Fire Research Note No. 854

SMOKE TRAVEL IN SHOPPING MALLS EXPERIMENTS IN CO-OPERATION WITH GLASGOW FIRE BRIGADE - PART 2

by

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December 1970

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SUMMARY

Following an earlier report which dealt with measurements of the rate of smoke spread and the depth of the smoke layer in experimental fires in a disused railway tunnel representing a pedestrian mall, data are now given for the temperature and opacity of the smoke layer.

The fall of temperature of the smoke layer as it passed along the tunnel could be accounted for entirely by convection and radiation transfer to the walls and floor of the tunnel so that there seems to have been little mixing of the layer with the cold air underneath, a factor which could also lead to a fall in temperature along the tunnel.

One smoke test was made outside the tunnel under a canopy. This emphasised the dependence of smoke spread on the wind conditions and showed that smoke logging to a low level could occur even when the smoke was not completely confined.

Values can be derived for the optical density of the smoke produced by burning a given weight of kerosine in a given volume, enabling an estimate of the visibility to be derived in other comparable situations where the burning rate and mixing conditions are known. The values obtained exhibit substantial variation so that the precision of an estimate of visibility is low, though sufficient for the present purpose. Such variation has a bearing on the problem of relating the behaviour of materials in a smoke test to some assumed real fire situation, a problem which itself falls outside the scope of this report.

KEY WORDS: Smoke, Spread, Shopping Mall, Tunnel, Visibility, Temperature.

DEPARTMENT OF TRADE AND INDUSTRY AND FIRE OFFICES' COMMITTEE

JOINT FIRE RESEARCH ORGANIZATION

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1. INTRODUCTION

A previous note[1] reported experiments in which the movement of smoke along a disused railway tunnel, representing a pedestrian mall, was measured visually. Analyses have now been made of the measurements of the optical density of the smoke and the gas temperature and these are reported in the present note.

A note is also included on a test carried out at the same time in the open air in which the movement of smoke under a canopy was followed.

2. EXPERIMENTAL ARRANGEMENTS FOR TUNNEL TESTS

The tunnel (Fig.1) and the standard fires* are described in detail in the first report[1]. For completeness a drawing of the cross-section of the tunnel is given here (Fig.2) and also graphs for the cross-sectional area and perimeter of a section of the tunnel above a horizontal line (Figs. 3 and 4)

The test conditions were:

<u>Test 1</u>. 1 tray burnt at the centre of the longer part of the tunnel

<u>Test 2</u>. 4 trays burnt as above

<u>Test 3</u>. 2 trays burnt as above

<u>Test 4</u>. One end (Dalmarnock) sealed by means of a tarpaulin sheet and one tray burnt 55 m (180 ft) from this end

<u>Test 5</u>. 2 trays burnt just SE of the ventilation shaft, both ends of the tunnel being open

<u>Test 6</u>. 'Canopy' test - see Section 4.

The temperature of the hot gases in the tunnel was measured by means of 0.38 mm dia. (28 SWG) thermocouples placed at four positions along the tunnel (Fig.1), on either side of the fire in tests 1 to 3. At each position a bank of five thermocouples at distances of 0.2 m (0.7 ft), 0.5 m (1.6 ft), 1.0 m (3.3 ft), 1.6 m (5.3 ft) and 2.3 m (7.5 ft) below the apex of the ceiling was set up. The thermocouples were mounted on a length of angle steel which was attached to the ceiling by a pin fired into the brickwork.

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*Each fire used 1, 2 or 4 trays 1.2 m (4 ft) square containing 10 gal kerosine.

The optical density of the smoke was measured at two positions (Fig.1) by means of photocell smoke meters which measured the transmission of a beam of light over a horizontal path length of 0.50 m. Sooting up of the glass windows through which the beam passed was prevented by the use of 'Everclean' windows[2]. At each position two smoke meters were set up, at 0.45 m ($1\frac{1}{2}$ ft) and 2.60 m (8.5 ft) from the apex of the roof.

3. RESULTS AND DISCUSSION OF THE TUNNEL TESTS (TESTS 1 to 5)

3.1. Optical Density of the Smoke

Some justification is perhaps first required for these measurements. If in a pedestrian mall the smoke-laden gases could always be maintained as a coherent layer under the ceiling and well above head height then clearly the optical density of the layer would be of no special importance and there would be no need to measure it during experimental work. Neither is the precise optical density of the layer important in a situation where substantial quantities of smoke are brought down to ground level, for example by the layer reaching a closed end or an open end with a cross wind, since this is a very serious situation where the visibility at ground level would be dangerously low with most kinds of smoke. This is a situation which must strenuously be avoided in the pedestrian malls.

There remains however, another class of danger, that in which there is some slight mixing of the smoke layer into the air beneath. The extent to which this can be tolerated will depend on the resulting visibility at ground level and this will in turn depend not only on the mixing conditions but also on the density of the smoke layer, so that it is necessary to collect information on this and on the optical density of the smoke produced by various materials.

The measurements of the optical density of the smoke are plotted in Figs 5 to 9 and the relation of Rasbash[3] is used to show the equivalent visibility.

In the first test the readings of the smoke meters at equal distances on both sides of the fire are in good agreement and give an optical density in the region of 0.6, corresponding to a visibility of about 1.3 m (4.3 ft), until the fuel burnt out, when the readings dropped fairly sharply to a lower level. At about the time when the fuel burnt out the reading of one of the lower smoke meters which had been indicating virtually no obscuration, rose for a short period to a reading nearer that of the upper meter at that time. The temperature records show that the temperature of the gases near the upper smoke meters fell substantially at about this time. The effect of a lowering of the smoke level at the end of the fire was noticed in Japanese tests[4] in a car park and is due to the mixture of hot gases containing less and less smoke into the smoke layer as the fire dies down.

As is entirely to be expected from the visual observations[1] the readings show that dense smoke hardly extended down to the level of the lower smoke meters, 2.6 m ($8\frac{1}{2}$ ft) from the ceiling,in this test.

As the size of the fire (i.e. the number of trays used) was increased so the smoke became denser (Figs 6 and 7) not only at the upper but particularly at the lower position. Indeed Fig.6 shows that with 4 trays the optical density of smoke 2.6 m ($8\frac{1}{2}$ ft) from the ceiling was of the order of half that at the upper position long before the fire had burnt out, whilst as we saw above, with only one tray the density at the lower position was generally negligible.

At some times the smoke was so dense in Test 2 that the reading of the photocell fell to a value indistinguishable from zero on the recorder chart. In view of the accuracy of the recorder this corresponds to a visibility of less than 0.6 m (2 ft) and thus only a lower limit can be given for the optical density of the smoke for part of this test.

As in Test 1 there is good agreement in the readings given on both sides of the fire at the upper position for Tests 2 and 3, whilst there are substantial differences in the readings at the lower position. This is to be expected since the lower meters are not far from the bottom of the smoke layer, so that their readings should be sensitive to the depth of the layer and to any thin smoke under the dense layer.

With tests 4 and 5 the fire was lit at an end of the tunnel and the curves for the readings at positions A and D are similar but with a delay corresponding to the time taken for the smoke to travel between the positions.

From the data it is possible to derive values for the quantity of smoke produced by kerosine so that the results of these tests can be related to other materials. The 'quantity' of smoke can be expressed in terms of its obscuring power. A convenient measure, which readily permits calculation of visibility in other situations where the rate of burning and the mixing conditions are known, is the optical density (D_S) produced along a 1 m path length by burning 1 gram of fuel in a stirred volume of 1 cubic metre. Two methods have been used to derive the standard optical density D_S. In the first (Method 1) the volume of smoke-laden gases produced by the fire and travelling past the smoke meter is taken as the product of the rate of advance of the smoke 'nose' and the cross sectional area of the tunnel above the observed level of the bottom of the layer of dense smoke. In the second the temperature of the gases is used to derive the dilution and hence the volume of gases passing the smoke meter.

Details of the calculations are given in Appendix 1.

Values obtained for the standard optical density (D_S) are given in Table 1. Clearly there is a substantial spread in these values and no great precision can be claimed. However it is significant that two entirely different and basically very simple methods of estimating the flow in the smoke-laden gas layer have yielded values for D_S which whilst not identical are not dissimilar.

Values of D_S given by method 2 are on the whole higher than those of method 1; a similar, but larger, bias has also been found in comparable measurements of D_S in the arcade facility at Boreham Wood[10]. These biases must be due to a difference in the gas flow given by the two methods since the optical density readings are common to both, and presumably arise because the methods are based on too great a simplification, yet without further studies of the processes governing the spread of the smoke layer or alternatively a much more comprehensively instrumented series of similar tests - and this is not practicable - it is hard to improve on these values, or eliminate the bias.

The spread in the values of D_S obtained even with the fuel burnt as far as possible identically from one test to another means that in comparable situations the visibility could not be predicted with high accuracy - some uncertainty must be accepted. This does not mean that it is futile to try to derive levels of optical density or visibility in a real or a large scale situation from measurements of D_S made in some other situation, possibly in a small scale test, but that it is not worth while to strive for a high precision, which in any case would not be necessary, and that any factors which have a small effect on smoke production can be neglected completely.

With regard to the question of whether the results are affected by changes in the smoke after its generation it can be said firstly that the data quoted should be valid for real situations because the size of the fire and the dimensions of the tunnel are representative of the real situation. Furthermore, with the possible exception of test 2, the values of standard optical density do not seem to depend markedly on the temperature of the layer at the point of measurement (Table 1) suggesting that over the range of measurement the smoke is stable and would not be affected much by further cooling, for example by agglomeration or condensation.

TABLE 1 - 'Standard' Optical Density of Kerosine Smoke

The optical density per metre produced by burning 1 gram of kerosine in a stirred volume of 1 cubic metre

Test number	Method 1 (Volume flow of smoke layer derived from direct observation)	Method 2 (Volume flow of smoke layer derived from temperature)	Peak temperature rise in smoke layer deg C
1	0.3_0	0.4_0	75
2	$> 0.5_7$	$> 0.5_9$	175
3	0.5_5	0.5_4	115
4	0.3_0	0.4_9	55
5	0.4_8*	0.4_6	45
Mean	0.4_3	0.5_0	

*Result possibly affected by air entering ventilation shaft

Measurements made in the arcade facility at Boreham Wood of the smoke produced under well-ventilated fire conditions by various materials have shown that kerosine produces more smoke than an equal weight of wood but less smoke than foam rubber and expanded polystyrene. These will be reported in detail separately[10].

Thus in this respect the tunnel experiments represent a fairly bad, but by no means a worst situation.

3.2. Temperature measurements

Some typical temperature profiles are shown in Fig.10 together with the observed depth of the smoke layer. These show that the temperature of the layer is fairly uniform over most of its thickness, only falling towards the bottom of the layer. A number of temperature profiles were obtained for all the tests in the tunnel and the observed depth of the dense smoke layer plotted on them. There was naturally some variation in the relative position of the bottom of the layer (Fig.11) but an average of about 40 profiles gave a temperature for the observed bottom of the dense smoke layer in the region of 40-50 per cent of the peak temperature of the profile.

