Fire Research Note No. 832

SMOKE TRAVEL IN SHOPPING MALLS
EXPERIMENTS IN CO-OPERATION WITH
GLASGOW FIRE BRIGADE - PART 1

by

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SUMMARY

With the object of estimating the hazard from the smoke logging of a pedestrian mall measurements of the rate of travel of smoke and the depth of the smoke layer have been made in a disused railway tunnel 600 m (2000 ft) long. The ends were open or closed and three sizes of fire were used. The smoke layer, at first dense and well stratified, travelled at a speed in the order of 1 m/s (3 ft/s). Both the speed of travel of the smoke and the thickness of the layer (which both increase with the size of the fire) agree with a theory recently developed.

Thinner smoke was formed under the dense layer, sometimes causing smoke-logging to the floor, particularly at the ends of the tunnel, the closed end situation being particularly bad.

KEY WORDS: Smoke, Spread, Shopping Mall, Tunnel, Escape means.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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1. INTRODUCTION

Town centre developments usually comprising shops and pedestrian malls, offices, hotels etc built together in effect as one large building are now becoming fairly common and have created a pressing need for more information on the spread of smoke and fire within them in order that standards of safety for the occupants may be established .

Experiments are in progress at the Fire Research Station on a model scale and in a large experimental building to investigate some features of the spread of smoke and fire within a pedestrian mall but the experimental buildings could not be made long enough to represent adequately the length of a typical pedestrian mall. A theory has been produced[1] which appears to fit data from experiments on the spread of smoke through an underground car park in Tokyo[2], the only data of their kind known to the authors. It was however felt that additional verification was advisable, particularly on independent determinations of the value of some of the constants in the relationships found, in experiments where the comparison with the theory was more direct. The J.F.R.O. was accordingly very glad to avail itself of an offer by Mr G Cooper, Firemaster of Glasgow Fire Brigade to take part in fire tests which were to be run in a disused railway tunnel in Glasgow. This was sufficiently high and wide to represent a pedestrian mall adequately and was long enough to enable extensive observations to be made.

The tunnel was made available by British Rail and the tests were run by the Glasgow Fire Brigade who arranged for the supply of all the necessary facilities and services, and provided 20 observers equipped with breathing apparatus to make measurements of the rate of smoke spread and smoke layer depth within the tunnel. Valuable contributions to the project were also made by the Lighting Department of the Corporation of Glasgow, and the Glasgow Salvage Corps.

These measurements provided the principal experimental data. The J.F.R.O. team made measurements of gas temperature, optical density of smoke, and air velocity to supplement the other data and to try to extract the maximum information from them.

The combined operation was one of the largest of its kind ever carried out in the United Kingdom.

In view of the pressing need for the information obtained to be made available this interim report has been written; it is intended to follow this up with a more complete analysis.

The opportunity was also taken to see how smoke logging conditions could develop under a canopy projecting from the side of a building and one test, which will be reported separately, was carried out under such a canopy in the disused Bridgeton Cross Station.

2. EXPERIMENTAL ARRANGEMENTS

2.1. <u>The Tunnel</u>

The tunnel, Fig.1, ran in a straight line approximately NW to SE between the open Bridgeton Cross station (NW end) and Dalmarnock station (SE end) which was covered for most of its length. It was practically level, with a gradient of less than 1 part in 1000 and was 5.2 m (17 ft) high and 7.6 m (25 ft) wide. The cross-sectional shape was intermediate between circular and rectangular so that the ceiling was not markedly arched. About a third of the way along the tunnel from the Bridgeton Cross end there was a ventilation shaft (Fig.1), opening into the side of the tunnel.

This consisted of 5 openings each 3 m (10 ft) wide and about 4.9 m (16 ft) high, semi-circular in shape at the top; the apex of each opening was level with the apex of the ceiling of the tunnel, these being joined by barrel vaulting.

The openings gave on to a rectangular shaft rising to a walled opening at street level, the top of the wall (about $1\frac{1}{2}$ m (5 ft) high above ground level) being some 3 m (10 ft) above the apex of the tunnel making a horizontal rectangular opening with dimensions of about 20 m x $3\frac{1}{2}$ m (67 ft x 12 ft)

There was a similar shaft at Dalmarnock Station immediately beyond the point where the tunnel opened out into the wider station area.

The length between these shafts was 430 m (1416 ft).

The walls and ceiling of the tunnel were of smooth brickwork free from obstructions except thatat each end there were girders crossing or other obstructions which however did not reach more than about 0.6 m (2 ft) below the apex of the ceiling. The tunnel floor was fairly level ballast without rails or sleepers.

2.2. Standard fire

The standard unit fire used was produced by burning 10 gal of kerosine on cool water in a 1.2 m (4 ft) square tray. This was placed on the tunnel floor in the centre and covered with a 'spreader' 2.4 m (8 ft) square consisting of overlapping corrugated iron sheets laid on an angle metal framework to raise them 0.6 m (2 ft) above the ground. The spreader had the effect of increasing the area of the fire without greatly increasing the burning rate, and reducing the flame height thus producing lower temperatures in the gases beneath the ceiling than would have been obtained with an open tray 2.4 m (8 ft) square. This reduced the possibility of damage to the tunnel roof.

This arrangement had been used successfully in the Japanese experiments referredto earlier[2].

This fire burnt for approximately 8½ min on average and gave a convective heat output of about 2 MW.

Apart from the reproducibility and convenience of the kerosine another advantage is that it immediately begins to burn at a high rate and after about a minute its burning rate is fairly constant[3].

The tests were carried out with 1, 2 or 4 of these units burning together, the units being arranged in a line down the centre of the tunnel, with the spreaders about 1.2 m (4 ft) apart.

The kerosine was primed with a little petrol and then lit with a match or, when more than one unit was used, by means of electrical igniters. These igniters worked very well for test 2 (4 trays) but with tests 3 and 5 (2 trays) one tray did not ignite properly and had to be relit by hand so that a little delay will have occurred before the full burning rate was established.

2.3. Test conditions

The test conditions were as follows:-

Test 1

1 tray burned at the centre of the longer part of the tunnel.
Both ends of tunnel open.

Test 2

4 trays burned as above

Test 3

2 trays burned as above

Test 4

Dalmarnock end sealed by means of a tarpaulin sheet and one tray burned 55 m (180 ft) from this end.

Test 5

2 trays burnt just SE of the ventilation shaft, both ends of the tunnel being open.

Test 6

'Canopy' test, to be reported separately.

3. MEASUREMENTS

3.1. Smoke travel and layer depth

Poles reaching from floor to ceiling painted black and white in 0.3 m (1 ft) wide bands were set up at 18.3 m (60 ft) or 36.6 m (120 ft) intervals along the tunnel on either side of the fire and were used by 20 observers to record smoke measurements. The observers were equipped with breathing apparatus, a pro-forma sheet, clip board and pencil, torch and stop clock or stop watch, and were asked to record the time of arrival of the smoke front, the subsequent depth of smoke, differentiating between 'dense' and 'thin' smoke, and to note reverse flow of smoke back towards the fire, and any other behaviour of interest.

3.2. Gas temperature

The temperature of the hot gases in the tunnel was measured by means of thermocouples set up at 4 positions along the tunnel (Fig 1) on either side of the fire in Tests 1 to 3.

3.3. Optical density of the smoke

The optical density of the smoke was measured at two positions (Fig 1) by means of a photocell smoke meter which measured the transmission of a beam of light over a path length of 0.50 m. 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.

3.4. Other measurements

The velocity of air entering or leaving the tunnel mouth was measured with an electronic vane anemometer. A few measurements of carbon dioxide concentration at head height were made with a Draeger apparatus. Various other records made by observers at the tunnel mouths, or at other positions within the tunnel* have been made use of. In tests 4 and 5 the travel of the smoke front over a long distance was recorded by an observer walking with it.

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*All equipped with breathing apparatus.

4. RESULTS AND DISCUSSION

4.1. Spread of smoke front

The smoke rose up and flowed along under the ceiling in a layer behind a clearly defined 'front' or 'nose' whose progress could be followed very closely.

The velocity of ambient air movement within the tunnel was not large enough to affect the rate of spread to any great extent beyond causing some slight asymmetry in spread and, occasionally by its fluctuation, causing some variation in the spread rate. According to theory the velocity of advance of the smoke should be the algebraic sum of its velocity due to buoyancy and the wind velocity so that the asymmetry could be eliminated by taking an average of the spread in both directions.

To a first approximation the rates of spread were constant, average values obtained being given in Table 1 but a closer examination revealed the systematic variations described in Section 4.3.

The rate of spread with the closed end fire (1 tray) was about the same as that of the 2 tray fire with both ends of the tunnel open.

Table 1
Average rates of advance of the smoke front

Test No	No.of Trays	Rate of spread m/s		
		Towards NW	Towards SE	Mean
1	1	1.01	0.55	0.78 (2.6 ft/s)
3	2	0.79	1.13	0.96 (3.1 ft/s)
2	4	1.37	1.16	1.26 (4.1 ft/s)
4 (Closed end)	1	0.92	-	0.92 (3.0 ft/s)
5 (Fire near vent)	2	1.01	0.64	0.82 (2.7 ft/s)

4.2. Depth of smoke layer

No attempt has yet been made to examine in detail the data on smoke layer thickness after 10 min*, approximately the time of the end of the burning.

