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EXPERIMENTS ON DETECTION OF INSULATING OIL FIRES IN A TRANSMISSION CABLE TUNNEL

by

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SUMMARY

This note describes experiments carried out in a 132 kV transmission cable tunnel to examine the problem of detection of fires in cable insulating oil. Fires of various surface areas were used, and measurements of smoke density and air temperature rise made up to a distance of 115 m (377 ft) from the fire, with and without the ventilating air current flowing. The results enable the response times of heat and smoke detectors to be compared for a range of conditions, and indicate how systems using the two methods of detection can be designed to have an equivalent performance.

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

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1. Introduction

The experiments were conducted in a 132 kV transmission cable tunnel to examine the problem of the detection of a fire following a cable fault. Since it is difficult to simulate a cable fault, it was decided to consider the detection of a fire in the cable insulating oil following rupture of the cable sheathing. No other materials, such as polyvinyl chloride, were used in the experimental fires. The cable tunnel was situated at Sale, near Manchester, and was approximately 152 m (500 ft) long, 4.6 m (15 ft) wide and 2.4 m (8 ft) high. The tunnel was ventilated by a fan at an air flow rate of 368 m^3/min (13,000 ft^3/min), which represents a mean air velocity of 32.9 m/min (108 ft/min). The work was carried out in collaboration with the Transmission Project Group of the Central Electricity Generating Board to determine the most effective method of detecting fires in the tunnel. Experiments were performed with oil fires of different surface areas, and measurements were made of the optical density of smoke produced and of the resulting air temperature rise, up to a maximum distance of 115 m (377 ft) from the fire. The detection time of a proprietary smoke detector was also recorded.

2. Experimental

The cable tunnel was 4.6 m wide and 2.4 m high, and had a row of pillars situated at 1.65 m (5 ft 5 in) from one side of the tunnel (Figure 1). Measurements of smoke density and air temperature rise were made along the tunnel centre line, which was approximately 0.61 m (2 ft) from the line of pillars (Figure 1). Four measuring points were used, situated 5 m (16.4 ft) apart, with the point nearest the end of the tunnel (point 4) situated at 12.8 m (42 ft) from the tunnel end, and 1.8 m (6 ft) from the exit shaft to the ventilating fan. A proprietary ionisation chamber smoke detector was positioned at point 3. Measurements were made both with the ventilating air flowing and with the tunnel unventilated.

The smoke density measurements were made using optical density meters incorporating cadmium sulphide photocells (Mullard ORP 12) and tungsten filament lamp bulbs. The optical path length of the meters used at measuring points 1 and 2 was 1 m (3.28 ft) and at points 3 and 4 it was 0.5 m (1.64 ft). The optical paths were arranged at right angles to the tunnel axis (Figure 1). Each meter was calibrated using neutral density optical filters. The calibration gives the change in photocell current in terms of the percentage reduction in the intensity of light falling on it. The air temperatures were measured by 0.122 mm (40 S.W.G.) diameter chromel-alumel wire thermocouples incorporating a cold junction at 0°C. Both measurements were made at a distance of 12.1 cm ($4\frac{3}{4}$ in) below the roof of the tunnel.

The fires used in the experiments were tray fires of the transmission cable insulating oil, which had a closed flash point of 121°C (250°F) (maximum) and a viscosity of 15 centistokes at 20°C. Three fires were used in square trays of side length 0.30, 0.46, and 0.61 m (1, $1\frac{1}{2}$, and 2 ft), the largest being the maximum size to which it was considered the fire should be allowed to develop before being detected. The location of the fires with respect to the measuring points is shown in Figure 1. At positions A and B all three fire sizes were used to obtain a comparison of conditions with the fire on each side of the line of pillars. At positions C, D, E, F and G only, the 0.61 m square fire was used to examine the effect of distance along the tunnel up to a maximum of 115 m (377 ft) from the furthest measuring position (point 4).

The smoke density and air temperature rise were measured continuously during the fires using pen recorders and rotary switching units scanning each measuring point. The time of detection for the proprietary ionisation chamber smoke detector was obtained by the time taken for a fire warning to be indicated on its normal control equipment.

It should be noted that the experiments were carried out in smoke clear conditions in the tunnel, with no fogging or other aerosols present in the atmosphere.