Fig.10 illustrates the increase in thickness and in temperature of the layer with increasing size of fire.

The temperature in the upper part of the layer rises to a high value immediately after the arrival of the smoke 'nose' but usually then increases slightly to a maximum value (Figs 12 and 13) before falling as the fire dies down. This gradual rise is due to the heating up of the tunnel walls and ceiling and the consequently decreasing heat loss from the layer.

The peak temperature in the upper part of the layer falls with increasing distance from the fire (Fig.14). The logarithm of temperature rise (Θ) falls linearly with distance from the fire (X). This implies that $\frac{d\,\Theta}{d\,X} \propto -\,\Theta$ which is consistent with any one or a combination of the three following processes:

(a) heat loss by turbulent forced convection

(b) heat loss by radiation (since the temperature range is not large)

(c) temperature decreasing due to a constant rate of mixing of cool air into the layer.

The data in Fig 14 refer to rather large distances from the fire but can be plotted with temperature data from other tests for short distances in Fig.15. The departure of the data of tests 4 and 5 from a linear relation connecting them with the data for test 3 may well be due to the importance of radiation transfer from the gases (see later), since over a temperature interval as large as this the radiation heat transfer coefficient cannot be taken as even approximately constant.

However there are also some differences in the experimental conditions. For example test 4 with one tray burnt 55 m from a sealed end might give a similar flow of hot gases along the main part of the tunnel as test 3 where a two tray fire allowed gases to pass in both directions but some heat loss is bound to occur in test 4 by circulation of gases in the region between the fire and the sealed end and so somewhat lower temperatures might be expected in the gases flowing along the main part of the tunnel.

Table 2 gives the values obtained for the heat loss from the layer of hot gases, expressed as a rate of heat loss per metre length per deg C excess temperature. These values have been derived from the slopes of the lines in Figs 14 and 15. The mass flow of gases has been obtained from the cross sectional area of the layer above the

TABLE 2 Measured heat losses

Test number	Number of trays	Rate of heat loss per unit length of tunnel $W\ m^{-1}\ deg\ C^{-1}$
1	1	52
2	4	114
3	2	100
4	1*	87
5	2	95

*One end of tunnel sealed

TABLE 3 Measured and calculated heat losses for Test 3

Measured heat loss $W\ m^{-1}\ deg\ C^{-1}$		100
Calculated heat losses $W\ m^{-1}\ deg\ C^{-1}$	Forced convection	25
	Radiation from CO_2 and water vapour	60 } Combined* 200
	Radiation from smoke particles	190 }
	Total	225

*Combined using the relation given in Appendix 2.

TABLE 4 Log of canopy test

Time	Observations
0	Fire lit
30 s	Nose of smoke travelled 30 m (100 ft)
40 s	Nose of smoke travelled 40 m (130 ft)
50 s	Nose of smoke travelled 50 m (165 ft)
55 s	Nose of smoke travelled 60 m (200 ft)
1 min 40 s to 3 min	Thick smoke down to platform level up to 40 m
3 min 45 s to 4 min 30 s	Smoke cleared from under canopy, emerging in a plume from in front of fire
6 min	Smoke now mostly under canopy again
7 min	Largely clear under canopy
7 min 30 s	Less smoke being produced. Fire dying down

observed layer depth (given in ref.1) assuming that the layer velocity is equal to the velocity of advance of the smoke 'nose'. The temperature rise of the surface of the tunnel walls and ceiling* has also been neglected since calculation[5] has shown that in the rather short heating times (a few minutes) of these experiments the rise in temperature of the wall surface was in the order of only 8 per cent of the gas temperature rise.

Table 3 compares the observed heat loss rate for test 3 with calculated values. The convection loss was obtained from the conventional relation for turbulent forced convection[7]:

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.4}$$

where Nu is the Nusselt number

Re is the Reynolds number

Pr is the Prandtl number

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*For this calculation the thermal constants of the brickwork were taken as:

Thermal conductivity	=	$1.13\ W\ m^{-1} deg\ C^{-1}$
Density	=	$2300\ kg/m^3$
Specific heat	=	$8.4 \times 10^2\ J\ kg^{-1} deg\ C^{-1}$
Diffusivity	=	$6 \times 10^{-7}\ m^2/s$

These are for engineering bricks with 5 per cent moisture[6].

and taking the area of the tunnel in contact with the layer as the transfer area.

The radiation from carbon dioxide and water vapour was obtained[7] taking, as before, the flow of gas in the layer to be the product of the cross-sectional area of the layer and the speed of the smoke 'nose', with a density obtained from the temperature measurements.

The emissivity for the radiation from the smoke particles was derived from the measured optical density of the smoke layer, assuming that the extinction cross section of the smoke particles was similar for infra-red and for visible wave lengths. However, it is likely that the extinction cross-section of smoke particles is substantially smaller for infra-red than for visible wave lengths* and hence the emissivity and the radiation transfer may be substantially over estimated.

If in Table 3 we compare the calculated heat loss terms with the measured total heat loss we see that the convection term and the CO_2 and water vapour radiation term are together nearly equal to the measured heat loss term, suggesting that the term for the radiation from the smoke particles is much too high. There is some imprecision in the above terms due to experimental error and to difficulties in definition but it seems clear that the fall in gas temperature could well be explained entirely in terms of convection and radiation heat losses so that the cooling due to mixing and hence the mixing itself is likely to be very small indeed.

4. SMOKE SPREAD UNDER CANOPY (TEST 6)

After the experiments in the tunnel, one test was made to observe the spread of smoke under a canopy, following a report of unusually bad smoke logging in an area between two buildings, each of which had a canopy projecting into the space between them.

A suitable site was found in Bridgeton Cross Station (Fig 16). One 4 ft square tray containing 10 gal kerosine, covered by an 8 ft square spreader as in the tunnel experiments was used and was placed at track level between a wall and a platform, about 4 ft below platform level and about 16 ft below the ceiling, which consisted of shallow vaults arranged

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*The smoke particles are probably in the size range 1 to 0.03μ [8] and Fig.3.8 of ref.[9] shows that for this size range the extinction cross section of water droplets decreases with increasing wave length.

at right angles to the direction of the track. There was a wind in the order of 2 m/s (7 ft/s) blowing in the direction of the railway track. A brief log of the test is given in Table 4.

Immediately after ignition the smoke was almost entirely contained under the canopy and travelled with the wind (and not against it) at a speed of about 1.1 m/s (3.5 ft/s), eventually extending more than 60 m (200 ft) under the canopy with thick smoke down to platform level for the first 40 m (130 ft). Because of changes in the wind this pattern of smoke flow alternated with a situation in which the space under the canopy was practically clear, the smoke emerging directly from under the canopy and rising in a plume without travelling along sideways. These patterns of smoke alternated several times during the life of the fire - about 8 minutes.

It is not easy to draw quantitative conclusions from a single test of this kind but the experiment does demonstrate that the path of the smoke-laden gases from a fire depends very much on the wind conditions. It is also clear that the smoke does not necessarily have to be completely confined in order to give smoke logging to a low level.

5. CONCLUSIONS

1. The measurements lead to values for the 'standard' optical density (D_S) of kerosine of between 0.3 m^{-1} and 0.5 m^{-1}. This is the optical density per metre produced by 1 gram of kerosine burned in a stirred volume of 1 cubic metre under the conditions obtaining in the tests reported here.
2. There is substantial variation in the values obtained for D_S from the individual tests and also a difference between values given by two different methods for estimating the flow of gases so that in applying this data to estimate optical density and hence visibility in other situations no great precision can be expected, nor is it worth taking into account factors having only a small influence on the smoke.
3. The temperature measurements support the visual measurements of layer depth and the predictions of the increase of thickness of layer with size of fire.
4. The fall of temperature of the layer as it travels along the tunnel appears to be largely due to a heat loss by radiation and convection rather than to a mixing of cold air into the layer. The heat loss per unit length of tunnel can be derived from the temperature measurements.
5. There appears to be very little mixing of air into the smoke layer.
6. The 'canopy' test (Test 6) outside the tunnel showed that the path taken by smoke-laden gases depends very much on the wind conditions and that smoke does not necessarily have to be completely confined in order to give smoke logging to a low level.

6. ACKNOWLEDGMENTS

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Messrs H.G.H.Wraight, P. Collinson, E.Dale and J.A.Gordon of the Fire Research Station assisted with the experimental work associated with the Joint Fire Research Organization measurements.

7. REFERENCES

(1) HESELDEN, A.J.M. and HINKLEY, P.L. Smoke travel in shopping malls. Experiments in co-operation with Glasgow Fire Brigade - Part 1. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization, Fire Research Note No.832 July 1970.

(2) CROSSE, P.A.E., LUCAS, D.H. and SNOWSILL, W.L. The design of an 'everclean window' for the observation of the optical density of flue gas. Journal of the Inst. of Fuel. 34, (1961) p.503.

(3) RASBASH, D.J. Smoke and toxic products produced at fires. Trans. J. Plastics Inst. Jan.1967 p.55

(4) Report of fire test in underground car park in March 1966. Fire Prevention Committee, Tokyo Metropolitan Fire Brigade, 1966.

(5) CARSLAW, H.S. and JAEGER, J.C. Conduction of heat in solids. Clarendon Press, Oxford, 1st Ed. 1947, p.53 and Fig.7.

(6) A Guide to Current Practice. Institution of Heating and Ventilating Engineers, 1959.

(7) FISHENDEN, M. and SAUNDERS, O.A. An introduction to heat transfer. Clarendon Press, Oxford, 1st Ed. 1950.

(8) Air Pollution Handbook. Ed. by P.L. Magill et al. McGraw Hill Book Co.,1956.

(9) MIDDLETON W.E.K. Vision through the atmosphere. University of Toronto Press, Toronto, 1952.

(10) HESELDEN, A.J.M. Fire problems of pedestrian precincts. Part I. The smoke production of various materials. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organisation Fire Research Note No. 856.

(11) BEÉR, J.M., and CLAUS, J. The 'traversing' method of radiation measurements in luminous flames. J. Inst. Fuel. 35 (1962) p.437.

APPENDIX 1

Details of methods for calculating the standard optical density of the smoke

METHOD 1

Let A be the cross-sectional area of the layer of smoke laden gases(m^2)

V be its velocity, assumed uniform over the whole cross section of the layer and equal to that of the 'nose' of the smoke layer (m/s)

R be the rate of burning of the kerosine (kg/s)

D be the optical density of the smoke layer assumed uniform over the whole cross-section of the layer (path length 0.5 m)

S be the weight of smoke (g) produced by 1 g of fuel.