Although the bottom of the smoke layer was well defined at first, as the fire progressed thinner smoke began to appear below this initial layer of fairly thick smoke and as time went on it became less easy to decide where the 'dense' layer ended and the 'thin' layer began.

The records of smoke depth have been dealt with as follows. First for each test diagrams showing the extent and depth of the smoke layer at particular times were formed, Fig.2 being an example with fairly bad smoke logging conditions, and then a number of these were drawn together on one diagram (Figs 3 to 7) taking data only for 'dense' smoke since these gave more consistent plots. The data on 'thin' smoke, usually present, are important in questions of smoke logging and the mechanism of mixing of smoke layers and air and are discussed later. However, there are several points to note in the curves for dense smoke shown in Figs 3 to 7.

There is substantial agreement between the depths given by the different observers. Each observer noted his data entirely on his own with no consultation with his neighbour and the difficulty of defining the base of the smoke layer has naturally led to some apparent 'waviness' in the base of the layer shown in Figs 2 to 7 although direct observation showed that the bottom of the layer was flat. However it seems that the observers were reasonably consistent in their judgement and this is very important. For example when as in Fig 6 there was a general, rather small, deepening of the smoke layer we find that most observers record this, so that by plotting data for various times we obtain a series of curves which do not overlap very much.

We must thus remember that some of the apparent variation in depth along the layer at any given time, in Figs 2 to 7, is due to differences between observers, inevitable in this kind of observation.

When it is also remembered that the measurements were of an unfamiliar kind and were made under conditions of some difficulty, in some cases darkness or semi-darkness, with the encumbrance of a breathing

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*Readings were taken up to 20 min.

apparatus and face mask it is gratifying to find that the data are so good.

An examination of the data on smoke layer depth has shown the following.

While the initially established and well stratified layer of dense smoke was spreading along the tunnel it was increasing a little in thickness.

Thinner smoke below the dense layer was noted by observers soon after the formation of the dense layer along its whole length and, usually, appeared to be travelling back towards the fire, or at least in the direction of the air movement near the floor. In some cases this formed deep layers, even reaching to floor level.

Although 'thin' by Fire Brigade standards it was dense enough to produce some apprehension in the authors.

When a layer of smoke reached an open end or a ventilation shaft, a layer or 'plug' of smoke reaching to ground level often formed, probably by the mixing produced by a cross current of air. This plug could be seen to consist, at a lower level, of smoke moving into the tunnel i.e. back towards the fire.

No direct observations are available to show how far smoke logging at ground level extended, i.e. how fast and how far this 'plug' of smoke travelled along towards the fire, since observers within the tunnel were in most tests not near the ends, but it is possible to make rough calculations of these quantities and this will be done in a future report.

When the fire died down and the rate of production of smoke ceased, the wind carried smoke along with it and in some cases created denser smoke at ground level than during the period when the fire was burning.

The case of the closed end is especially important. When the smoke layer reached the closed end an immediate deepening of the layer to approximately double the initial depth took place at the end and the lower part of this deepened layer (in all reaching to about $1\frac{1}{2}$ m (5 ft) above the floor) flowed back towards the fire. Conditions became noticeably hot between the fire and the closed end.

4.3. Comparison with theory

The means of the distances of travel upwind and downwind of the fire are plotted against time in Figs 8 to 10. The layer initially advanced relatively slowly but accelerated to a maximum velocity in approximately one minute after which the velocity tended to decrease slightly. The initial acceleration was probably due to the rate of burning of the fire increasing and the steel spreader 'warming up', the subsequent decrease in velocity was almost certainly due to the cooling of the nose of the advancing layer.

The rates of advance of the smoke layer in the Japanese experiments were in reasonable agreement with the theory, though lower than predicted, probably because in those experiments the car park was in effect a series of chambers joined by large openings rather than a continuous mall.

The rates of spread obtained in the present experiments, in a tunnel which should be closer to the theoretical conditions, agree more closely with the theory and with the results of various experiments on the flow of gravity currents (when a stream of fluid of high density flows in a fluid of lower density) quoted by Benjamin[4].

The calculated rates of spread of the layer (based on the results of the experiments on gravity currents) are shown in Figs 8-10. It was found that the delay in the attainment of the full rate of heat output of the fire could be allowed for by shifting the origin of the calculated curves to the right by 20 s for tests 1 and 2 and by 30 s for test 3 (in which there was some delay in the ignition of the second tray). There was then good agreement between the calculated and experimental result.

The mean depths of the advancing layers of thick smoke at various times were estimated from figs 3 to 7 and are compared with the calculated depths in figs 8 - 10. The calculated depths are in fair agreement with the measured depths although the latter are greater than the calculated depths and increase more rapidly with time.

4.4. Effect of vent

The vent at the side of the tunnel would not be expected to be as effective as a vent of a similar area in the roof of the tunnel. In the conditions of test 5 the vent was probably equivalent to a roof vent having an area of 10 m^2. No roof screens were fitted in the tunnel. Calculations suggested that the vents should have been sufficient to produce a just measurable reduction in both the rate of advance of the layer of hot gases and its depth. In test 5 the mean rate of spread was a little lower than in the corresponding 2 tray fire without the vent (test 3) but the depth of the layer was slightly greater in test 5 than in test 3.

It is likely that the effect of the vent was largely nullified by wind. A good deal of irregularity was noted in the rate of spread on test 5 and this was certainly caused by changes in the wind through the tunnel. At one point smoke was seen blowing back into the vents.

4.5. Optical density of the smoke

These measurements were taken to relate the visibility of the smoke produced to the mass of material burnt in order that the results of the experiments could be applied to other situations. The data were recorded successfully but beyond noting that they are in qualitative agreement with the visual observations of the smoke no analysis has yet been made. This will be included in Part 2 of this note.

4.6. Temperature measurements

All the temperature data were recorded successfully but no comprehensive analysis has yet been made; this will be included in Part 2 of this note.

4.7. Carbon dioxide concentrations

The highest reading was recorded during the second test (4 trays). This was 0.8 per cent, noted at 2 m (6 ft) above ground level at 4 and 7 mins, a value which is too low to constitute a hazard to life. In test 3 the concentration was only 0.1 per cent.

5. PRACTICAL IMPLICATION

5.1. Comparison between paraffin tray and some other fires

Each of the paraffin tray fires produced heat and hot gases at about the same rate as a 2.4 m square wood crib consisting of 7 layers of 25 mm square section sticks with 75 mm spaces between the sticks. A roughly comparable fire might be a fully developed fire in lounge furniture pushed close together (but not stacked up) and covering a 2.4 m square area.

The crib fire would produce a lower density of smoke than the burning paraffin but the burning furniture might possibly produce a comparable density particularly if foam cushions were involved. It is intended to carry out some experiments at Boreham Wood in which the density of smoke from fires in some typical shop contents will be measured.

The four tray fire would be equivalent to four of the cribs or arrangements of furniture described above.

If a fire 'flashed over' in a small shop with an open front 6 m x 3 m high and became 'ventilation controlled' the heat output would be roughly four times the combined heat output of the four trays but the mass of hot gases produced would be less than half that produced by the four trays. Thus the gases would be correspondingly hotter and, with materials producing a comparable amount of smoke to paraffin, the smoke would be correspondingly denser.

5.2. Smoke logging a mall

The rate of travel of smoke in the mall was greater than predicted from the results of the Japanese experiment although the dense smoke layer was at first less deep. However the experiments have shown the importance of smoke mixing into the layer of air travelling back towards the fire. When the fire is small (equivalent to a single tray of paraffin) this smoke may not in theory be sufficiently dense to prevent escape in the early stages but the possibility of its causing panic (particularly in conjunction with the dense smoke above it) requires further consideration. When the fire is larger (equivalent to the four trays of paraffin) this smoke can soon reduce visibility sufficiently to make escape difficult.

It is evident that in an open-ended mall wind effects particularly at the end of the mall can considerably increase this mixing of smoke into the flow of air towards the fire.

Test 4 showed that when the nose of the dense smoke layer reaches a closed end of the mall the smoke layer will curl underneath and travel back towards the fire thus approximately doubling the depth of dense smoke. In the experiment the bottom of the layer was then below head level and it would have been very difficult for a person to escape once the return flow of thick smoke had passed him. In any case he would be tempted to flee away from the advancing smoke i.e. back towards the fire.

In a mall closed at both ends, after the return flow of smoke has reached the fire the dense smoke would continue to descend to floor level and thereafter there would be a general accumulation of heat and combustion products within the mall. Thus the situation within an unvented mall closed at both ends would generally be even worse after a time than in one completely open at both ends. Although this suggests that ventilation through the open ends of a mall may reduce the hazard the other experiments show that it will not reduce it to an acceptable level. The experiments have shown that the preliminary note on smoke movement slightly under-estimated the rate of travel of smoke and they have provided evidence to show that the note did not over-estimate the possible smoke logging of an open-ended mall at ground level. The situation in an unvented mall (ie one with closed ends) would be even worse.

5.3. Venting

The experiments provided confirmation that an inadequate or poorly designed roof venting system will have little if any beneficial effect on smoke logging within a mall and that adverse pressures due to the wind can largely nullify the effect of vents and cause mixing of smoke into the relatively clear air near the ground.

Wind effects are likely to be particularly important in complexes where there may be large differences in height between one part and another and the resulting wind patterns may be hard to predict. It is not sufficient merely to provide a sufficient area of opening on the roof calculated on the basis of still air conditions. Roof venting will be the subject of experiments to be carried out at the Joint Fire Research Organization in the future.

