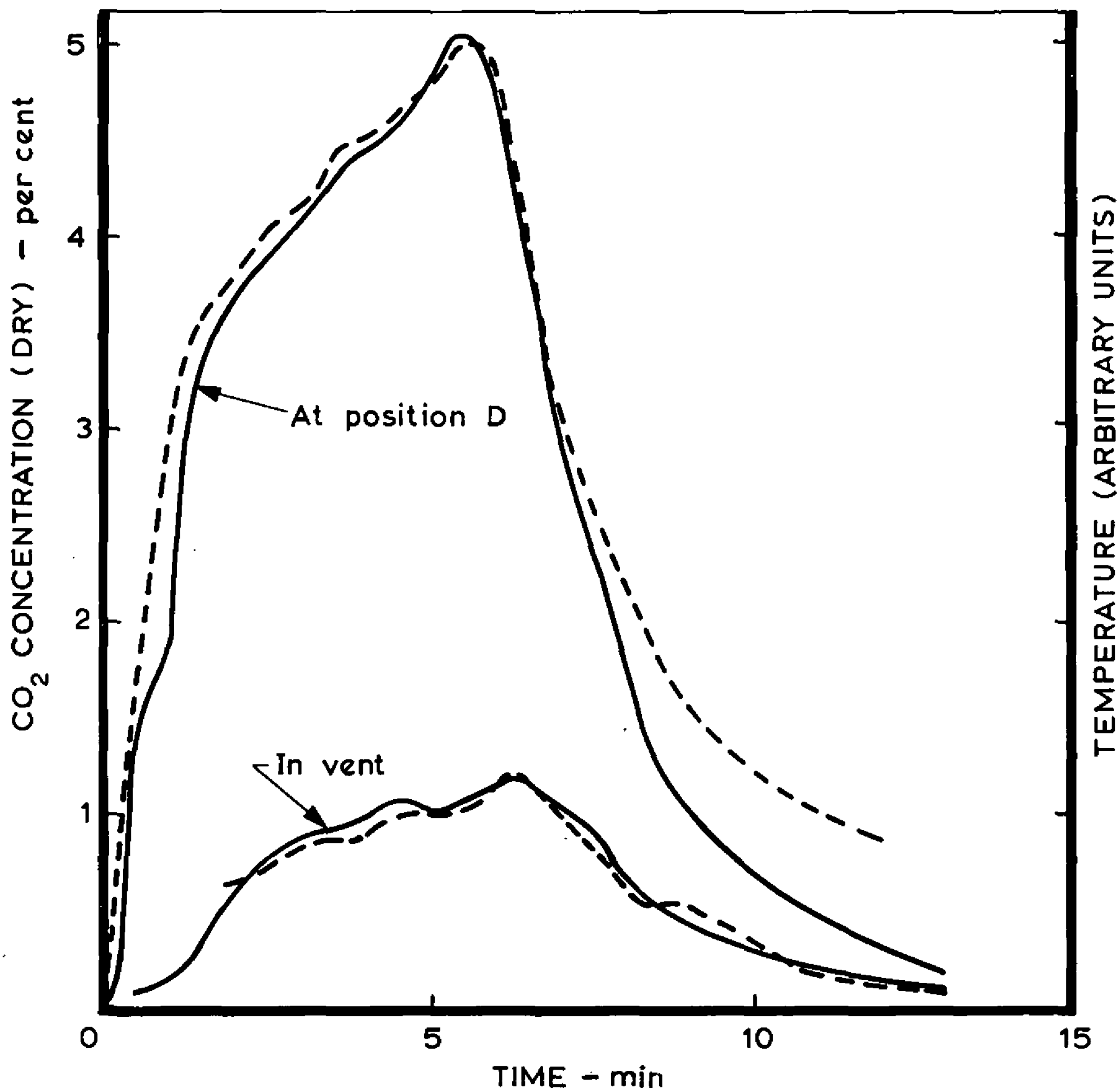


FIG. 13 DEFORMATION OF SMOKE LAYER AT BASE OF VENT SHAFT (TEST 101)