The fraction of light (T) transmitted by a smoke layer is, by Beer's Law:

$$T = e^{-lcB} \qquad (1)$$

where l is the path length (m)

c is the concentration of the smoke (kg/m^3)

B is a constant which depends on the nature of the smoke particles

The optical density is $- \log_{10}T = \frac{lcB}{2.303}$ (2)

For the smoke in the tunnel

$$D = \frac{0.50\ c\ B}{2.303} \qquad (3)$$

The mass of smoke flowing in one direction is

$$\frac{SR}{2} = VA. \frac{2.303D}{0.50B} \quad kg/s \qquad (4)$$

The standard optical density D_S, produced by 1 g of fuel burned in a volume of 1 m^3 and with a path length of 1 m is, from equation (2)

$$D_S = \frac{SB}{2303}$$

$$= \frac{DVA}{250\ R} \quad \text{from (4)}$$

METHOD 2

We use the same notation as for Method 1, with the following additions:

q is the net calorific value of kerosine J/kg

c is the specific heat of air $J\ kg^{-1}\ K^{-1}$

M is the mass flow rate of hot gases past the section of the tunnel at which smoke density was measured kg/s

ρ is the density of the hot gas layer at the measuring point kg/m^3

θ_F is the temperature rise above ambient of the ceiling layer immediately above the centre of the fire (obtained by extrapolation of the temperature records)

We assume that mixing of air into the layer can be neglected (Section 3.2) If we assume that about $\frac{1}{4}$ of the heat generated by the fire is lost by radiation from the flames* then considering the flow in one direction:

$$\frac{3}{4}\left(\frac{1}{2}\ R\ q\right) = Mc\ \theta_F \qquad (5)$$

Also the measured optical density

$$D = \frac{0.50}{2.303} \cdot \frac{R\ S\ \rho}{2M} \cdot B \qquad (6)$$

and

$$D_S = \frac{SB}{2303}$$

$$= \frac{3}{2000}\ D\ \frac{q}{\rho\ c\ \theta_F}$$

by substituting for SB from equation (6) and R/M from equation (5).

*Values in this region have been obtained at the JFRO for various fuels.

APPENDIX 2

Combination of luminous and non-luminous emissivities

The total effective emissivity (E_T) of a flame containing both radiating soot particles and radiating gases has been given by Beér and Claus[11] as

$$E_T = 1 - (1 - E_G) \exp (- K \int C dl)$$

where E_G is the emissivity of the radiating gases

K is the extinction coefficient of the soot particles

C is the soot concentration at a point

dl is an element of path length

Using this relation to obtain the total effective emissivity of a layer of hot gas containing smoke particles, we can equate E_G to the combined emissivity of the carbon dioxide and water vapour and $K \int C\, dl$ to $l_E\ cB$

where l_E is the equivalent path length (m) and c

and B are as in Appendix I, e.g. see equation (1). The product cB was obtained from equation (3) of Appendix I.