6. CONCLUSIONS

1. A relatively small fire can produce a large volume of hot gas laden with smoke which under unfavourable conditions can lead to substantial smoke logging.
2. In the experiments the smoke was dense and at first was confined to a well stratified layer moving along under the ceiling at a speed in the order of 1 m/s (3 ft/s).
3. The rate of advance of the smoke 'front' was in reasonable agreement with a theory described elsewhere.
4. The depth of the dense smoke layer and its slight increase with time were both in reasonable agreement with values predicted from theory.
5. The larger the fire the deeper the layer of smoke, the denser the smoke and the hotter the gases. The speed of advance of the smoke front increased only slightly as the size of fire increased.
6. Thinner smoke formed under the layer of denser smoke, at times forming a layer reaching to near ground level.
7. When the smoke layer reached an open end a plug of smoke extending from ceiling to floor was formed on several occasions by cross mixing at the entrance. This plug was drawn back into the tunnel by the movement of air towards the fire.

8. When the smoke layer reached a closed end the layer immediately deepened to give thick smoke to within $1\frac{1}{2}$ m (5 ft) of the floor and this deeper layer moved back towards the fire.
9. Data on the optical density and temperature of the smoke were recorded and will assist in applying the results to other situations.
10. The experiments confirm earlier predictions that even a small fire can give rise to a serious escape problem.

7. ACKNOWLEDGMENTS

The authors would like to thank Mr.G.Cooper, Firemaster of Glasgow Fire Brigade, for the opportunity to take part in these tests and to thank the officers and men of the Brigade for their efficient and enthusiastic work on the preparation and execution of this project and for their help with the measurements.

Thanks are also due to a number of other organisations and individuals for their help:

Mr A Bell, Regional Fire Officer, British Rail, made the tunnel available for the tests.

Mr.D. R. Colvin and Mr.Duncan, Lighting Department, Corporation of Glasgow provided lighting and power supplies within the tunnel.

Mr. R. Bevan, Chief Salvage Officer, Glasgow Salvage Corps, kindly made arrangements to close one end of the tunnel for the purposes of Test 4.

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.

8. REFERENCES

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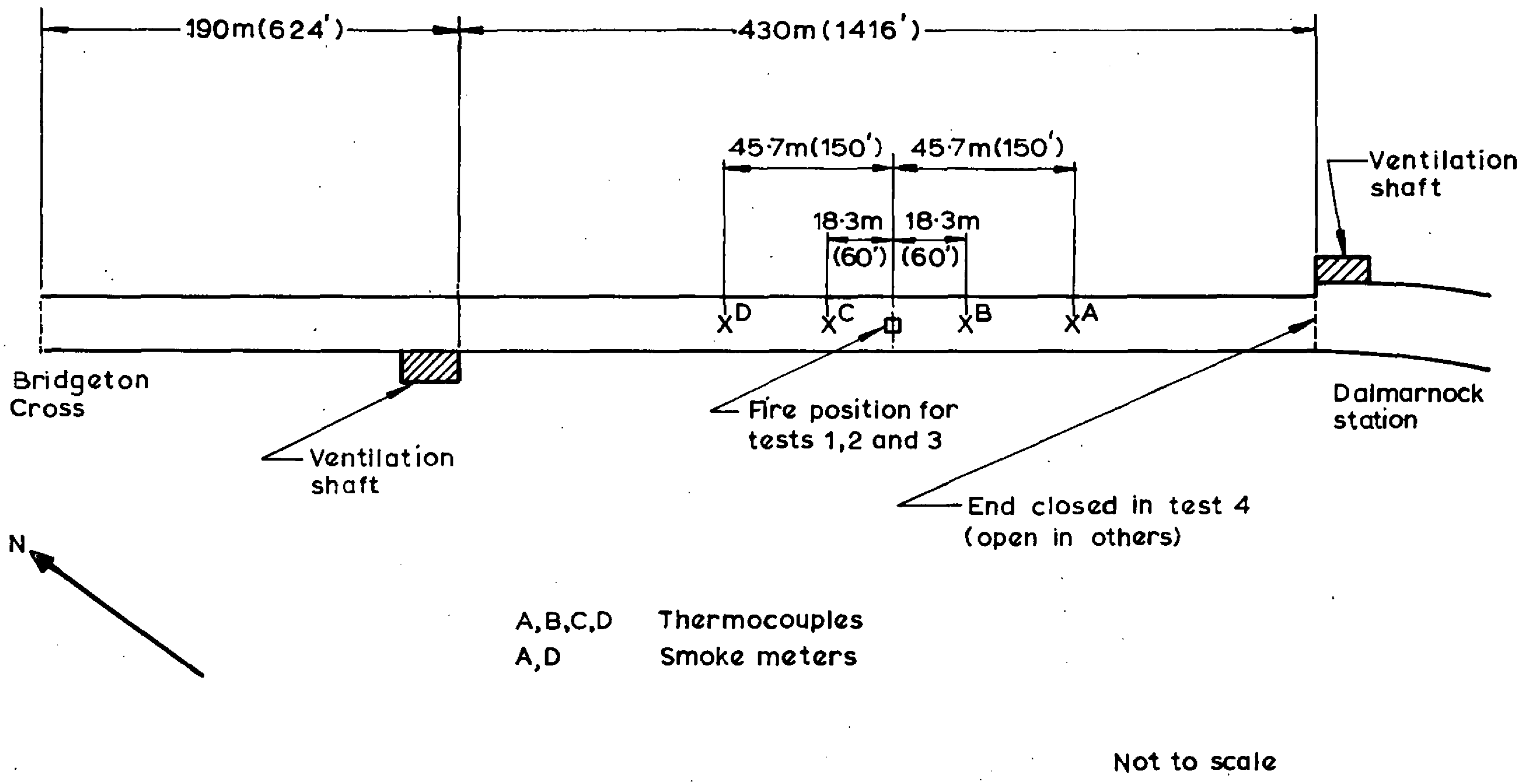

FIG.1 SCHEMATIC PLAN OF TUNNEL

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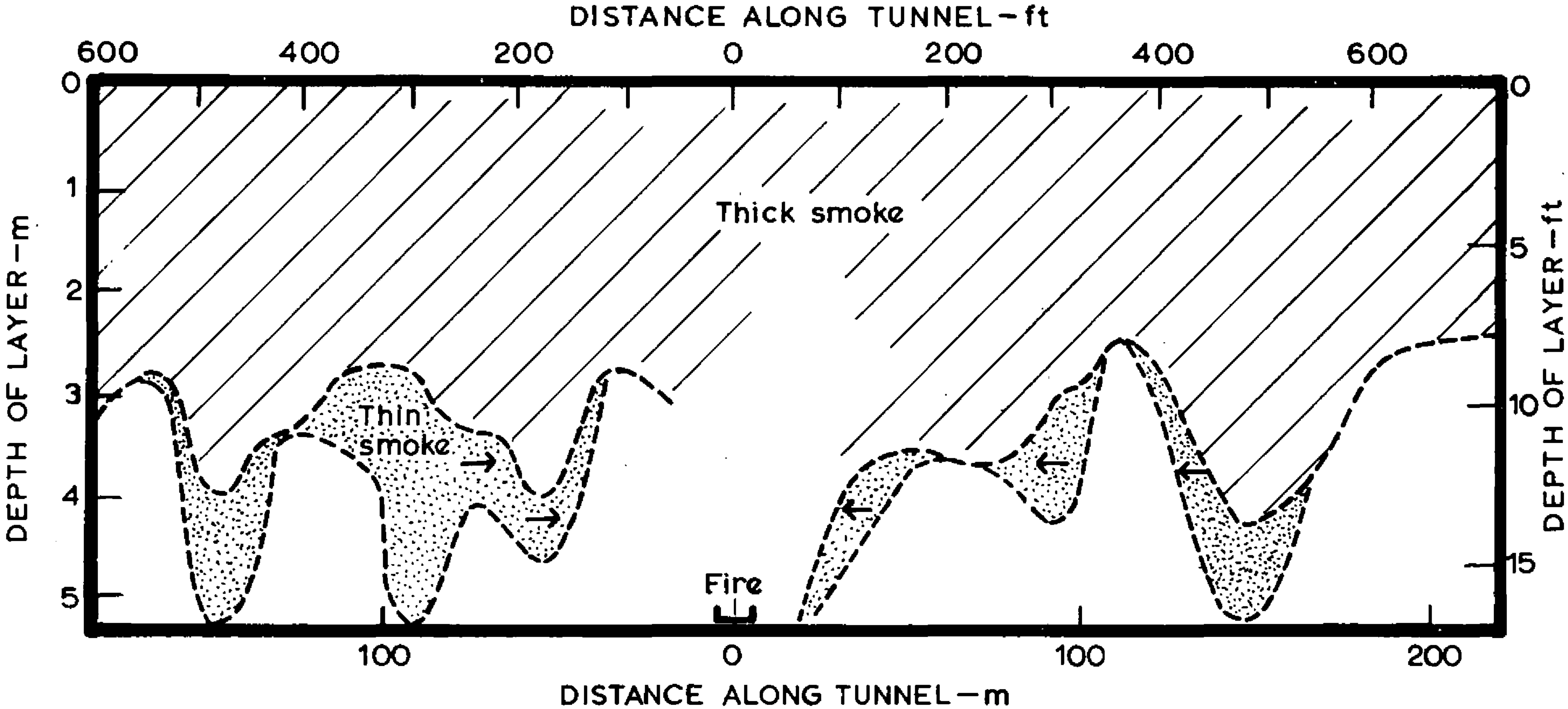