- - - - Temperatures at CO_2 measurement position (arbitrary units)

——— CO_2 concentration

Readings at $\frac{1}{2}$ min intervals

FIG. 14 CORRELATION BETWEEN CO_2 CONCENTRATION AND TEMPERATURE FOR TEST 125

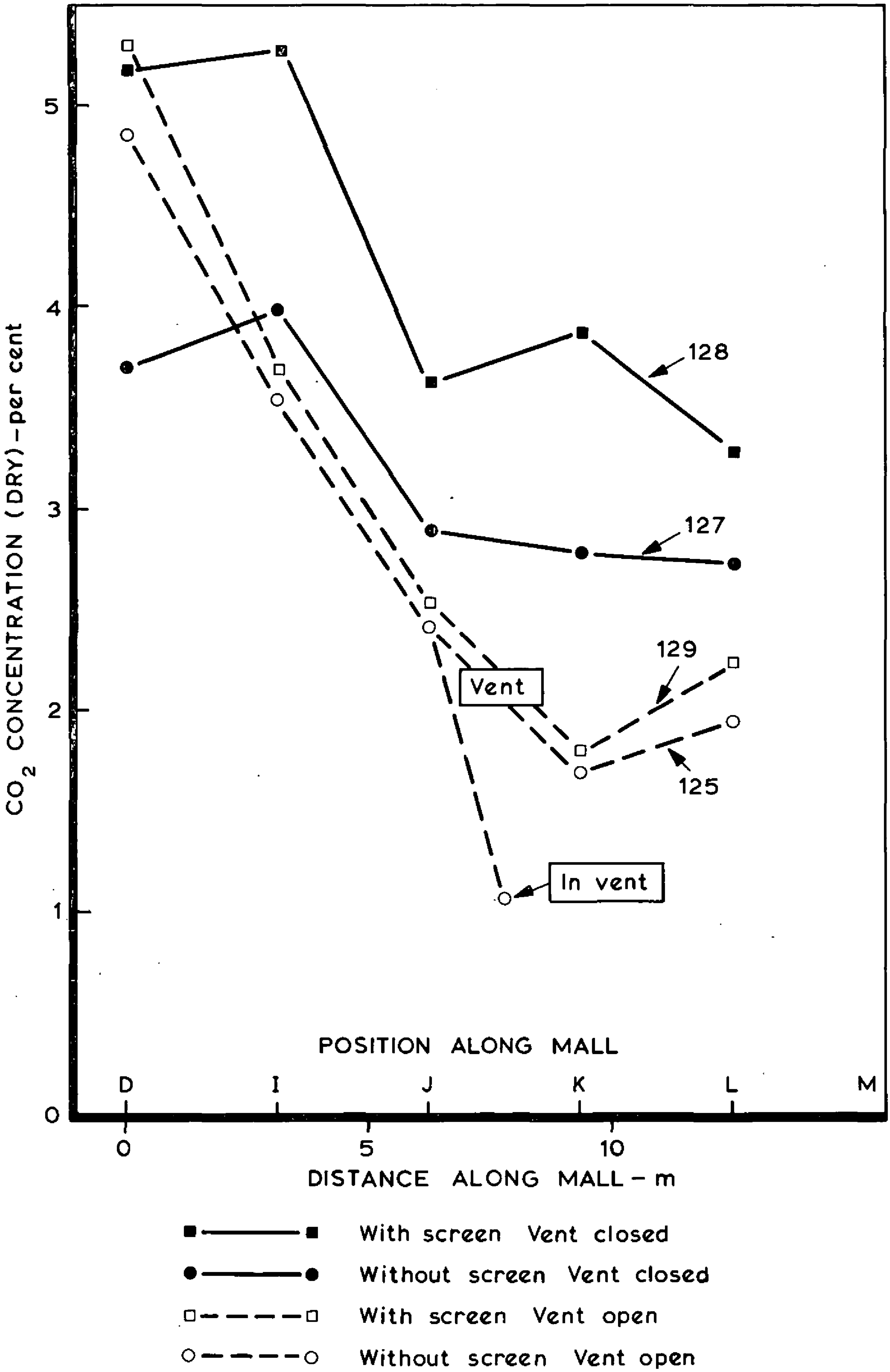


FIG. 15 CO_2 CONCENTRATIONS IN GASES PASSING ALONG MALL IN 5 MIN

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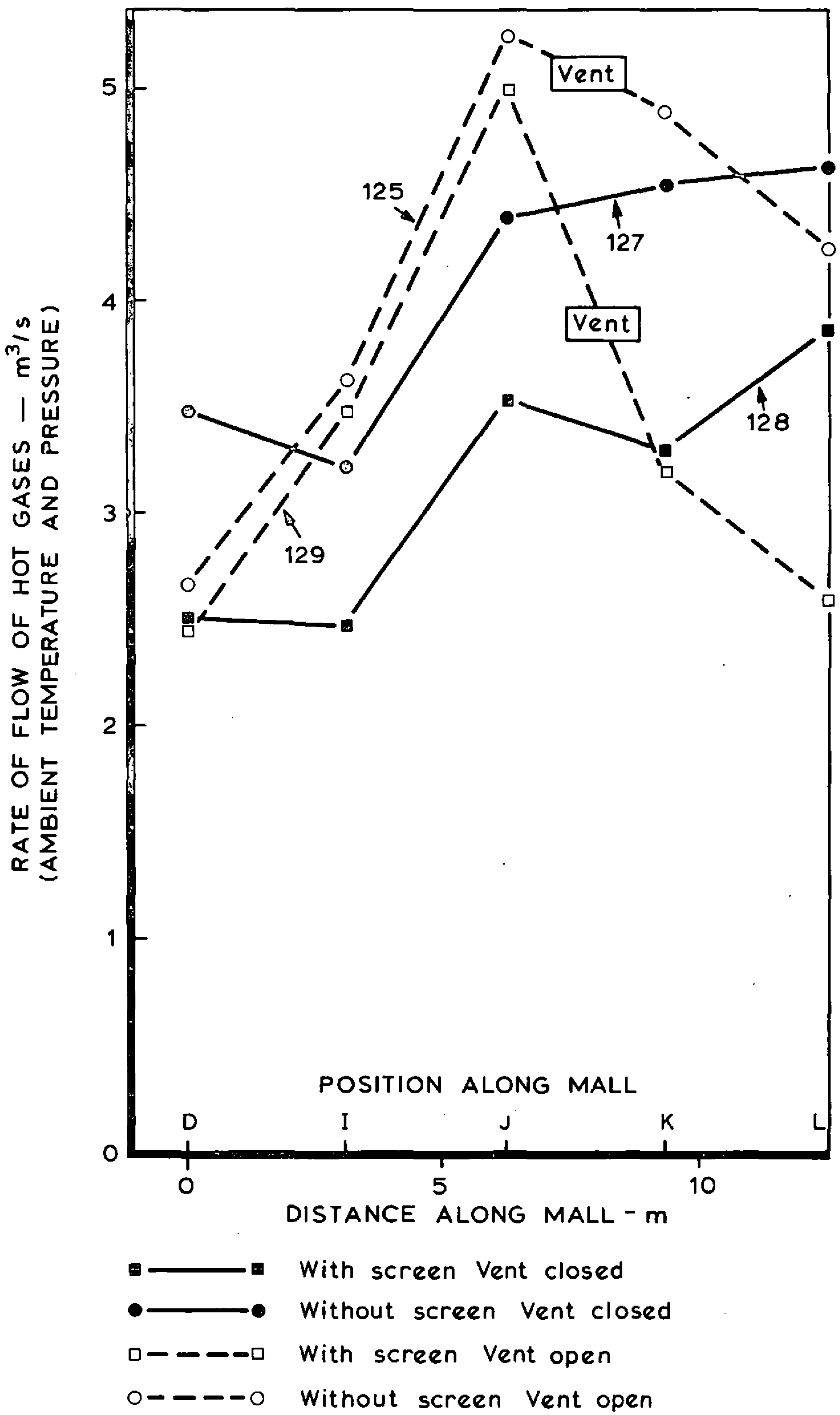