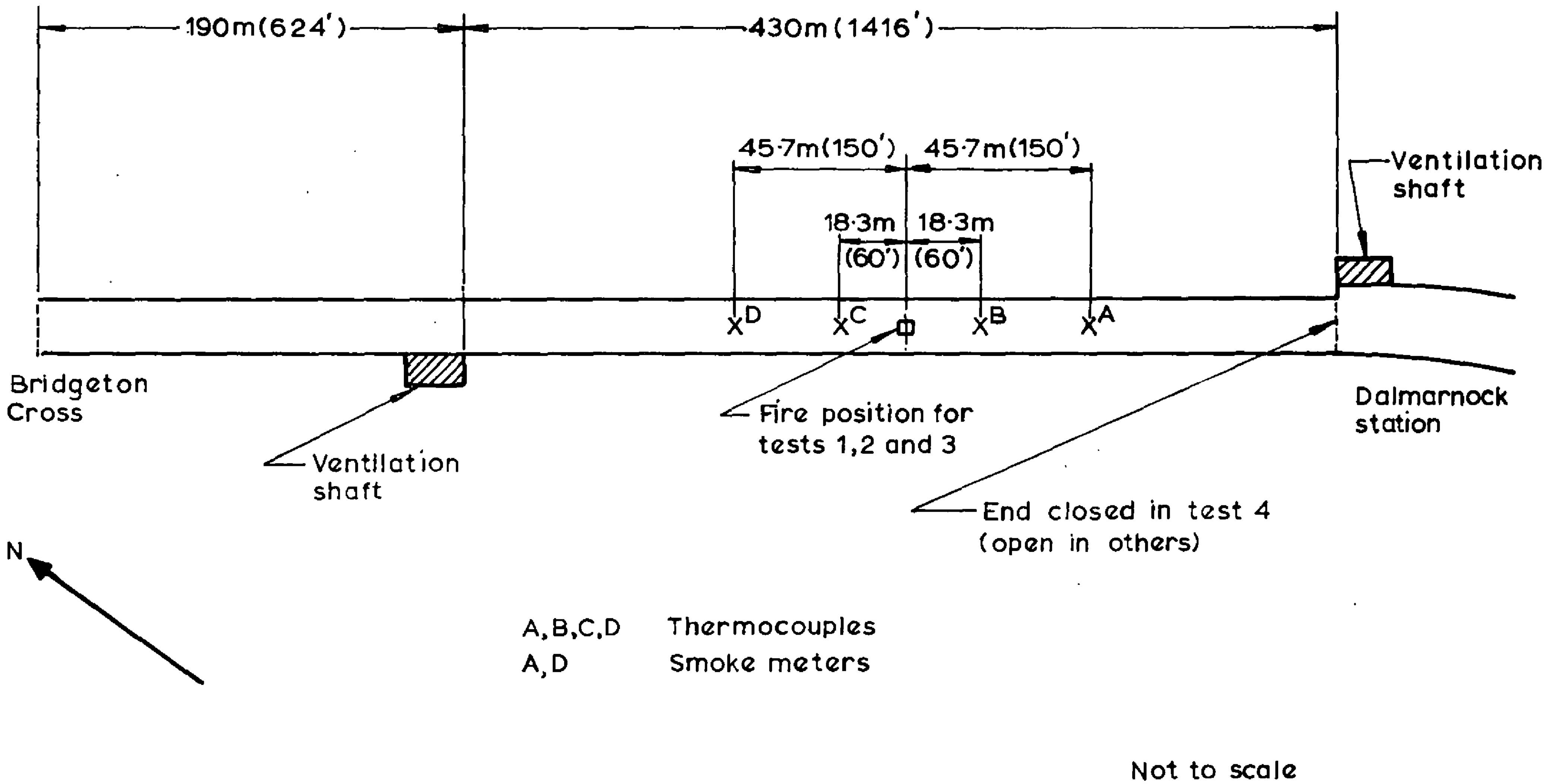


FIG.1 SCHEMATIC PLAN OF TUNNEL

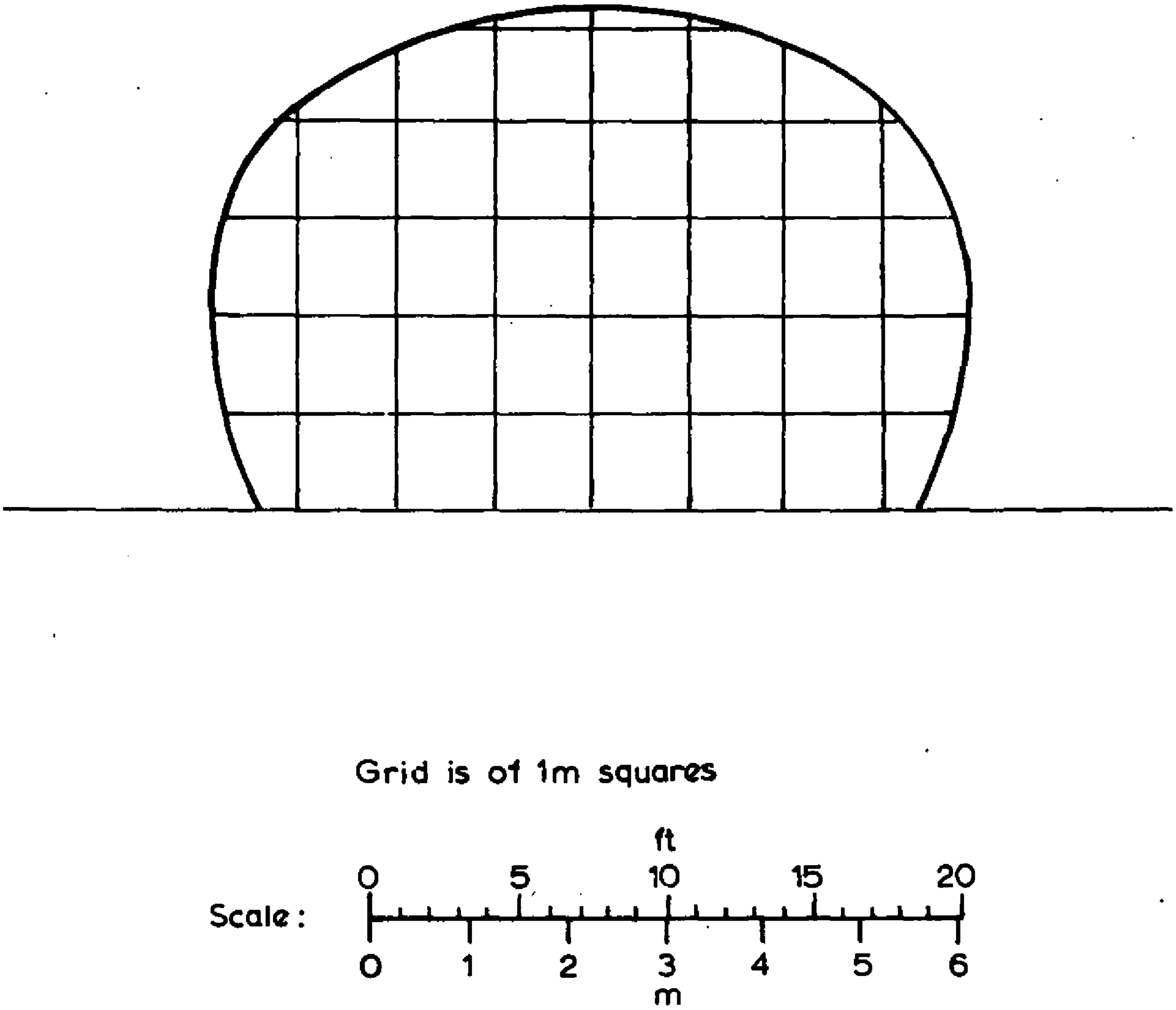


FIG. 2 CROSS-SECTIONAL SHAPE OF TUNNEL

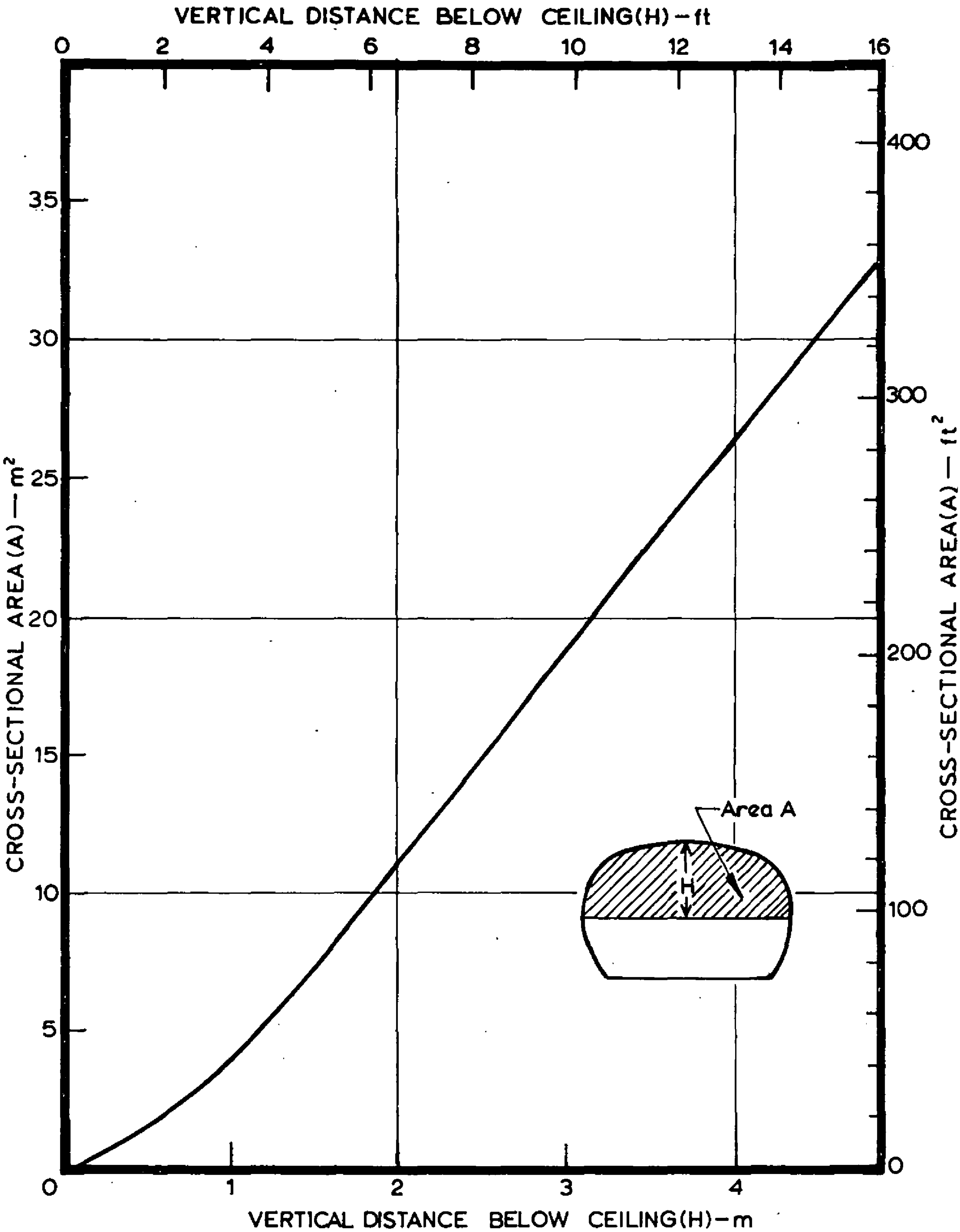


FIG.3 CROSS-SECTIONAL AREA OF LAYER

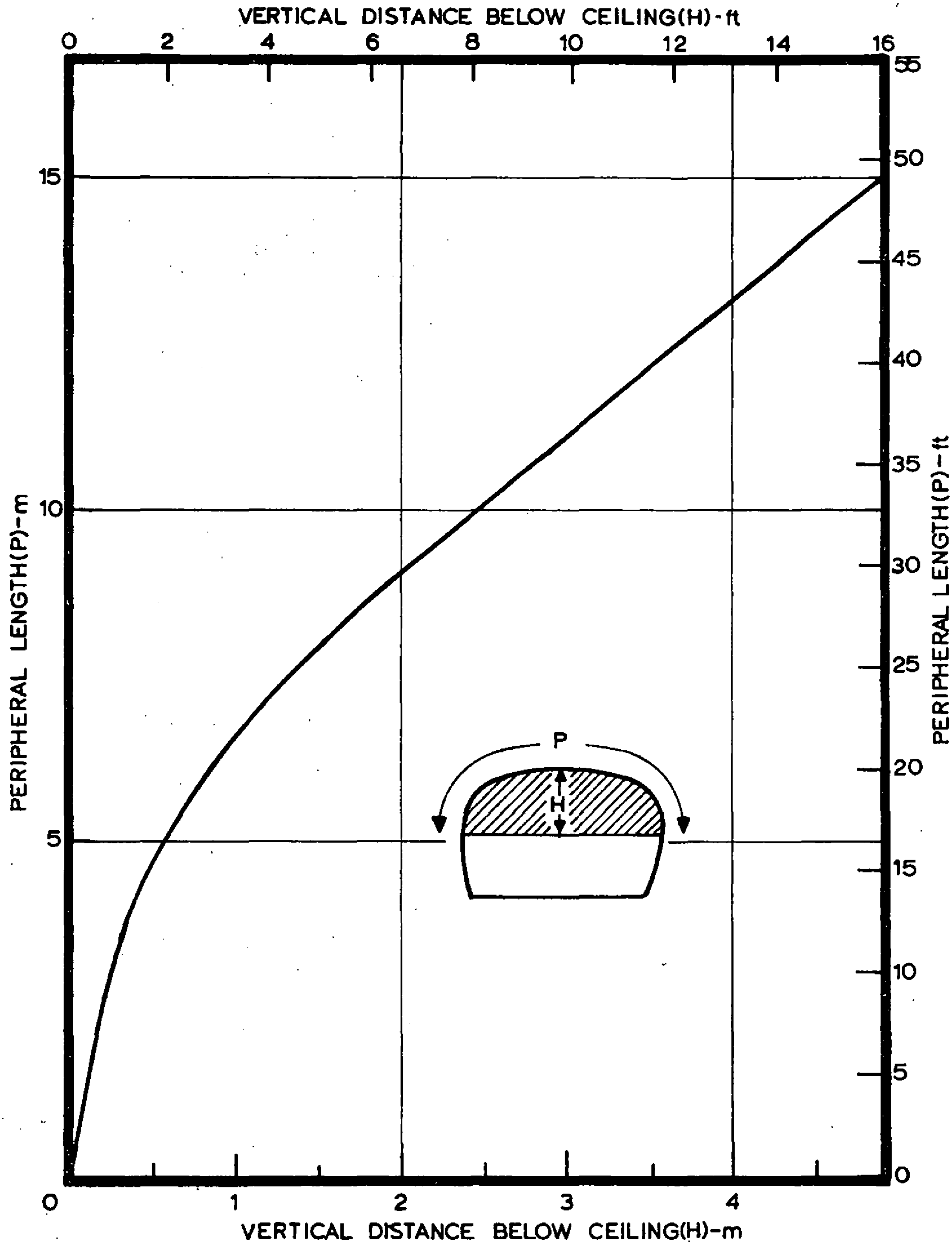


FIG. 4 PERIPHERAL LENGTH OF LAYER

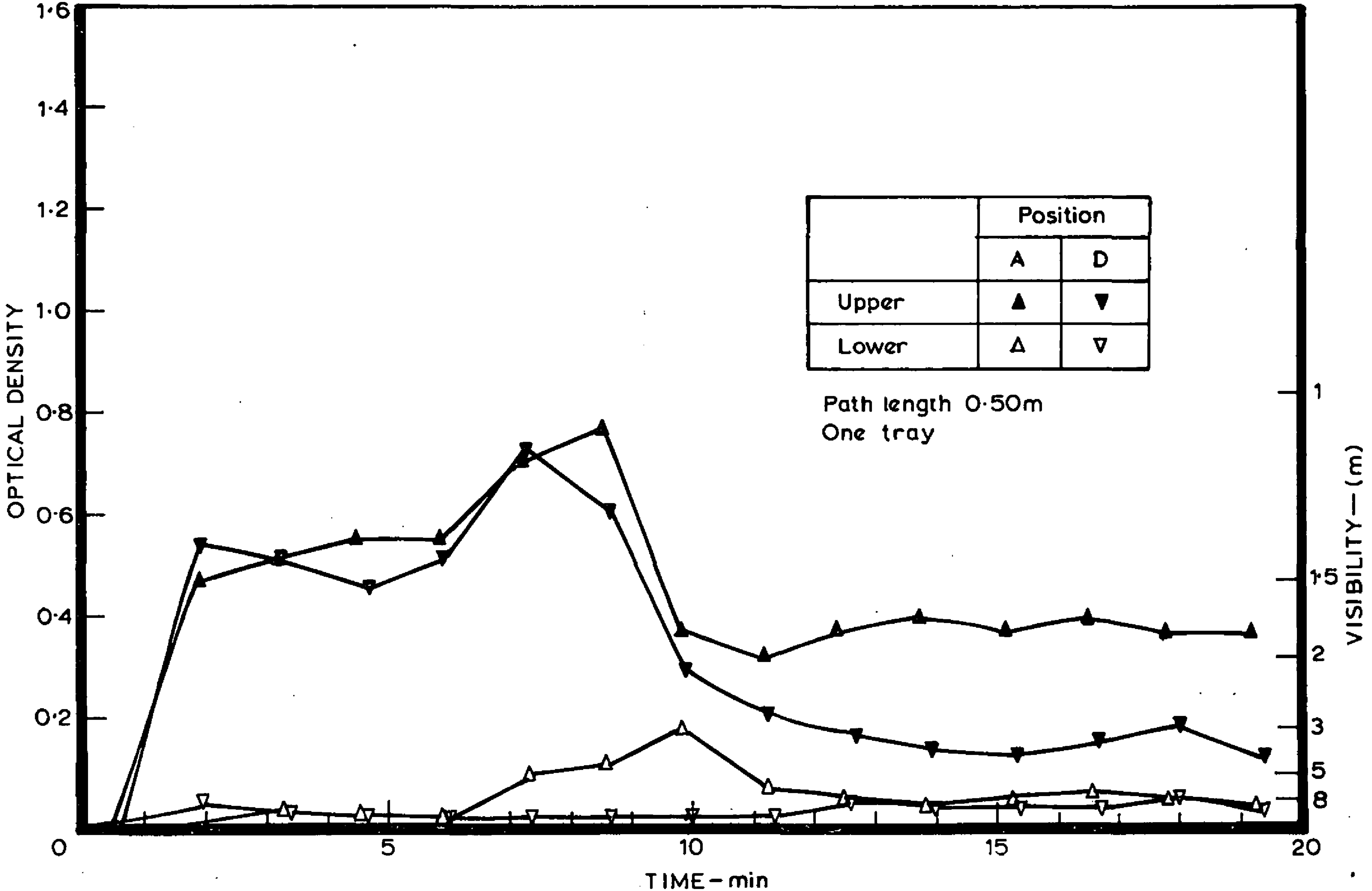


FIG.5 OPTICAL DENSITY (TEST No.1)