3. Results

(1) Smoke measurements

The increase in the percentage obscuration due to the smoke was generally very rapid, following the initial time delay before smoke arrived at the measuring point. Some typical results showing the measured percentage obscuration plotted against time are shown in Figure 2. The practical implication of these results is that detection of smoke can be achieved very rapidly once the smoke has reached the detection position, since the time taken to reach a level suitable for a fire warning (e.g. 15 per cent obscuration per metre) is very short. The time delay before smoke was observed at the measuring points is plotted against distance from the 0.37 m^2 (4 ft^2) fire in Figure 3. The results show a practically linear increase in the time lag for the ventilated tunnel, representing a smoke velocity of 41.8 m/min (137 ft/min). The time lag is greater with no ventilating air current, as would be expected, and begins to increase rapidly beyond about 76 m (250 ft) from the fire. At distances of 91 m (300 ft) and more from the fire, the smoke takes several minutes to reach the measuring point, e.g. it takes 10 min at 113 m (370 ft), compared with 2.7 min for the ventilated condition.

(2) Smoke detection

(a) Optical density

To examine the rapidity with which smoke can be detected in the tunnel, the criterion used was the time taken for the obscuration level to reach 15 per cent over a 1 m optical path length. The readings for the measuring instruments using a 50 cm path length were corrected to the equivalent readings for a 1 m path. This criterion represents an optical density of 0.07 and a 4.7 per cent obscuration over a 30.5 cm (1 ft) path length.

In the series of experiments with the fires in positions A and B (Figure 1) it was found that there was little difference in detection time between the two fire positions. In addition, the detection time was not significantly dependent on whether or not the ventilating air current was flowing. Therefore, at distances up to the maximum of 17.1 m (56 ft) from the fires (position 4 in Figure 1), the smoke built up rapidly in the tunnel irrespective of which side of the pillars the fire was located, and the natural convection currents from the fire had sufficient momentum to result in a build up in smoke density which was as rapid as when the ventilating air was flowing.

The effect of fire area is shown in Figure 4, which gives the mean detection times at 17.1 m (56 ft) from the fire for the two fire positions, and for the ventilated and unventilated condition. The effect of fire size is that the detection time decreased as the fire area became larger, and the curve is flattening out at a size of fire of area 0.37 m^2 (4 ft^2). This would be expected since even for a large fire the smoke takes a finite time to reach the detection point, which was about 25 s for a distance of 17.1 m from the fire, assuming an air velocity of 41.8 m/min. The effect of increasing the fire area by a factor of 4 was to halve the time of detection, if the mean values at each measuring position are taken.

The effect of distance along the tunnel can be ascertained from the measurements for the 0.37 m^2 fire in positions A, B, C, D, E, F and G (Figure 1). The times required for detection (15 per cent obscuration per metre) are shown in Figure 5 plotted against distance from the fire. These curves are very similar to those shown in Figure 3 for the time taken to reach the measuring point, since the time taken to reach 15 per cent per metre obscuration was relatively small once smoke had reached a particular point in the tunnel. The overall average response time (to reach 15 per cent per metre obscuration) following the arrival of smoke was 16½ s. Figure 5 shows that with the ventilating air flowing, the response time increased almost linearly between 12.2 m (40 ft) and 116 m (380 ft), and that smoke would be detected in 3½ min at 113 m (370 ft) from the fire. When the ventilating air was not flowing, the detection time was greater beyond about 21.3 m (70 ft) and began to increase very rapidly beyond 76.2 m (250 ft), so that at 113 m (370 ft) the detection time would be as long as 10.7 min. This effect arises because the hot gases from the fire flowing under the tunnel roof gradually lose momentum by viscous drag, and beyond 76.2 m (250 ft) the velocity was decreasing progressively more rapidly and fell to about 3.05 m/min (10 ft/min).

(b) Proprietary ionisation chamber smoke detector

The detector was mounted under the tunnel roof at position 3. The response times were generally similar to those required for the optical density to reach a level of 15 per cent per metre and showed the same effects of fire area and distance from the fire as have been described for the optical measurements. Again there was no significant difference between fire positions A and B.

(3) Air temperature measurements

Some typical curves showing the increase of air temperature with time from ignition of the fire are given in Figure 6. For the smaller fire areas, and when measurements were made at considerable distances from the fire, the air temperature reached a relatively constant "plateau" value which is typical of steadily burning fires. In other cases the air temperature rose to well above that required for detection and therefore the fire was not continued for a sufficient time for a plateau value to be established.

A comparison of the measurements for fire positions A and B, shows that there was little difference in the air temperature rise produced after a given time from ignition. The air temperature rise was not dependent on whether or not the ventilating air was flowing up to 7.06 m (23.2 ft) from the fire, but beyond this distance there was a larger temperature rise when the ventilation system was in operation. In the case of the 0.37 m^2 fire, in which measurements were made up to 115 m, the air temperature rise was generally larger when the ventilation was in operation, up to about 61 m (200 ft). Beyond this distance the air temperature rise was small, and there was little difference between the two conditions. The effect of distance along the tunnel is shown in Figure 7, which indicates how the temperature rise, at a given time from ignition, decreased with distance along the tunnel, and fell to only about 1 to 2 degC beyond 61 m (200 ft).