FIG. 16 INCREASE IN AMOUNT OF GASES REQUIRED TO BE VENTED WITH DISTANCE ALONG MALL

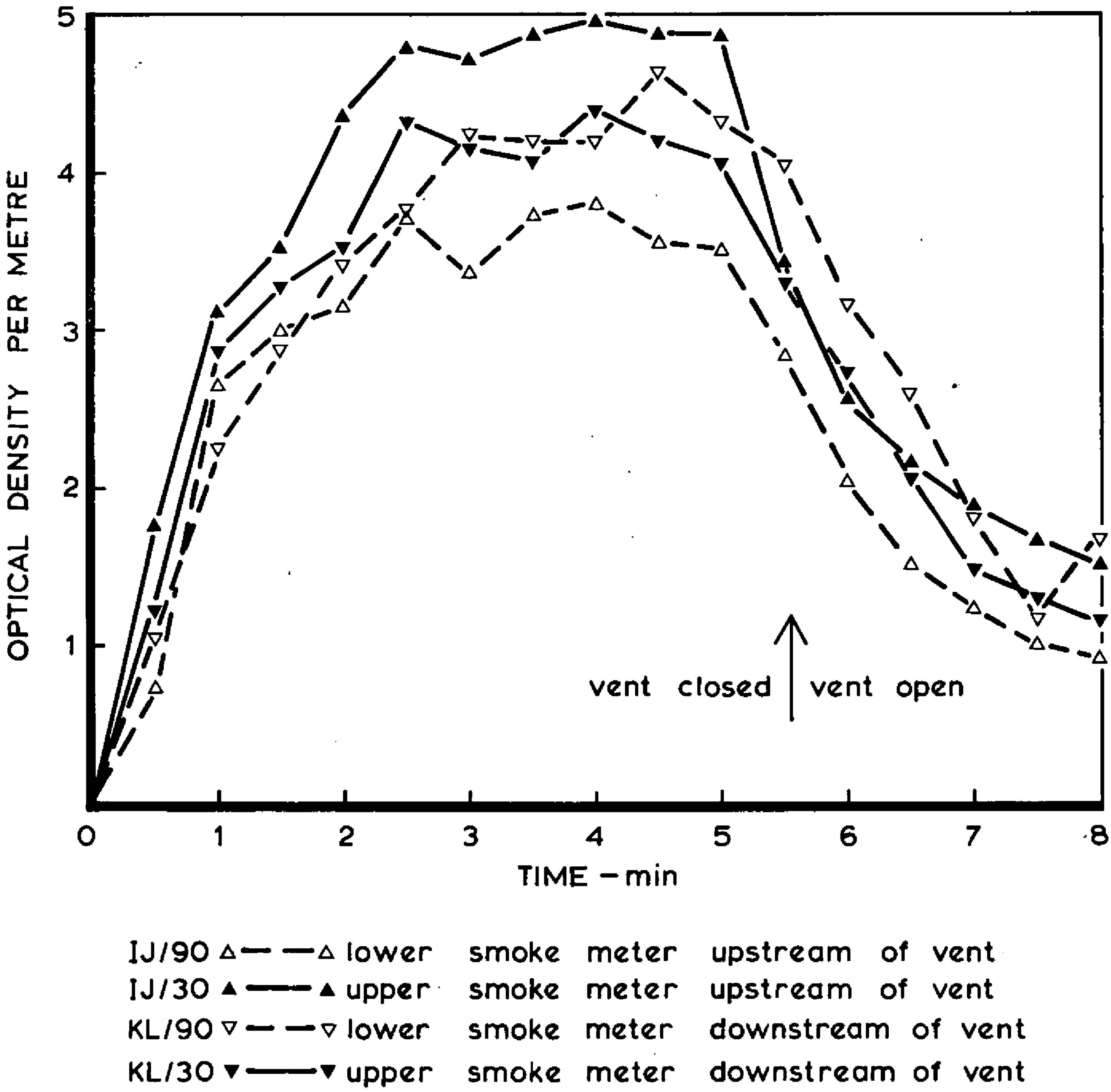


FIG. 17 OPTICAL DENSITY MEASUREMENTS FOR TEST 104