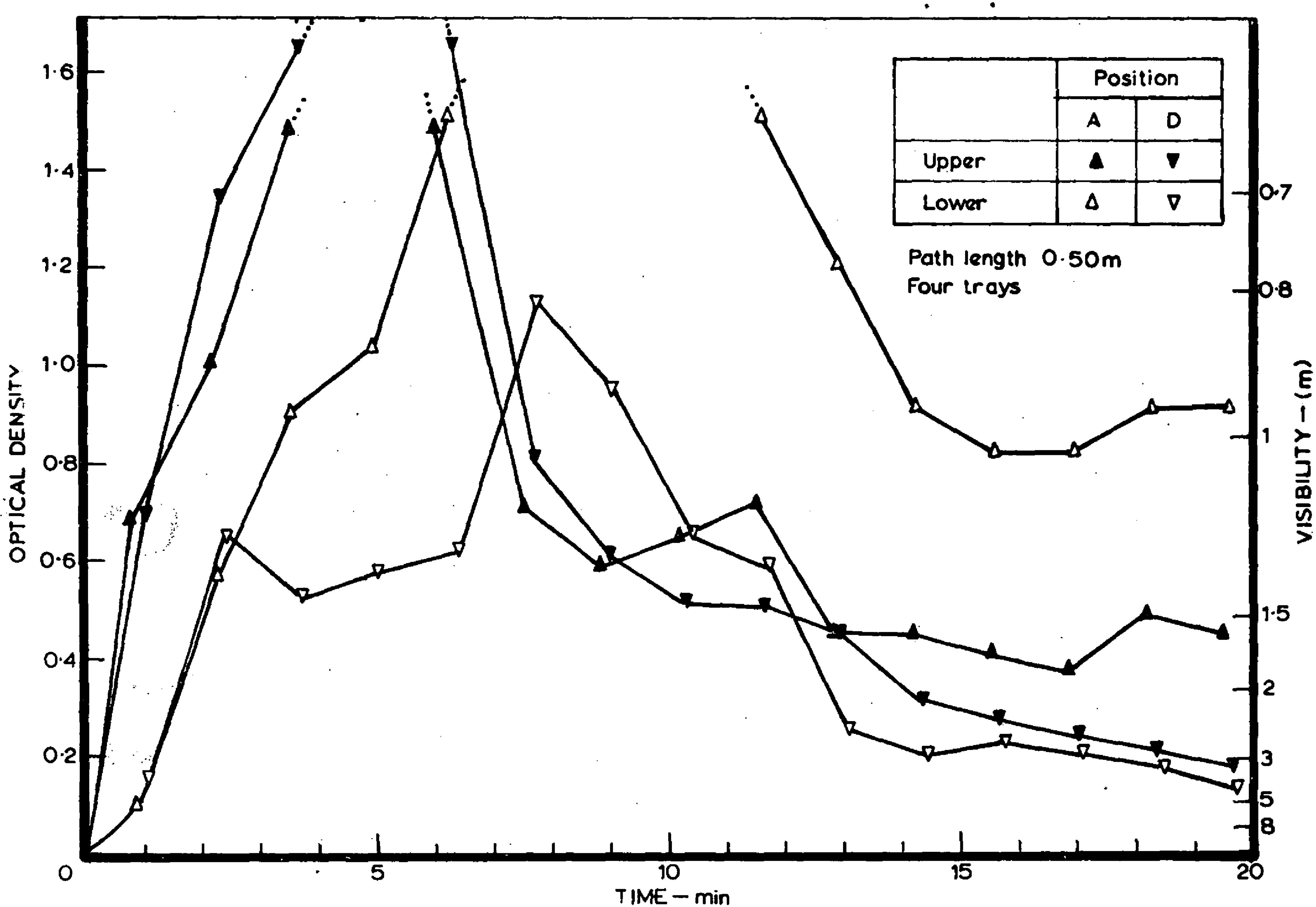


FIG.6 OPTICAL DENSITY (TEST No. 2)

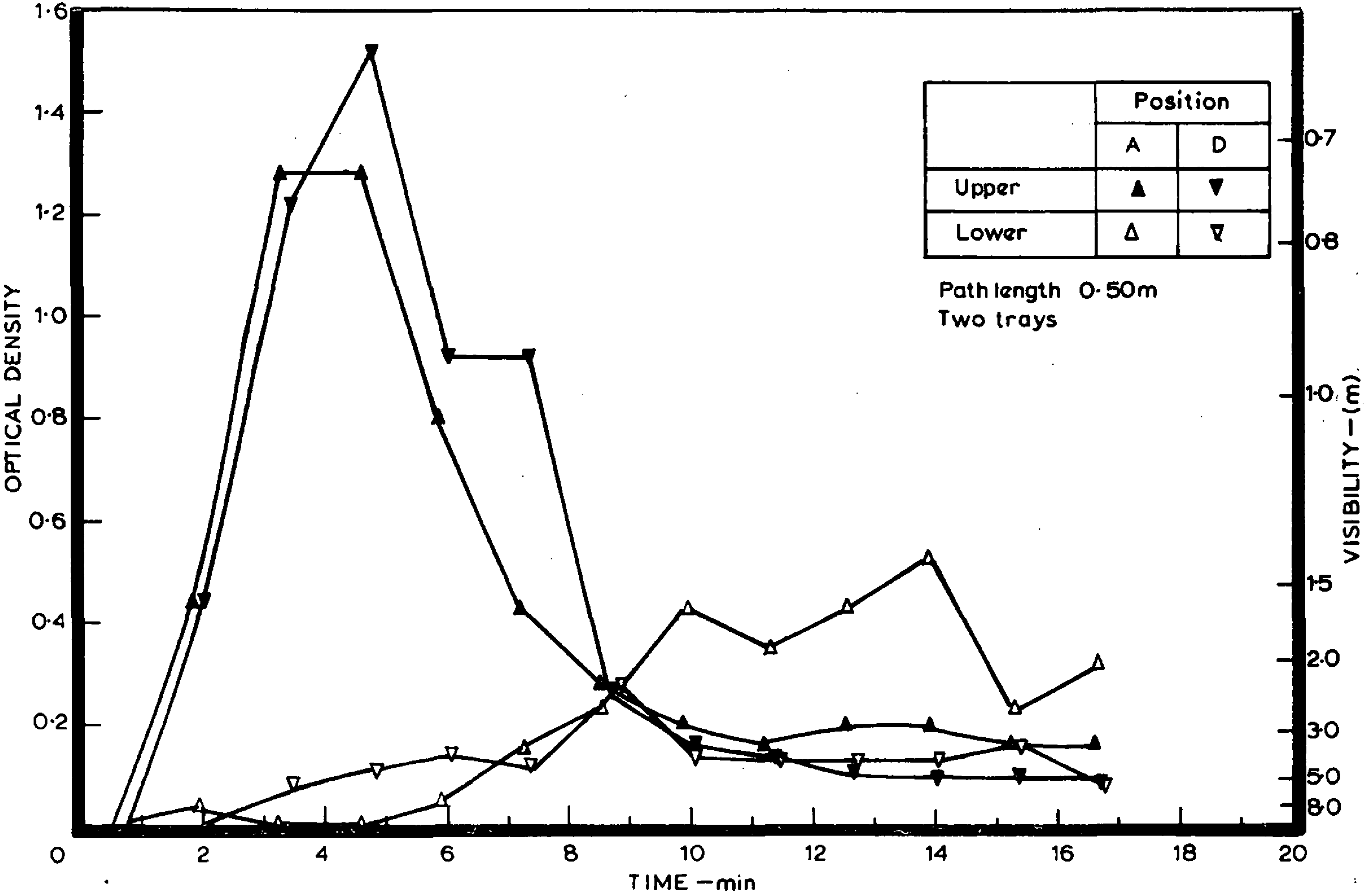


FIG. 7 OPTICAL DENSITY (TEST No.3)

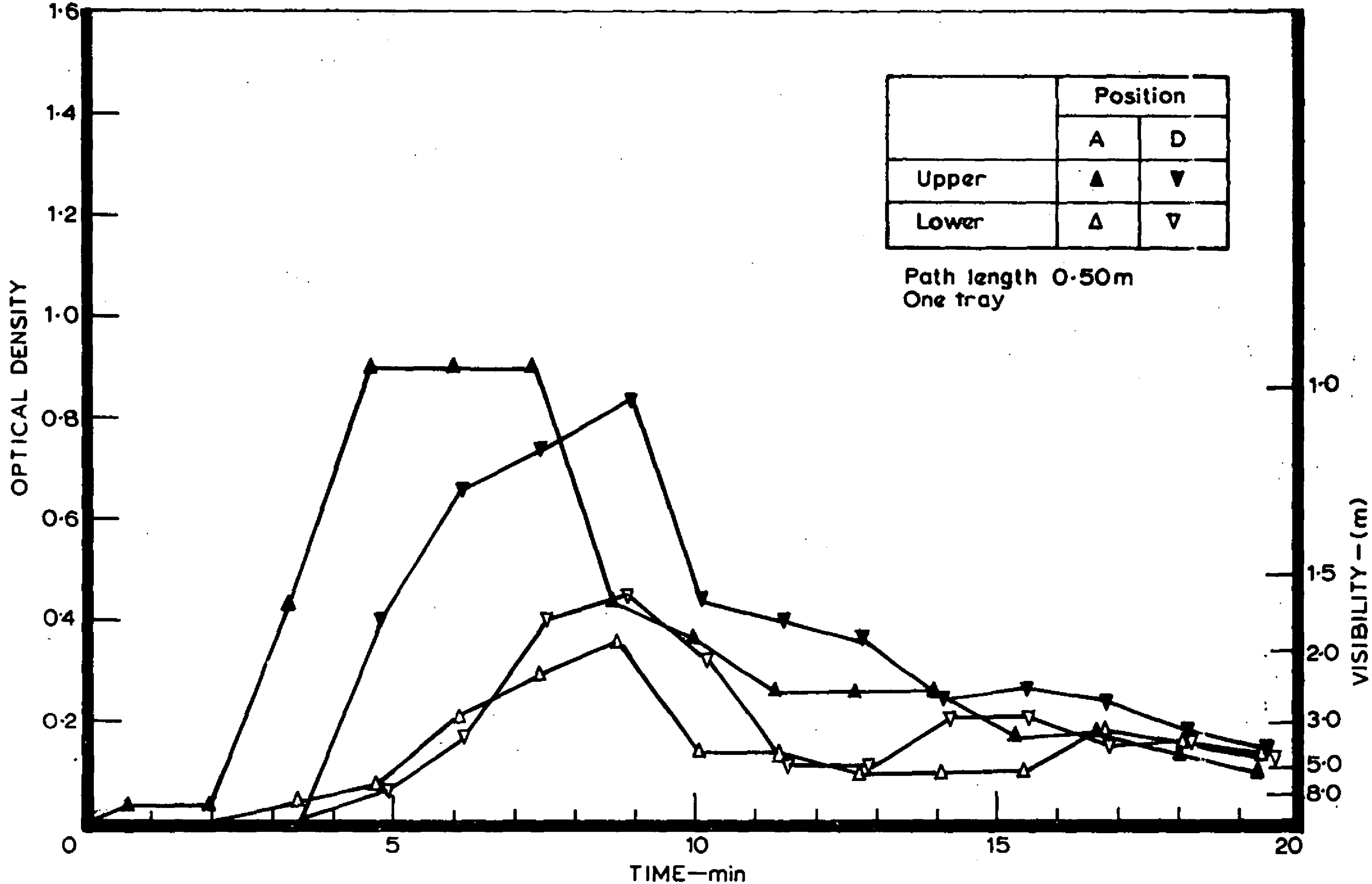


FIG.8 OPTICAL DENSITY (TEST No.4)