→ Return flow of smoke noted

Ratio of vertical to horizontal scales 10:1

FIG. 2 OBSERVED BASE OF THICK AND THIN SMOKE LAYER – TEST 2 AT 5 MINUTES

0858 FR832

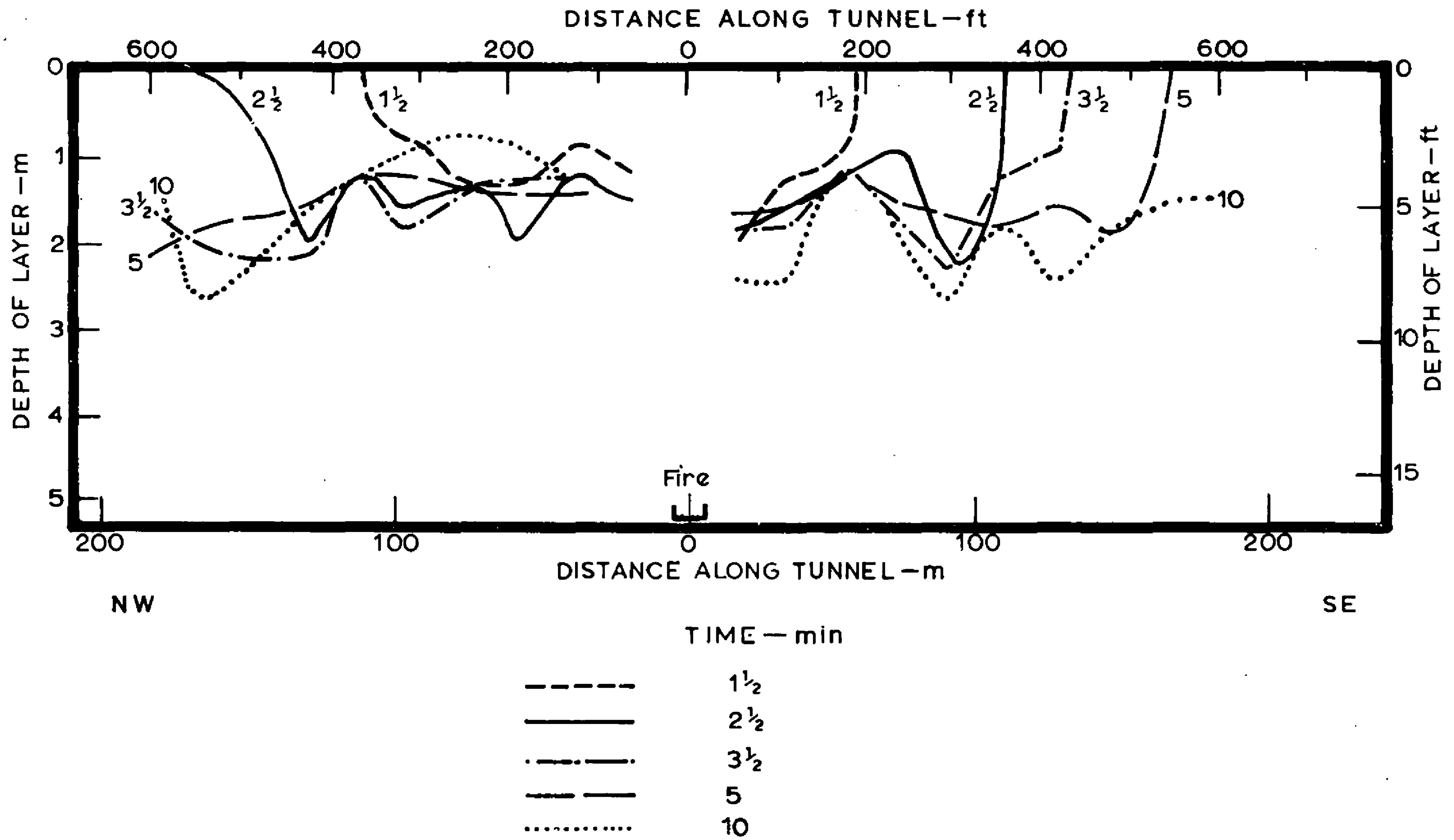

FIG.3 OBSERVED BASE OF SMOKE LAYER—TEST 1

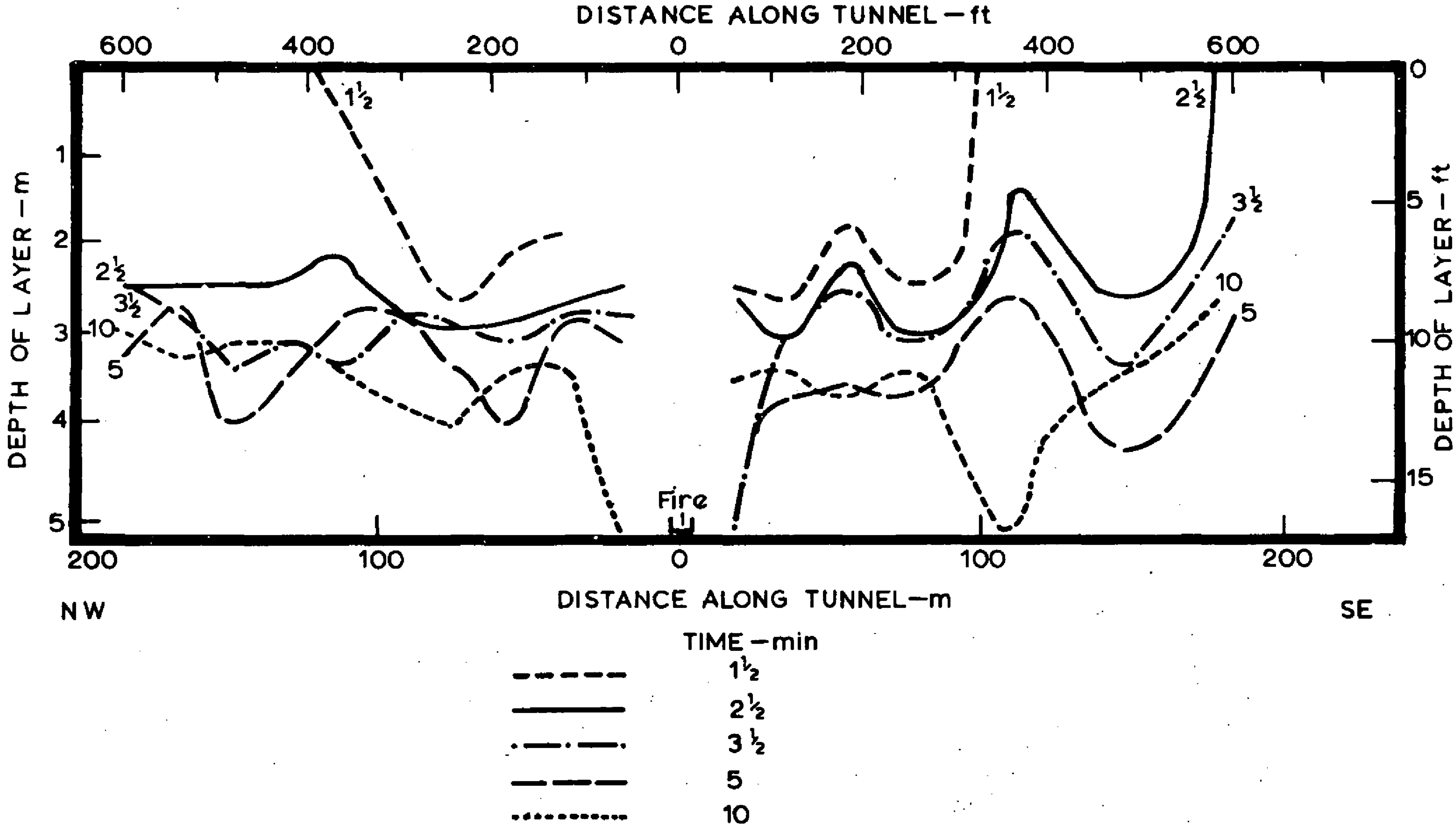