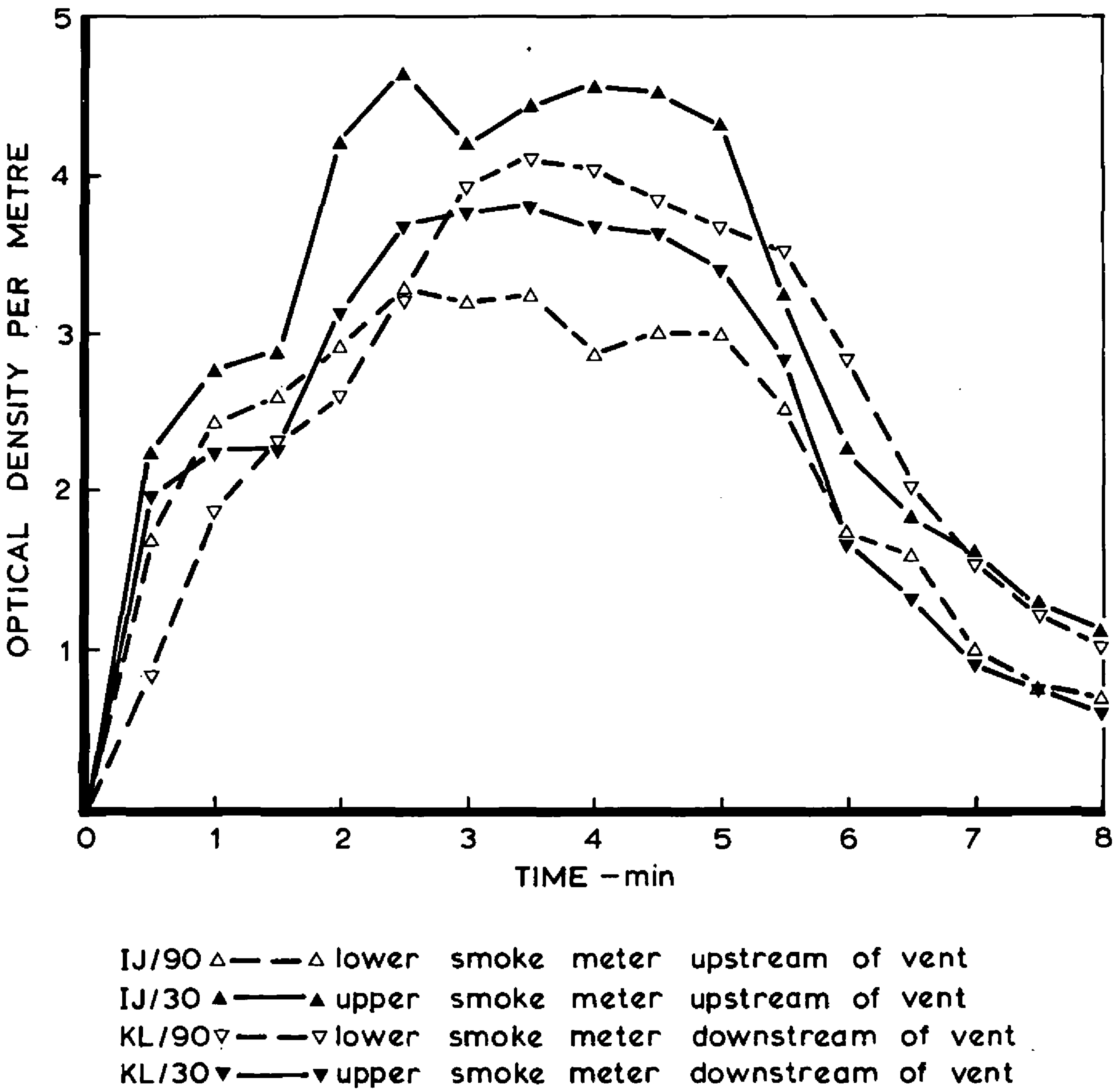
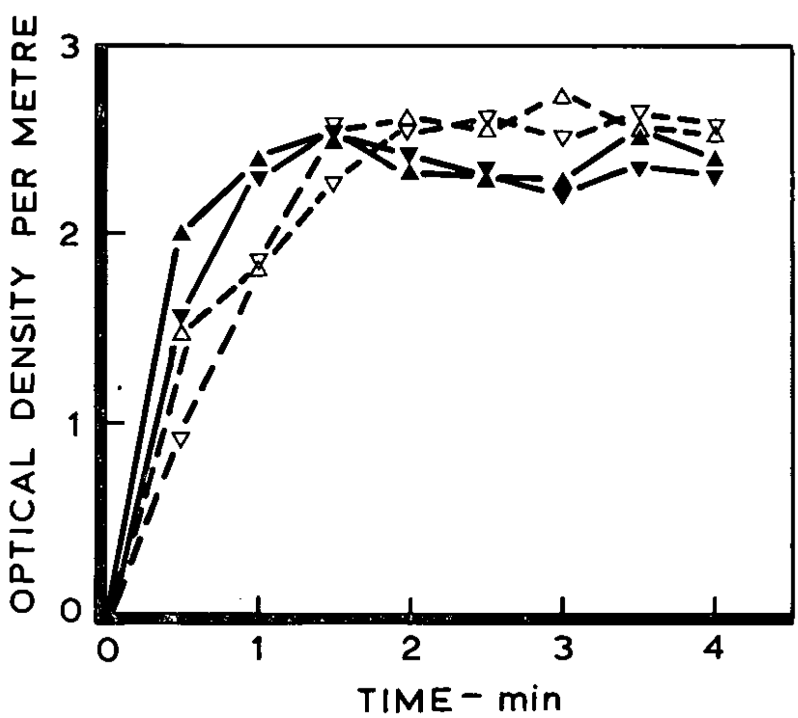