In positionsA and B, for which a range of fire areas was used, the air temperature increased almost in proportion to the surface area, as can be seen in Figure 8.

(4) Heat detection

The theoretical response of a heat-sensitive detector is considered in the Appendix. In order to facilitate the analysis of the results, and to obtain operating times of a heat detector having the maximum sensitivity for a fixed temperature type placed in the tunnel, an ideal detector with a fixed setting of 54.4°C (130°F), and negligible time constant ($\tau = 0$) will be considered. Such an ideal detector would respond immediately to any rise in air temperature due to a fire, so that its temperature was always equal to that of the surrounding air. The response times of such a detector when tested according to the requirements of B.S. 3116 : 1959 are shown in Figure 9, together with the upper and lower limits of response time specified in the Standard. A curve for a typical rate-of-rise detector is also given for comparison, which shows that the ideal fixed temperature detector is more sensitive over the range of rates of rise of air temperature specified.

The ventilation system is designed so that the fans will come into operation when the tunnel ambient temperature has reached 32°C (90°F). This means that in designing a heat detection system two possibilities of fire occurring at an ambient temperature of 32°C have to be considered, i.e. the ventilated condition and the unventilated condition. In addition the possibility of a fire occurring at low ambient temperature in the unventilated tunnel has to be taken into account, and an ambient temperature of 0°C (32°F) will be considered for this purpose.

The operating times of the ideal heat detector were obtained from the air temperature rise curves, such as Figure 6, assuming that the time constant of the fine wire thermocouples is negligible. These times of operation are discussed below.

(a) Unventilated tunnel.

Ambient temperature 0°C (32°F)

The temperature rise resulting from the fires was generally insufficient to cause operation of the ideal detector, except for the 0.37 m^2 fire, which would have operated at 2.06 m (6.75 ft) from the fire in position A, which was the minimum used in the experiments (Figure 1).

Ambient temperature 32°C (90°F)

The ideal heat detector would have been operated by a 0.37 m^2 fire up to a distance of 25 m (182 ft). The appropriate operating times are shown in Figure 10, obtained from the experimental curves of air temperature rise for a setting of the detector of 54.4°C (130°F).

At this ambient temperature the 0.21 m^2 (2.25 ft^2) fire would also have been detected up to the maximum distance of 17.1 m used for this size of fire. The 0.093 m^2 (1 ft^2) fire could also have been detected at a distance of 2.06 m, but not at distances of 7.05 m and further from the fire.

(b) Ventilated tunnel

When the tunnel ventilation is in operation, the ambient temperature is unlikely to rise above 32°C, so operation of the heat detectors is referred to this ambient temperature.

For the 0.37 m^2 fire, the detector would have operated up to a distance of 20 m (65.7 ft) from the fire; the operating times are given in Figure 10 which shows that there was no significant difference between the operating times for the ventilated and unventilated conditions.

The 0.21 m^2 fire would have been detected up to the maximum distance used for this size of fire (17.1 m), but the 0.093 m^2 fire would not have been detected, even at 2.06 m from the fire.

4. Discussion

The results of the experiments indicate that only the 0.37 m^2 fire would have been detected by a heat sensitive detector at an ambient temperature of 0°C, and therefore the comparison of heat and smoke detectors made in this section is applicable to a fire of this area, which was the maximum size considered acceptable.

The most convenient way of comparing detection by smoke and by convected heat is to determine the distance at which a detector has to be situated from the fire to give a warning of fire in a given time. These distances have been plotted in Figure 11, using the results for the ideal heat detector at an ambient temperature of 32°C, and the results for the proprietary ionisation chamber smoke detector. The distances have been expressed in terms of the detector spacing (distance between detectors) and this results in different curves depending on whether or not the ventilating air current is flowing. If the ventilating air is flowing, the detector spacing required is equal to the distance required to give operation in a given time, because the flow of smoke and hot gases is in the direction of the air flow only. If there is no ventilating air flow, the detector spacing required is twice the distance for detection in a given time, since the combustion products can flow in either direction along the tunnel, and the maximum distance the fire can be from the nearest detector is equal to half the spacing. In general, the conditions when the ventilating air flow is flowing should be considered in designing the detector system, since these give the smaller spacing.