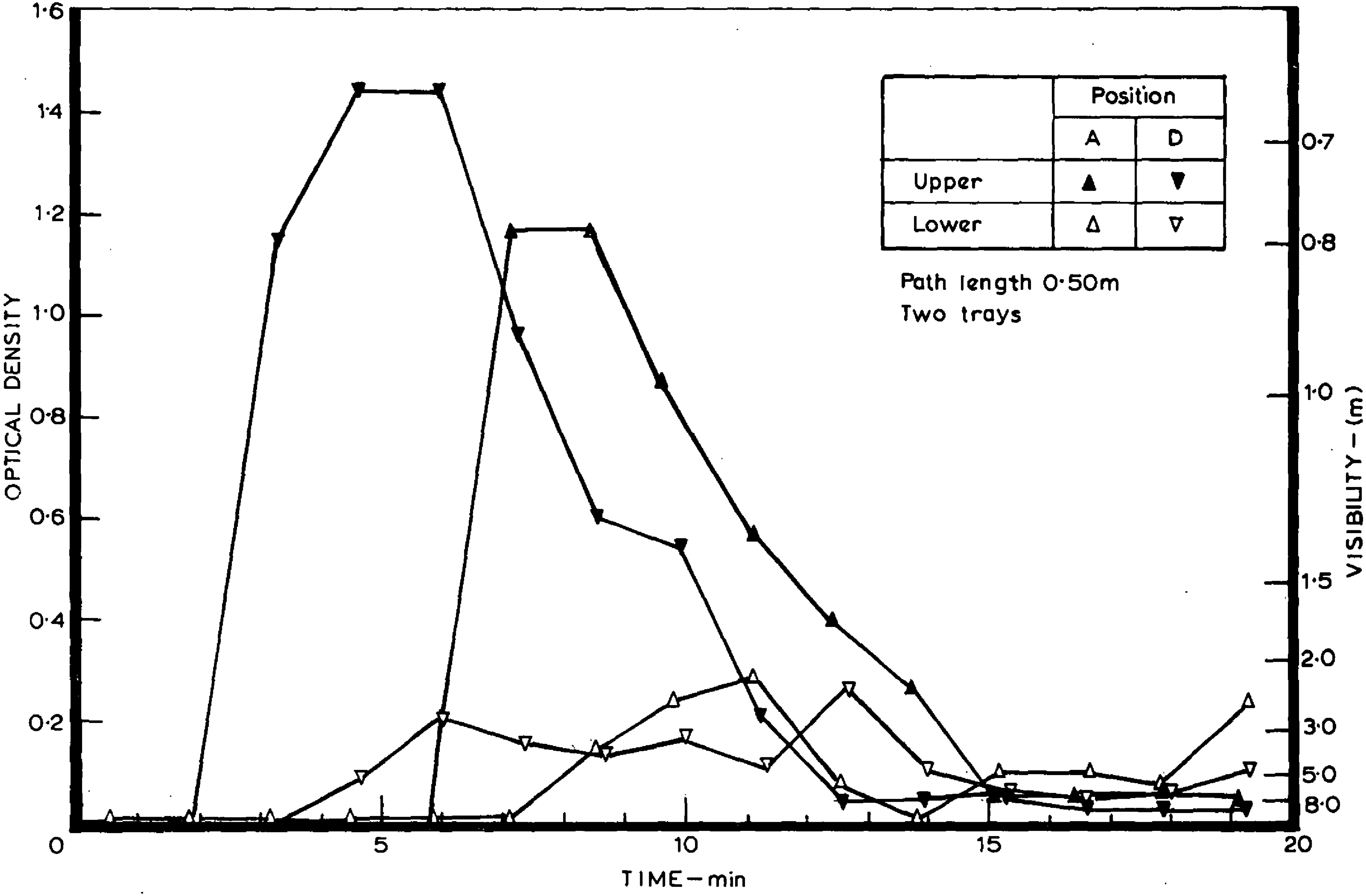
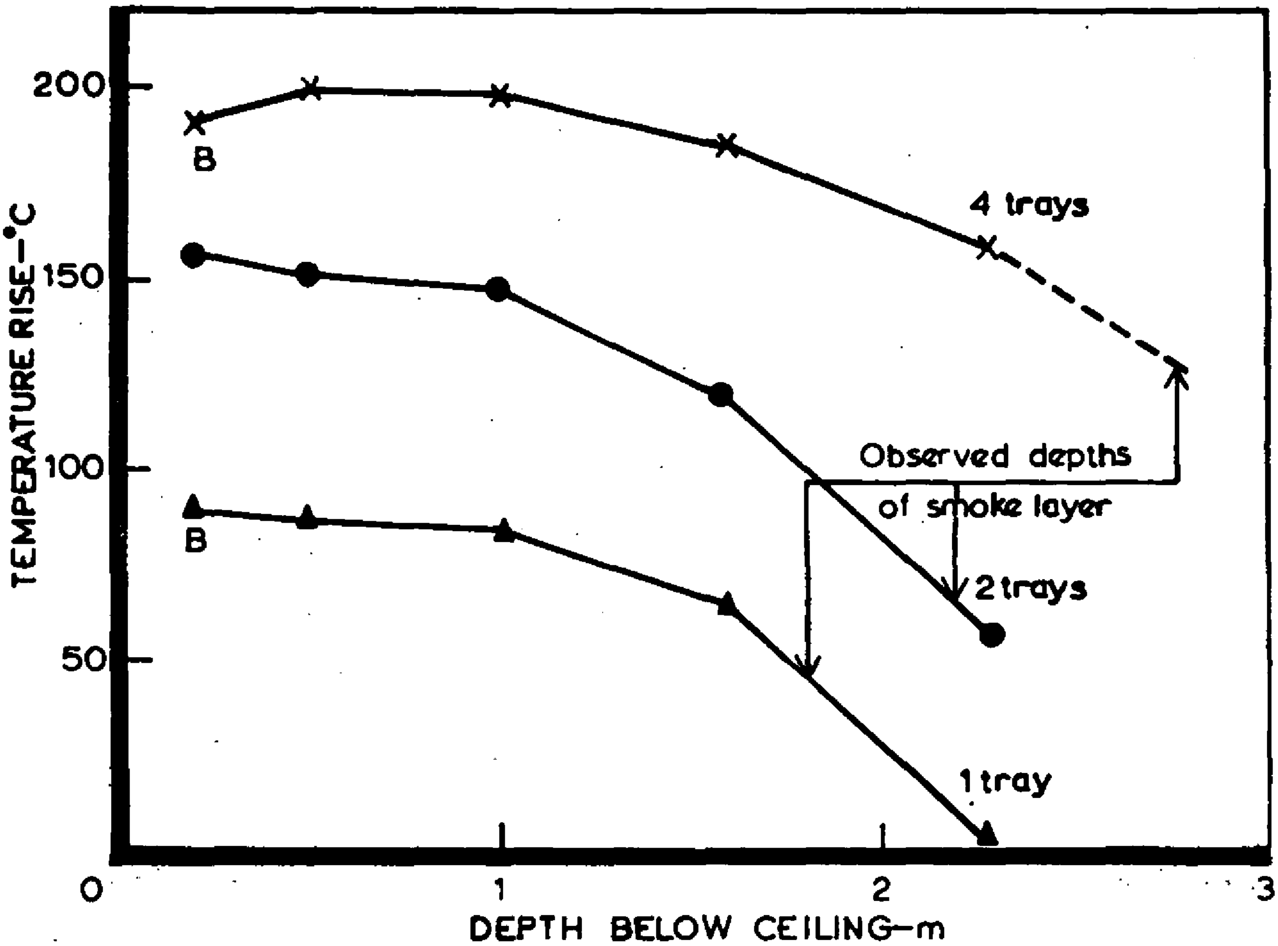


FIG.9 OPTICAL DENSITY (TEST No.5)