FIG. 4 OBSERVED BASE OF SMOKE LAYER – TEST 2

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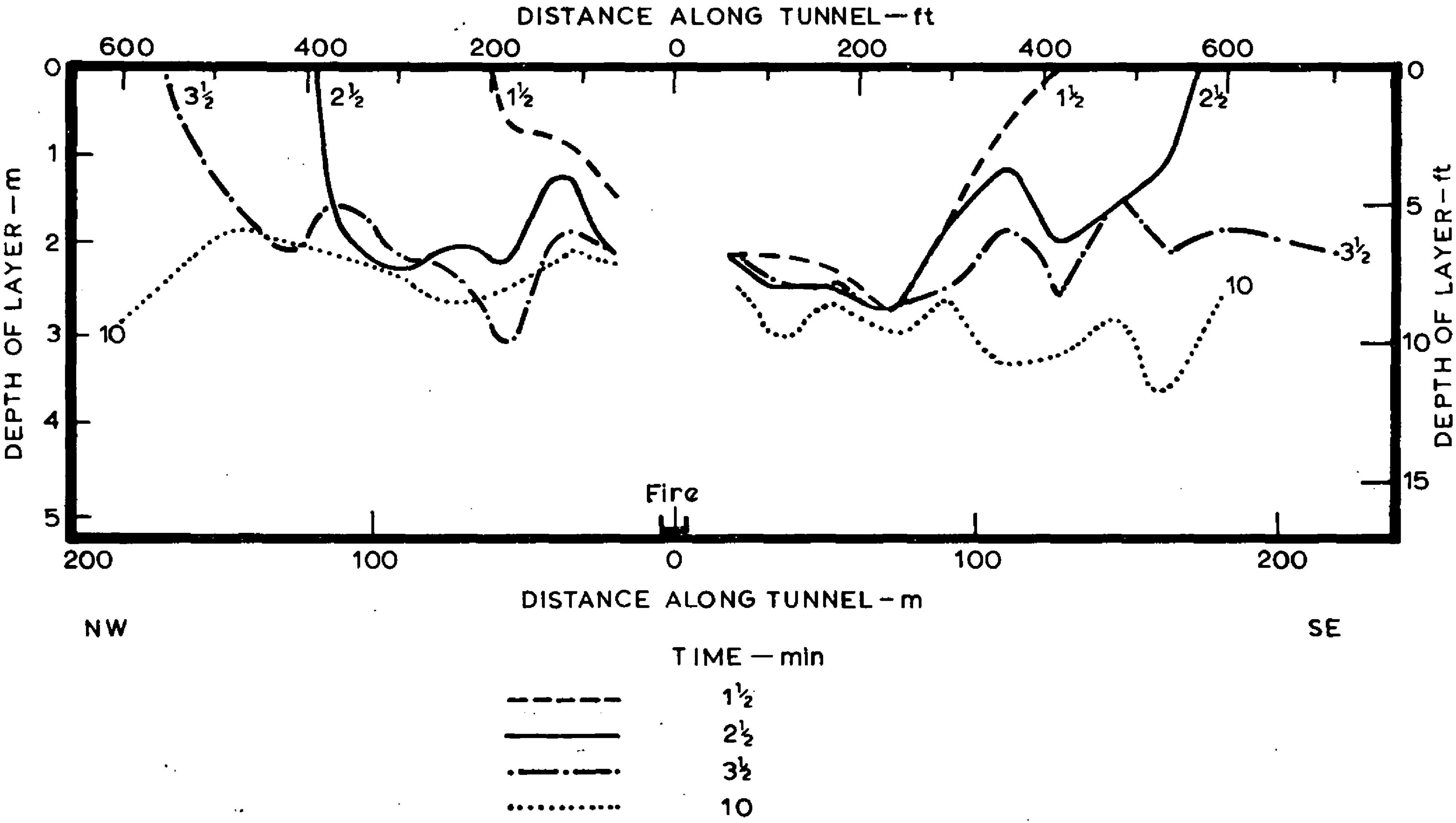
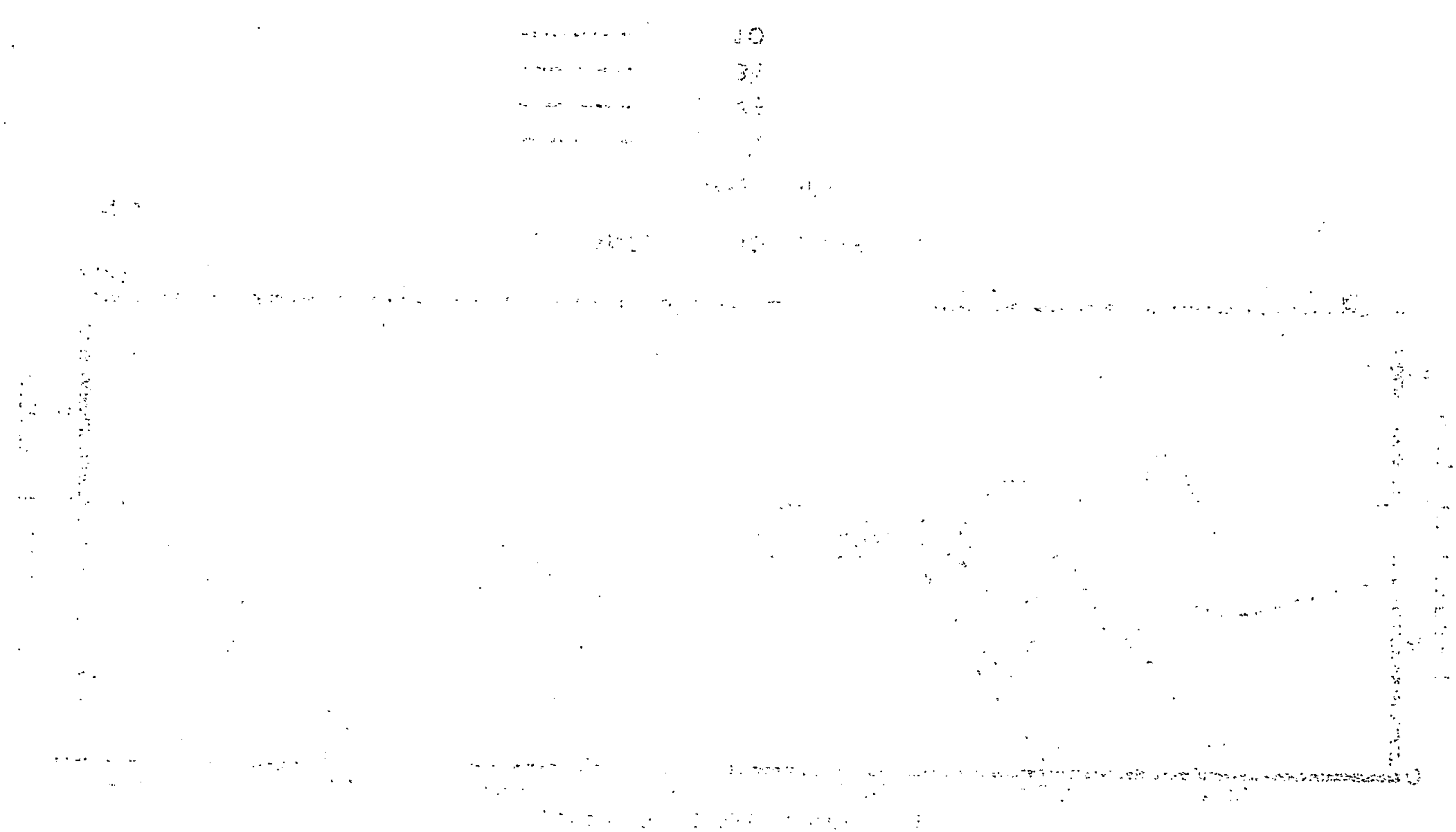


FIG.5 OBSERVED BASE OF SMOKE LAYER-TEST 3



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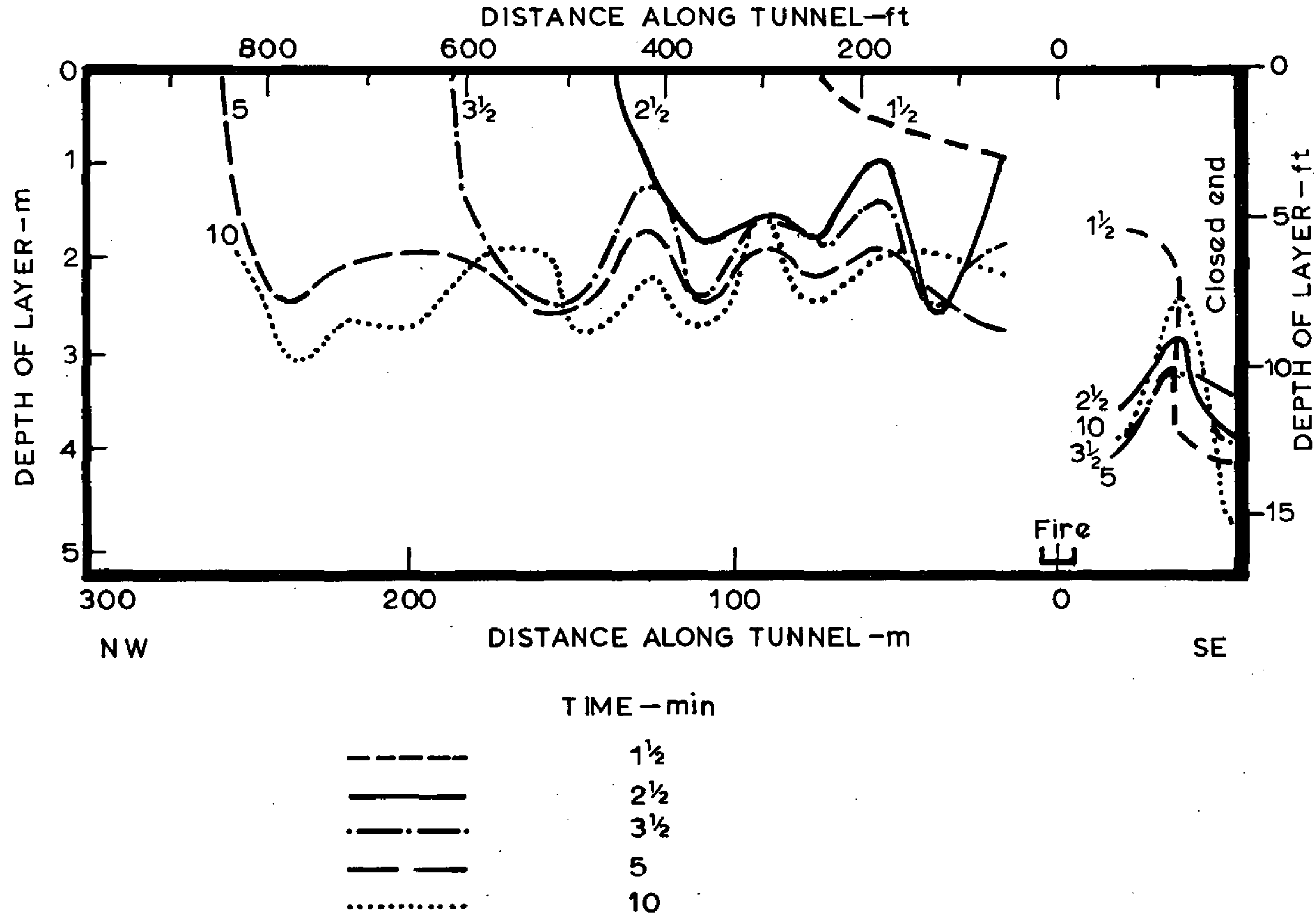