Figure 11 can be used in two ways; a comparison can be made by selecting a given time of detection and determining the spacings required for heat and smoke detectors, or the spacing required for a heat detection system can be taken, the operating time determined, and hence the spacing of a smoke detection system to give the same response time can be estimated. For example, if detection is required in no longer than 75 s, the curves show that a heat detection system would require a spacing of 13.7 m (45 ft), compared with 32 m (105 ft) for a smoke detection system. These figures apply to the ventilated tunnel at an ambient temperature of 32° C.

In order to design a system to detect a fire in the cable tunnel, the conditions to be taken into account are the range of ambient temperatures at which a fire may occur, and whether or not the tunnel is ventilated when the fire occurs. The ambient temperature may vary between 0°C and 32°C, but the 0°C condition is only applicable to the unventilated condition. The results indicate that a heat detector would respond to the 0.37 m^2 fire at a distance of about 2 m in 1.21 min, for an ambient temperature of 0°C, so that for the unventilated tunnel a spacing of 3.7 m (12 ft) should be appropriate for detection of a fire of this surface area. From Figure 11, the maximum response times of the ideal heat detector at this spacing would be 0.52 and 0.67 min for the unventilated and ventilated tunnel respectively, at an ambient temperature of 32°C. Therefore for a 12 ft detector spacing, the maximum operating times of the heat detector would be expected to range from 0.52 to 1.21 min. The maximum value (1.21 min) is appropriate for a slightly larger spacing, i.e. 4.1 m (13.5 ft), but it provides a margin of error for the 3.7 m spacing.

There are several criteria which may be used to determine the spacing of a smoke detection system which will have an equivalent performance to that of the heat detection system discussed above. Table 1 shows maximum response times for the heat detection system and for three spacings of smoke detector. The latter figures were obtained from the curves shown in Figure 11.

Table 1 : Maximum operating times of detectors (0.37 m^2 fire)

Type of detector	Spacing m (ft)	Maximum operating time (min)	
		Unventilated	Ventilated
Ideal heat detector	3.7 (12)	0.52 to 1.21 (32°C to 0°C ambient temperature)	0.67 (32°C ambient temperature)
Ionisation chamber smoke detector	7.3 (24)	0.42	0.67
	10.1 (33)	0.52	0.81
	24.4 (80)	0.87	1.12

The 7.3 m spacing gives a maximum response time equal to that of the heat detection system for the ventilated condition, and a more rapid response for the unventilated condition. For a 10.1 m spacing, the maximum response time would be equal to the minimum of that of a heat detector for the unventilated tunnel, but would result in a rather longer maximum time than the heat detector for the ventilated tunnel.

The 24.4 m spacing is chosen to give a maximum response time for the unventilated tunnel equal to the mean of those for the heat detector (0.87 min); the maximum response time for the ventilated tunnel would, however, be considerably longer than that for the heat detector.

A spacing of 10.1 m appears to be the most suitable, taking into account the greater cost of a smoke detection system. Such a spacing would give a maximum response time equal to the minimum expected for the ideal heat detector for the unventilated tunnel, and only about 20 per cent more (9s) for the ventilated tunnel. In practice, a commercial heat detector would generally be slower in response than the ideal heat detector selected as a basis for comparison, so that the relative performance of the smoke detector would be better than indicated. It would be expected that similar findings would apply to smoke detectors operating on other physical principles, such as optical types, which had similar settings for a warning of fire.

The above discussion applies to the 0.37 m^2 fire. For the 0.21 m^2 and the 0.093 m^2 fire, however, the smoke detector would be advantageous since it will respond to these smaller fires for both the ventilated and the unventilated condition (see Figure 4), taking a spacing of 10.1 m. In general, the heat detectors would not have been operated by the 0.093 m^2 fire at a 3.7 m spacing, because of the insufficient rise in air temperature produced. The 0.21 m^2 fire would be detected by the heat detector in the ventilated tunnel (ambient temperature equal to 32°C), but in the unventilated condition it would not be detected at an ambient temperature of 0°C. In the latter case, however, a heat detector would be expected to operate at an ambient temperature of 10°C, taking the 3.7 m detector spacing.

The results also show that smoke detectors can be used at large spacings if some sacrifice in response time can be accepted, whereas heat detectors must be closely spaced to enable fires to be detected at low ambient temperatures. Figure 11 shows that if a spacing of 30 m (98.5 ft) is taken, for example, the time of detection will be 0.96 min and 1.22 min for the unventilated and ventilated conditions respectively.

5. Experiments with 0.093 m^2 (1 ft^2) fire at position H

Some ancillary experiments were conducted with a 0.093 m^2 fire at position H to determine whether a fire in close proximity to the ventilation exit shaft would prove difficult to detect, because of the possibility of combustion products being carried across the tunnel directly into the shaft.