Distance from fire 18 m
4 min. after start of test

FIG. 10 PROFILES OF TEMPERATURE UNDER CEILING

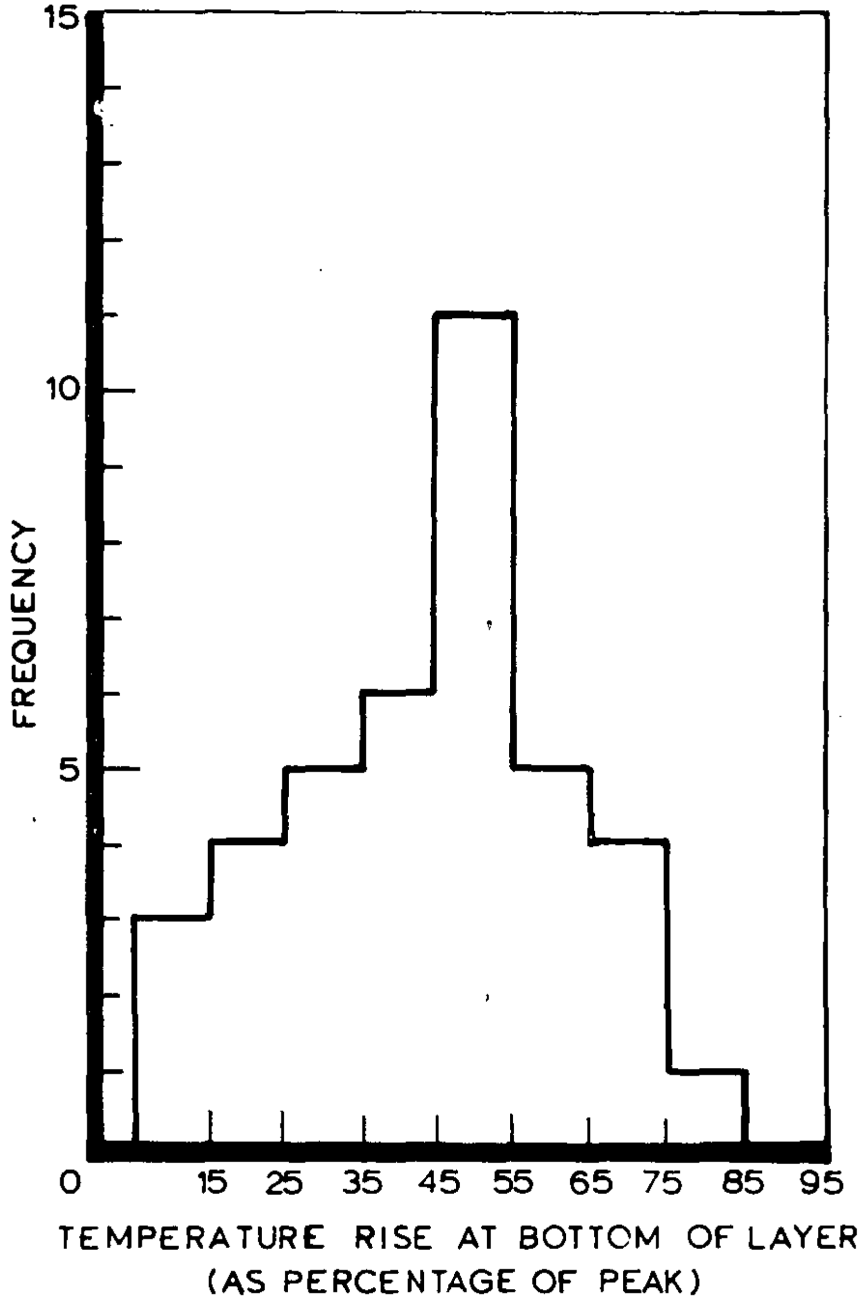
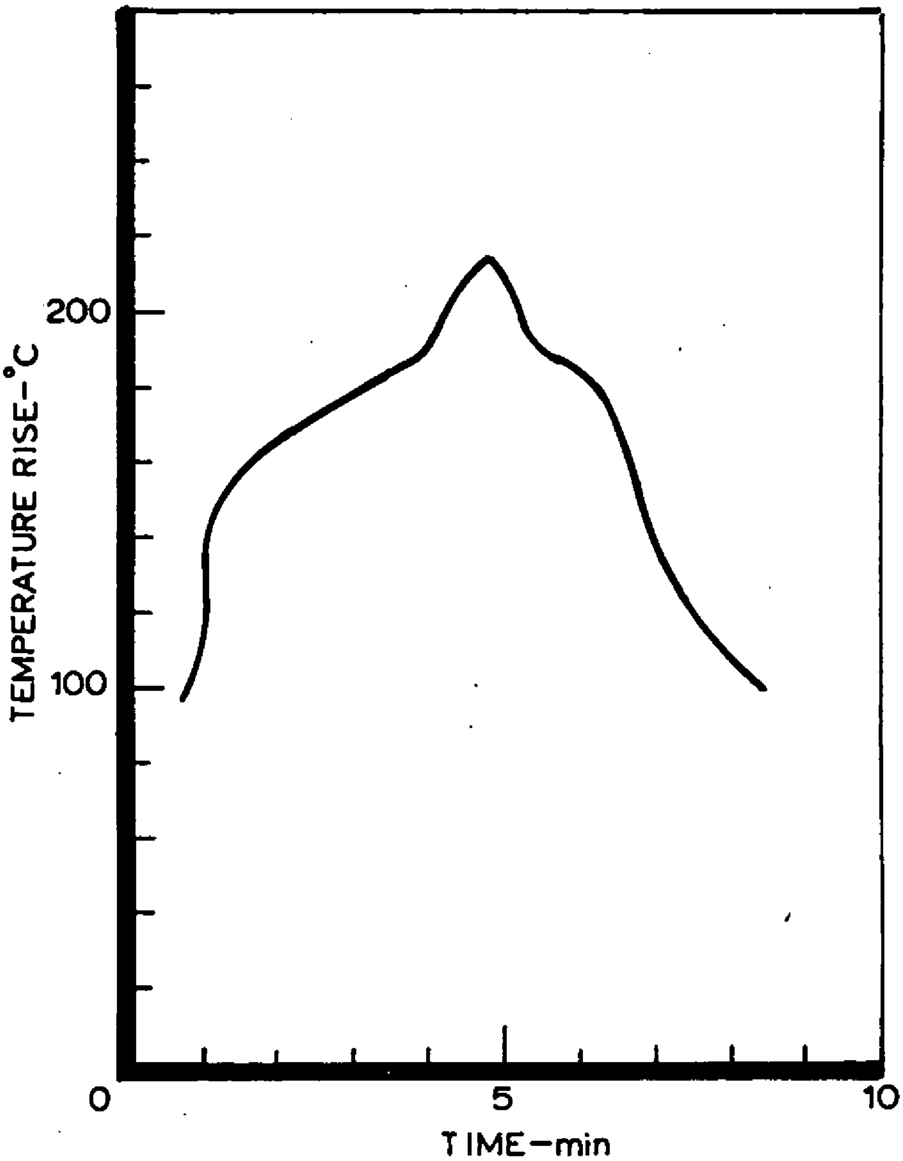
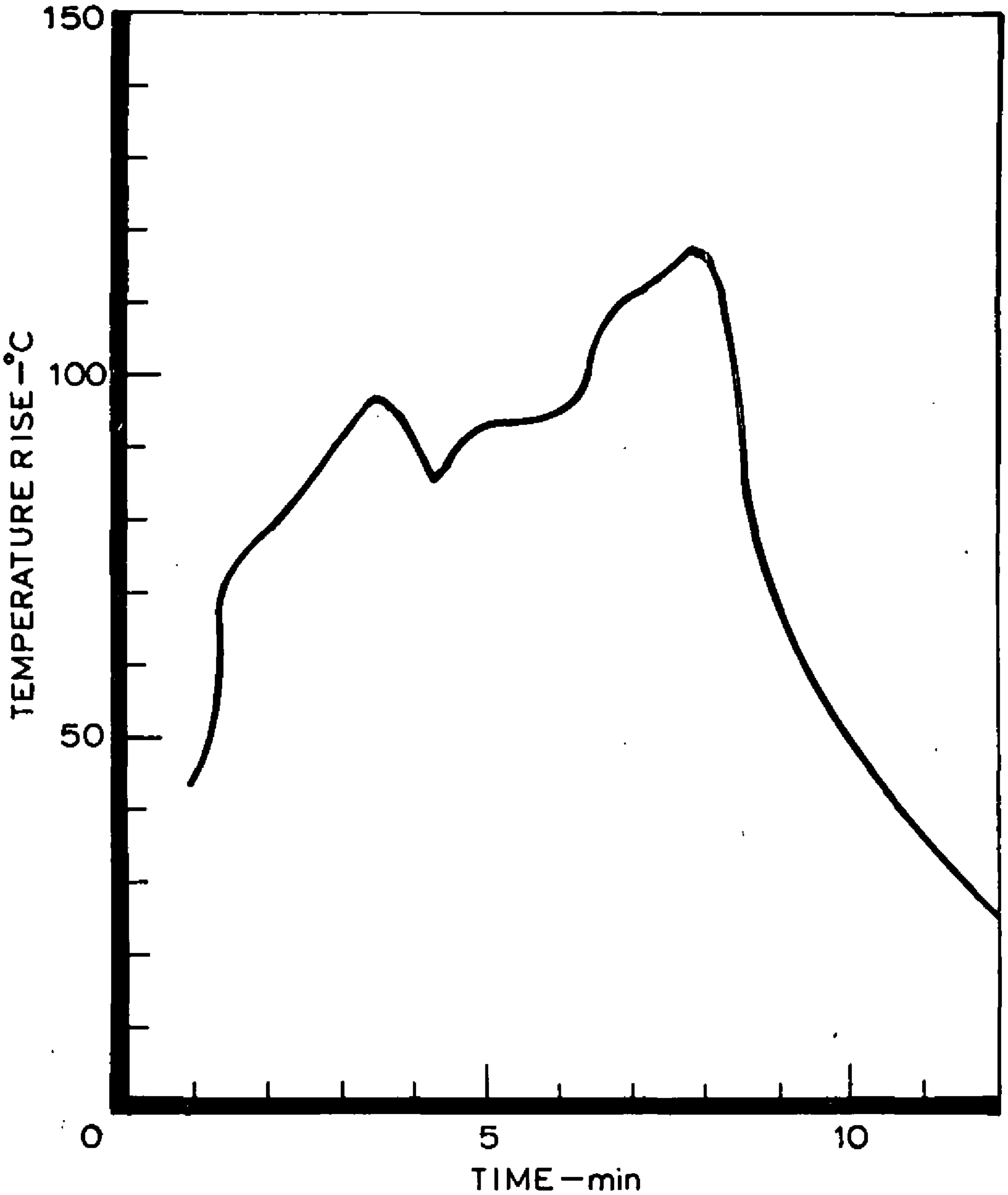


FIG.11 FREQUENCY DIAGRAM FOR TEMPERATURE RISE AT BOTTOM OF DENSE SMOKE LAYER



0·20m below ceiling. Readings at 20s intervals(approx.)