FIG.6 OBSERVED BASE OF SMOKE LAYER - TEST 4

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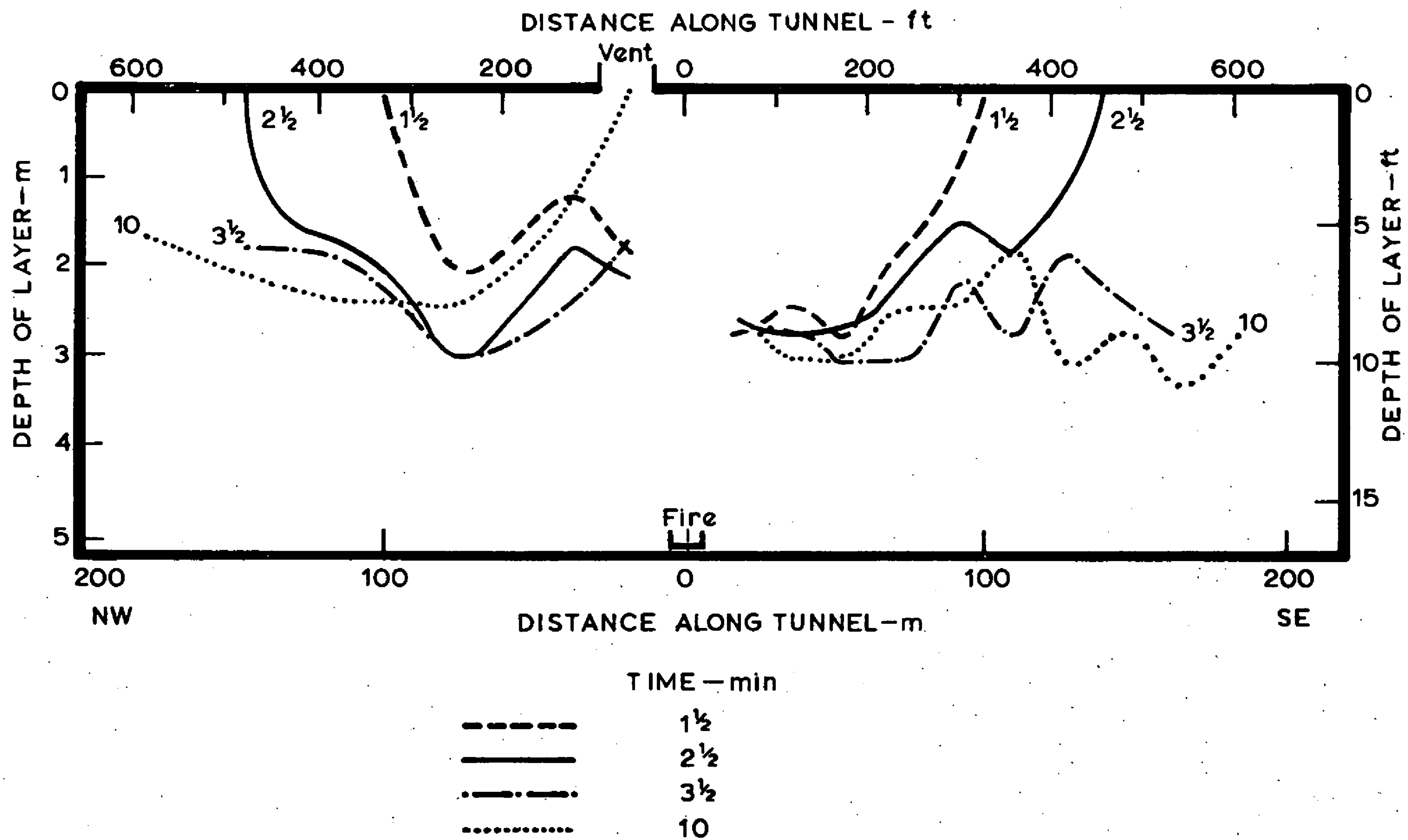


FIG.7 OBSERVED BASE OF SMOKE LAYER - TEST 5

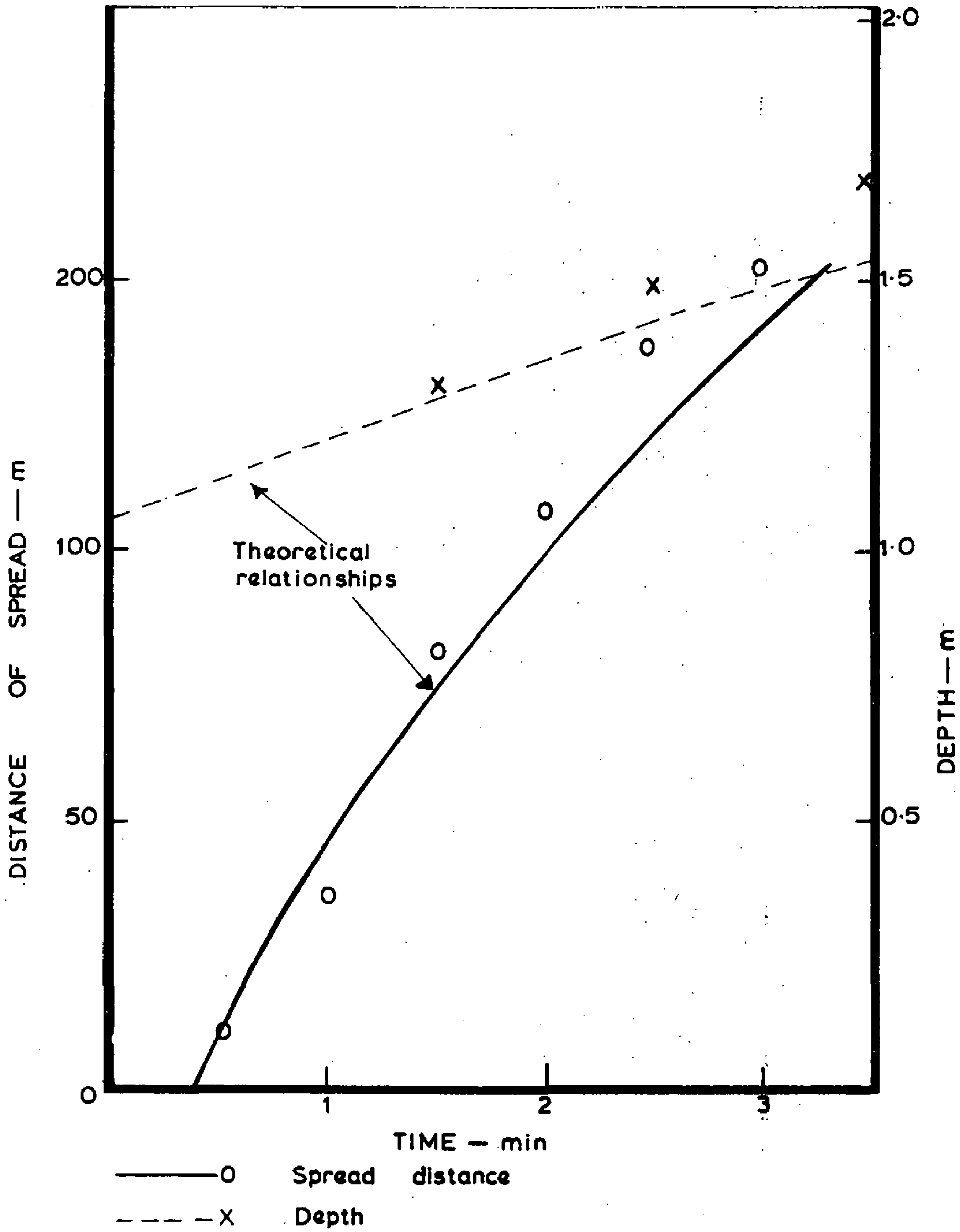
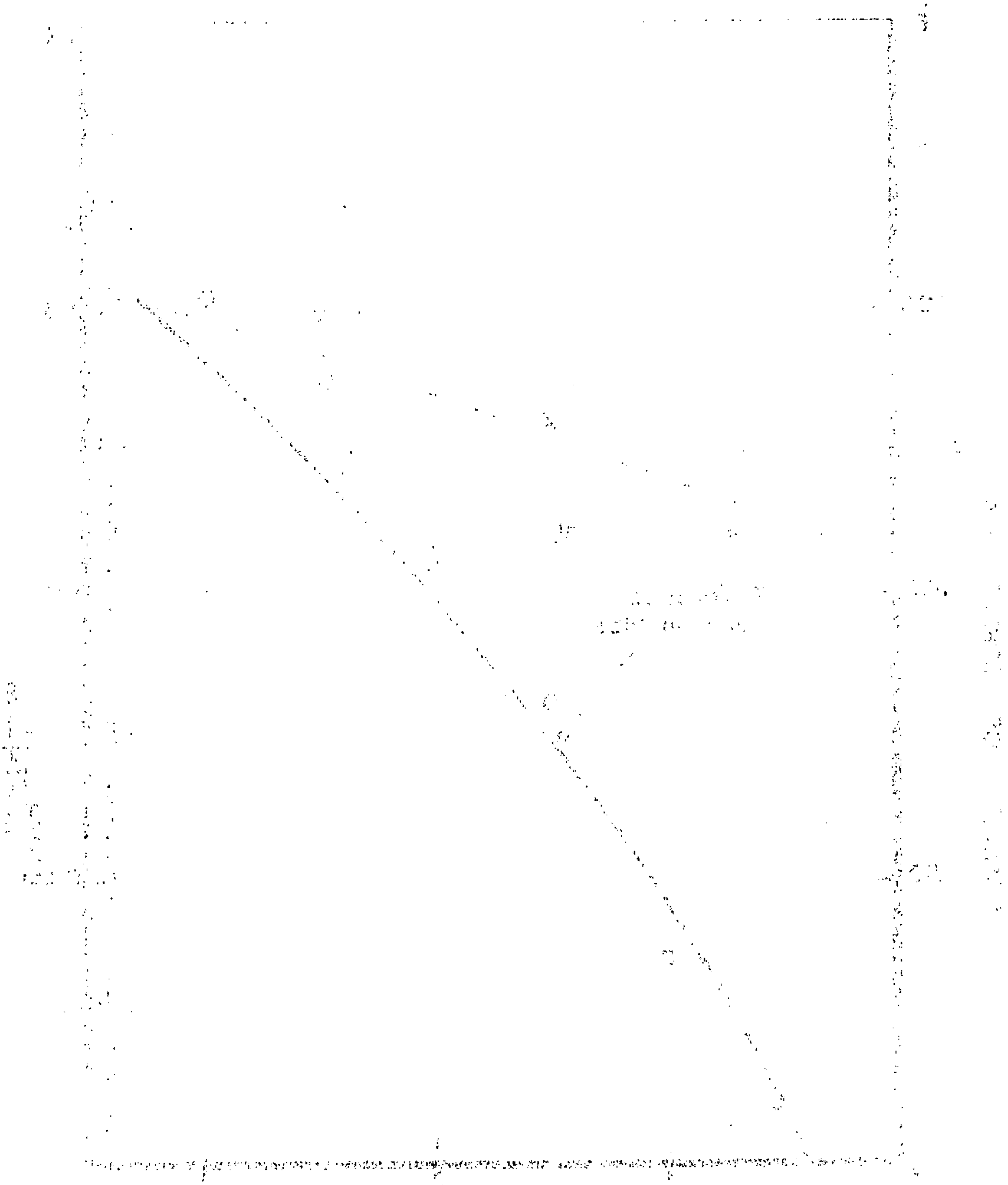