FIG. 18 OPTICAL DENSITY MEASUREMENTS FOR TEST 100



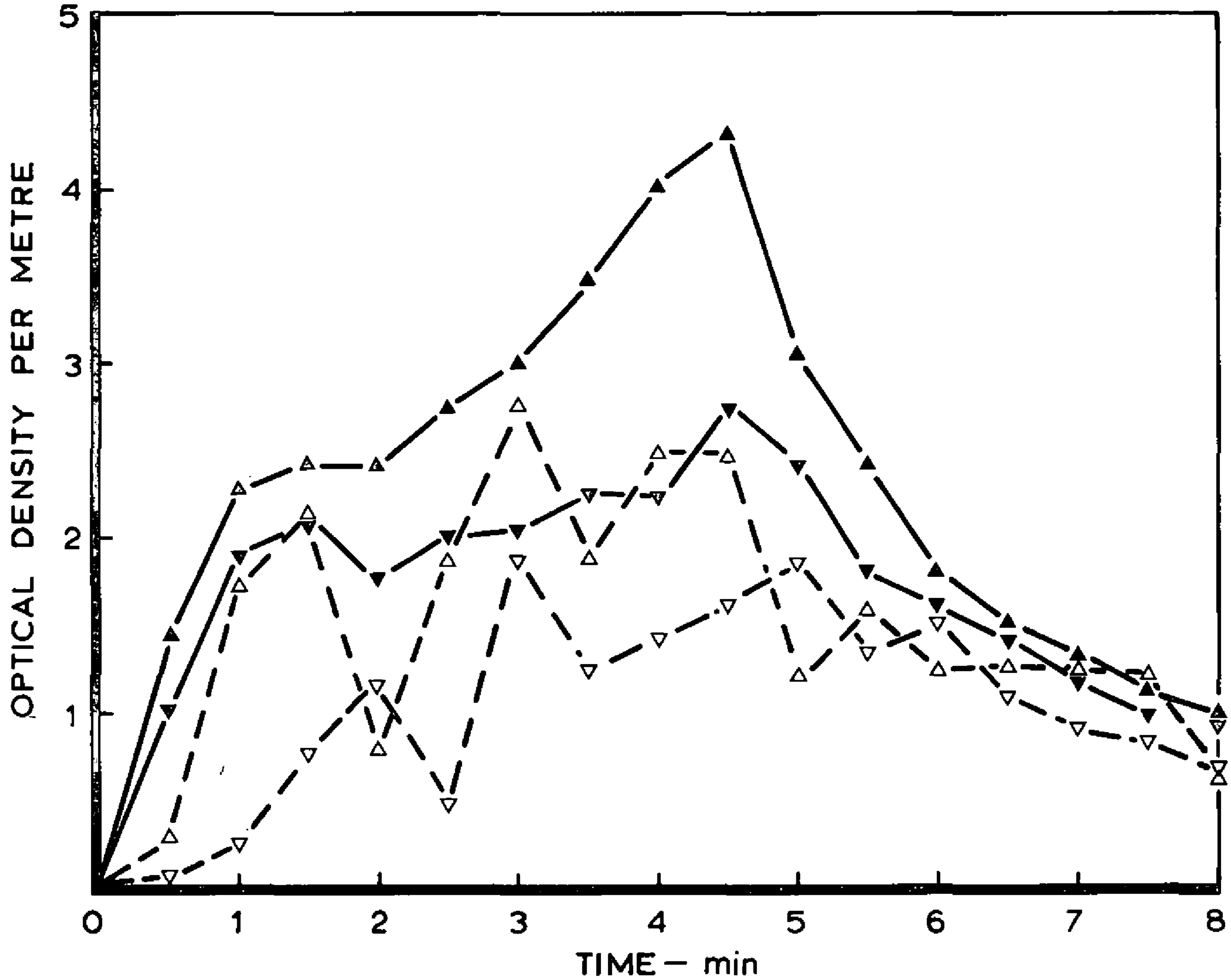
IJ/90 △ – – – △ lower smoke meter upstream of vent

IJ/30 ▲——▲ upper smoke meter upstream of vent

KL/90 ▽ – – – ▽ lower smoke meter downstream of vent

KL/30 ▼——▼ upper smoke meter downstream of vent

FIG. 19 OPTICAL DENSITY MEASUREMENTS FOR TEST 102



IJ/90 △— —△ lower smoke meter upstream of vent
IJ/30 ▲——▲ upper smoke meter upstream of vent
KL/90 ▽— —▽ lower smoke meter downstream of vent
KL/30 ▼——▼ upper smoke meter downstream of vent