FIG.12 TEMPERATURE RISE AT POSITION B
(TEST No.2)



0·20 m below ceiling. Readings at 20 s intervals

FIG. 13 TEMPERATURE RISE AT POSITION B (TEST No.1)

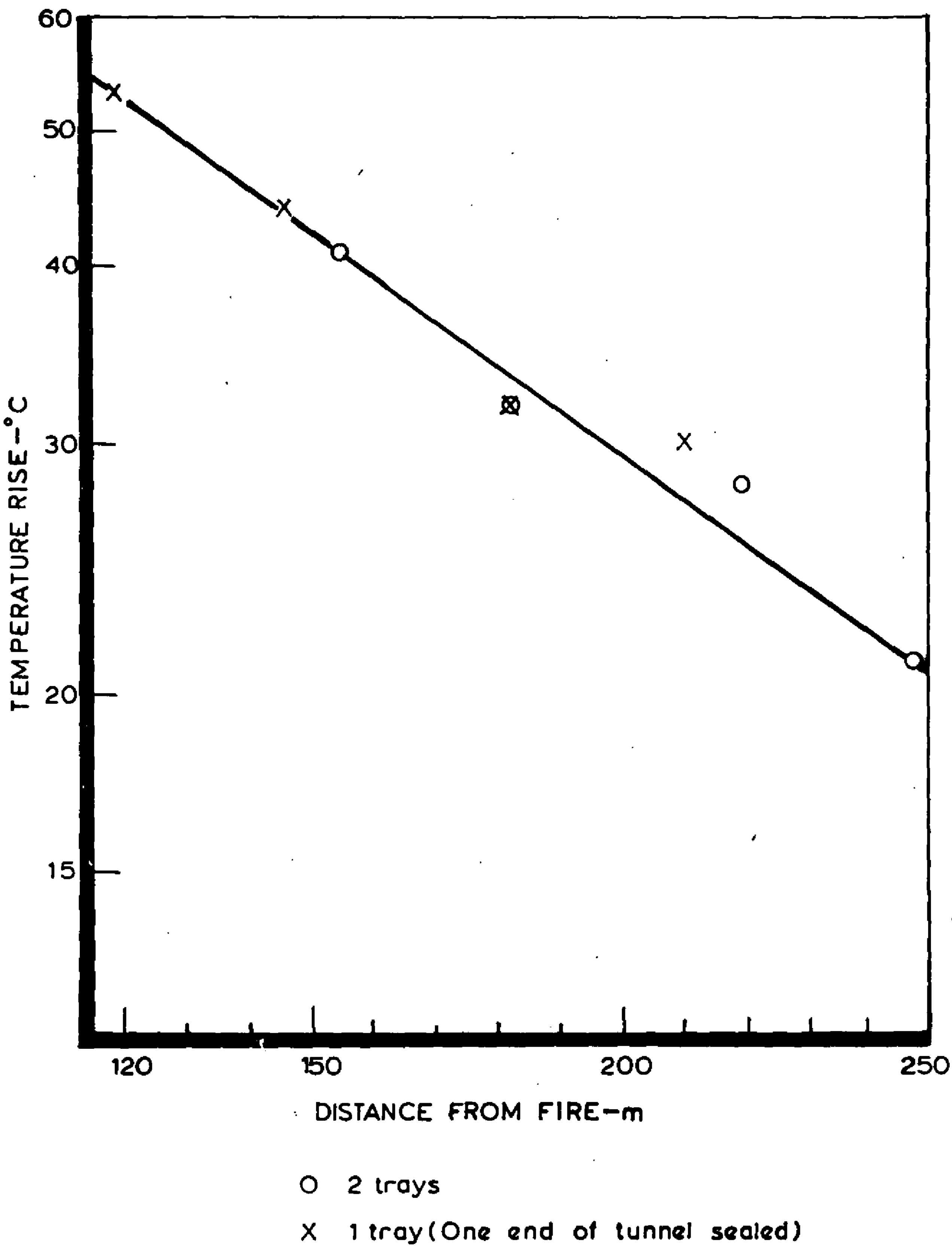
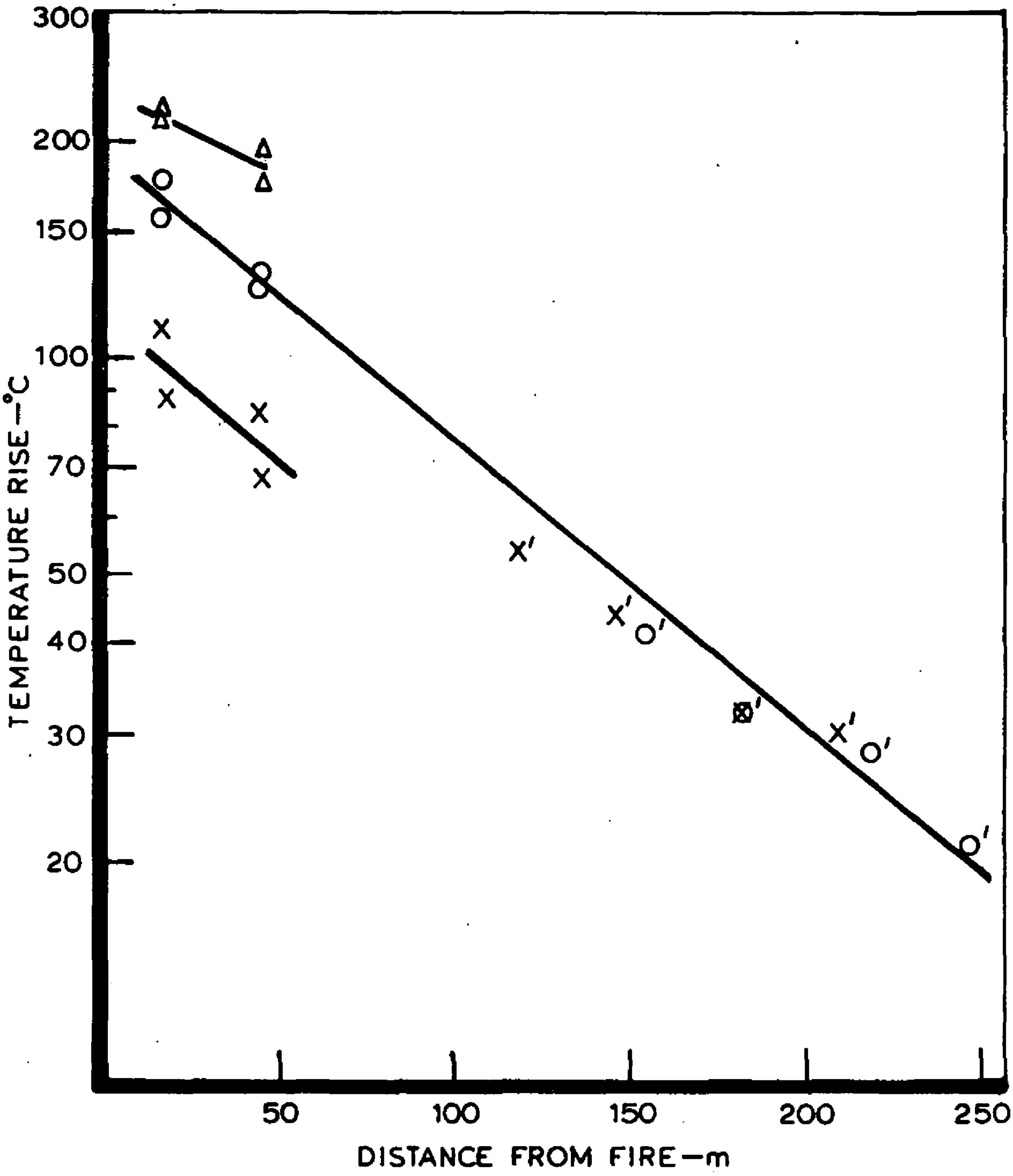


FIG. 14 VARIATION OF TEMPERATURE WITH DISTANCE (TESTS No. 4 and No. 5)



Δ	4 trays (Test No. 2)
O	2 trays (Test No.3)
O'	2 trays near vent (Test No.5)
X	1 tray (Test No. 1)
X'	1 tray near closed end (Test No.4)

FIG. 15 VARIATION OF TEMPERATURE WITH DISTANCE

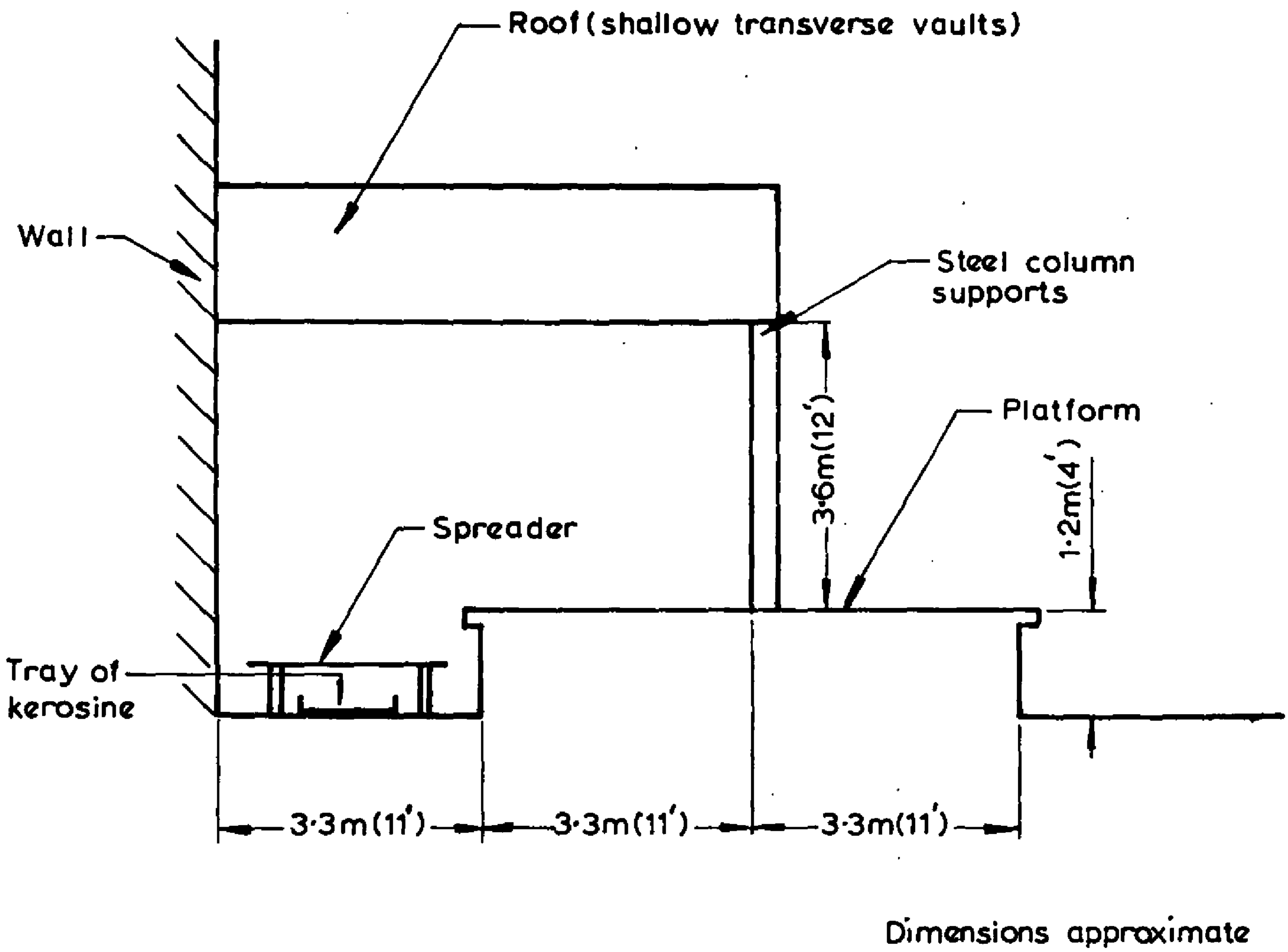


FIG.16 SECTION OF STATION USED FOR CANOPY TEST