FIG 8 DEPTH AND DISTANCE OF SPREAD
TEST 1 (1 TRAY)



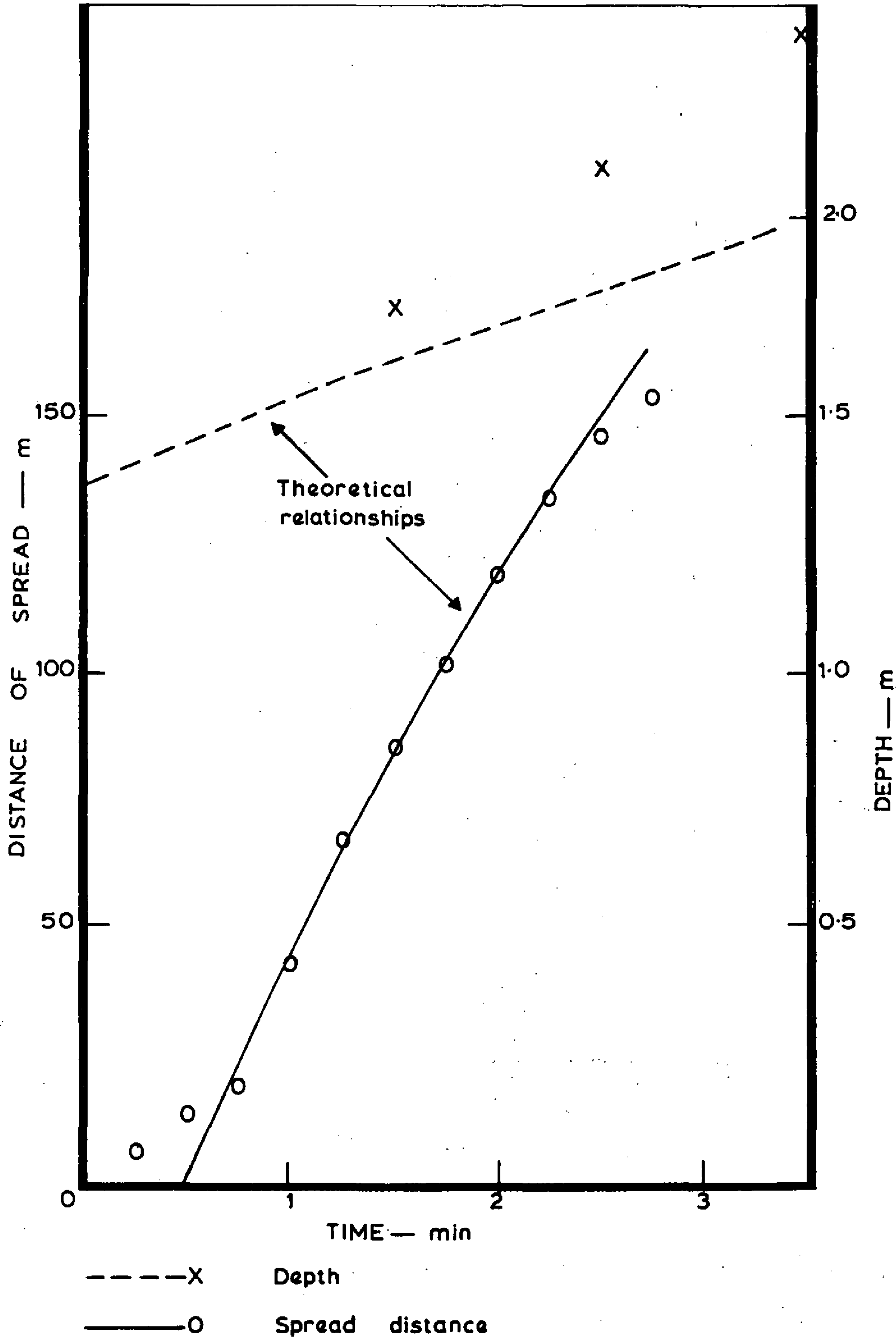
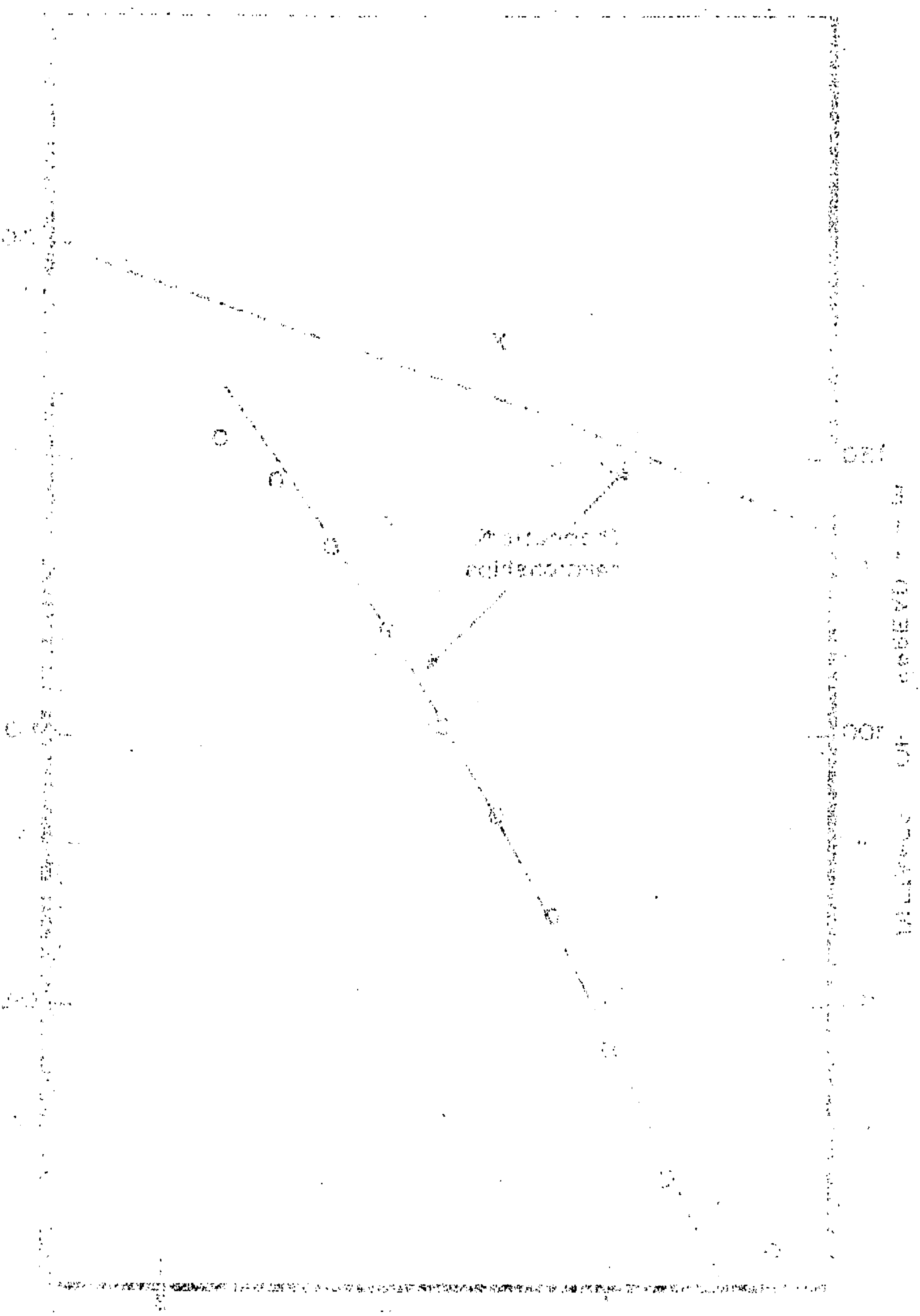