FIG. 20 OPTICAL DENSITY MEASUREMENTS FOR TEST 108

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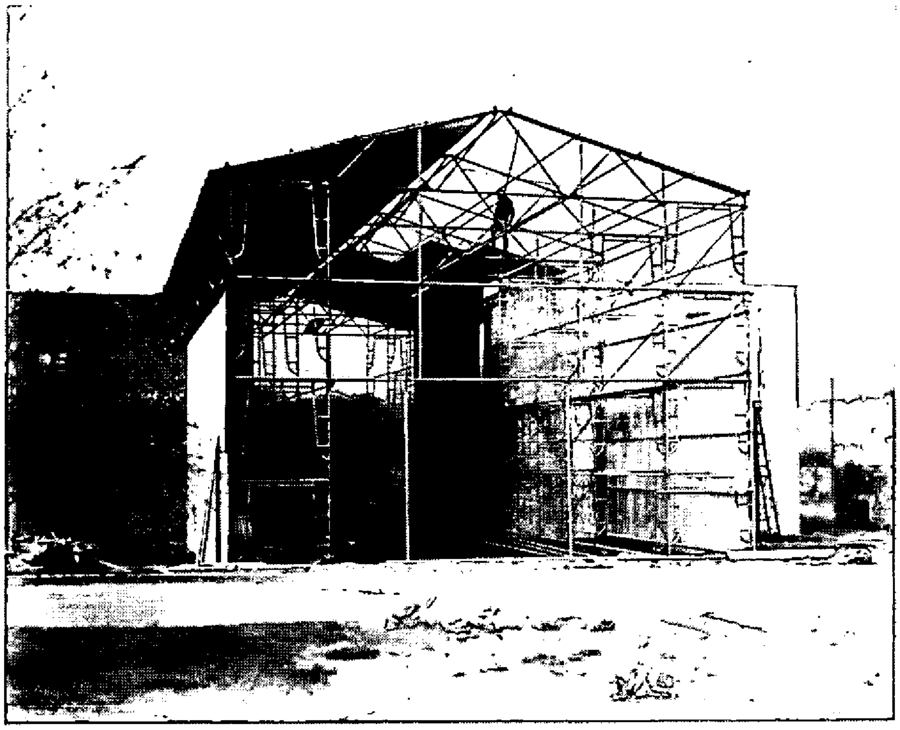

PLATE 1. ARCADE PARTLY ERECTED WITH FIRE COMPARTMENT IN BRICK BUILDING AT RIGHT

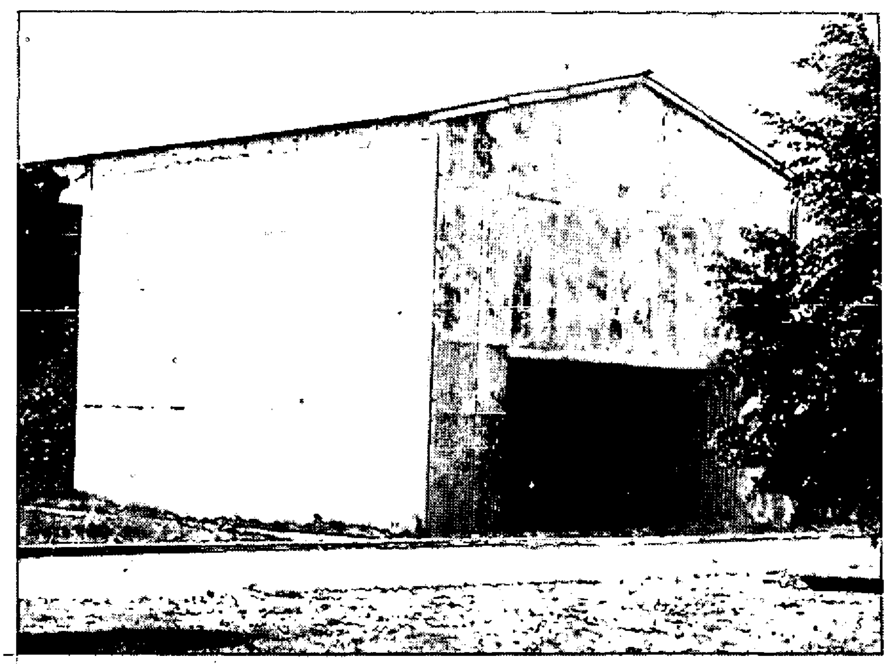

PLATE 2. ARCADE BUILDING COMPLETED SHOWING OPEN PANEL