FIG 9 DEPTH AND DISTANCE OF SPREAD
TEST 3 (2 TRAYS)



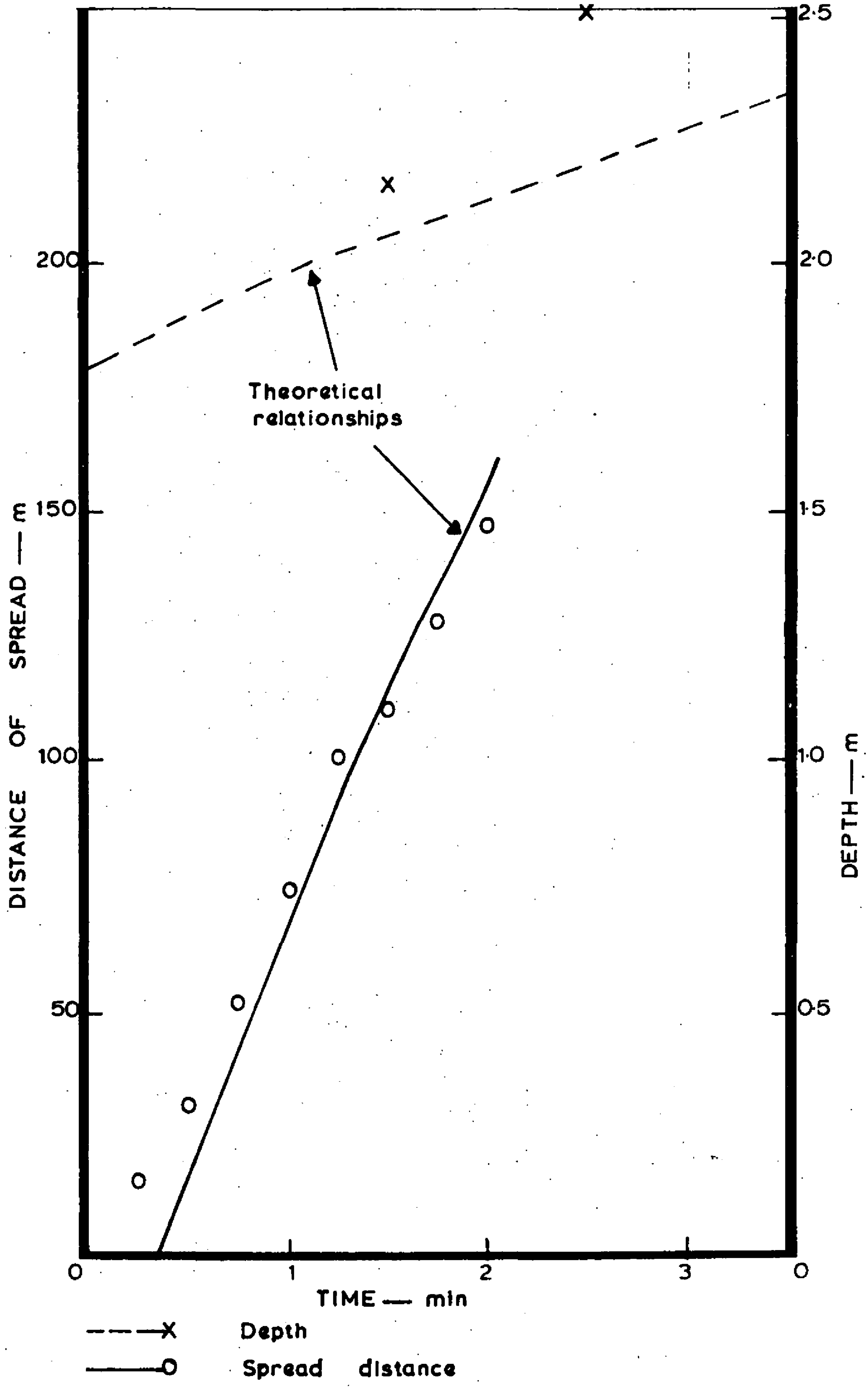


FIG 10 DEPTH AND DISTANCE OF SPREAD TEST 2 (4 TRAYS)

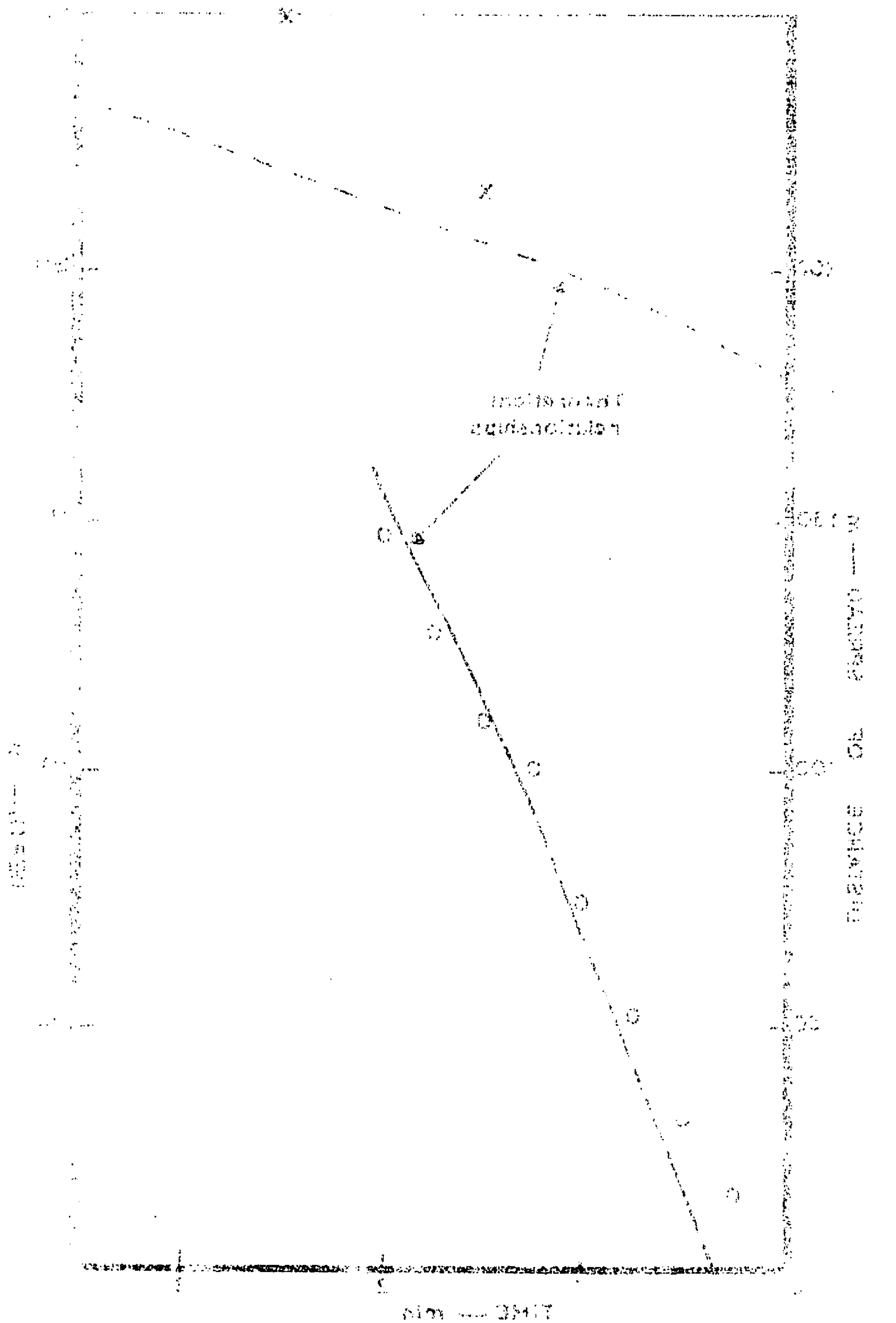


FIG. 10 DEPTH AND DISTANCE OF SPREAD
TEST 2 (A TR-15)