The air temperature measurements show that a fire of this area would not be detected by the ideal heat detector. It would, however, be detected by a smoke detection system, and the results indicate that the times of detection, at a given distance, would not be significantly more than for the fires situated at position A and B in the tunnel.

6. Conclusions

(1) Smoke detection

(a) The time of detection was found to be largely taken up in the movement of smoke along the tunnel to the detector, following which a rapid response occurred.

(b) With the ventilating air current flowing in the tunnel the time required to reach an optical percentage obscuration of 15 per cent per metre increased practically linearly with distance beyond 12 m (39.4 ft), and reached 3½ min at a distance of 113 m (370 ft).

(c) For the unventilated tunnel the time to reach an obscuration of 15 per cent per metre was greater than with ventilation beyond 21 m (68.9 ft), and increased rapidly beyond 76 m (250 ft), reaching a value of 10.7 min at 113 m.

(d) The operating times recorded for the proprietary ionisation chamber detector showed similar variations with distance from the fire as those observed for the optical measurements.

(2) Heat detection

(a) To detect a fire having an area of 0.37 m^2, which is judged the largest acceptable fire size, a spacing of 3.7 m (12 ft) would be required to cover the range of ambient temperatures from 0 to 32°C in the unventilated tunnel.

(b) At a 3.7 m spacing a fire of 0.21 m^2 (2.25 ft^2) in area would be detected in the ventilated tunnel, but in the unventilated tunnel this size of fire would not be detected at the lower ambient temperatures in the range 0 to 32°C.

(c) At a 3.7 m spacing a fire of 0.093 m^2 (1 ft^2) in area would not generally be detected.

(3) Design of detection system

(a) A heat detection system would require a spacing of 3.7 m (12 ft) in order to be able to detect a fire of 0.37 m^2 area fire at an ambient temperature of 0°C in the unventilated tunnel. Such a system would be expected to have maximum detection times ranging from 0.5 to 1.2 min in the unventilated tunnel (for ambient temperatures from 0° to 32°C), and 0.67 min for the ventilated tunnel (32°C ambient temperature).

(b) The spacing of a smoke detection system to give an equivalent performance to that of the heat detection system discussed in 3 (a) above, is dependent on the criteria which are adopted, and has to be a compromise to some extent. A spacing of 10.1 m (33 ft) is considered to be the most suitable, and gives a maximum response time for the ionisation chamber smoke detector equal to the minimum expected for the ideal heat detector in the unventilated tunnel (0.52 min), and only about 20 per cent more (9s) for the ventilated tunnel.

(c) A heat detection system is limited in its ability to detect the smaller fires at the 3.7 m spacing because they would not produce a sufficient rise in air temperature. A smoke detection system having an equivalent performance, in terms of speed of response to a fire of area 0.37 m^2, would not suffer from this limitation, however, and would be expected to respond to fires of area down to 0.093 m^2.

10. Acknowledgment

Mrs. P.S.M. Bedford carried out the analysis of the smoke obscuration and air temperature measurements.

11. Reference

(1) British Standard 3116 : 1959, Heat sensitive detectors for automatic fire alarm systems in buildings, British Standards Institution.

Appendix

Theoretical response of a heat detector

The rise in temperature of the sensitive element of a heat detector is caused by convective heat transfer from the combustion products rising from the fire. If θ_a and θ are the rise in the air temperature and in the temperature of the sensitive element, respectively, then the rise in temperature of the sensitive element $d\theta$, which takes place in an infinitesimal time dt (assuming that there are no heat losses from the sensitive element), is given by

$$HA\,(\theta_a - \theta)\,dt = C d\theta \qquad (1)$$

where H is the coefficient of convective heat transfer to the element,
A is the effective surface area of the sensitive element,
and C is the thermal capacity of the sensitive element.

Equation (1) reduces to:-

$$\frac{C}{HA}\,\frac{d\theta}{dt} + \theta = \theta_a \qquad (2)$$

In general θ_a, the rise in air temperature, is a function of time, f(t) say, so that equation (2) becomes:-

$$\tau\,\frac{d\theta}{dt} + \theta = f(t) \qquad (2a)$$

where τ is the time constant of the sensitive element $\left(= \frac{C}{HA}\right)$ and has dimensions of time.

In B.S. 3116 : 1959[1], the thermal tests involve linear rates of temperature rise, so that $f(t) = \alpha t$, where α is varied between 1 and 30 deg C/min. In this case the solution of equation (1) is:-

$$\theta = \alpha \left\{ t - \tau\,(1 - e^{-t/\tau}) \right\} \qquad (3)$$

and for most practical operating times this can be expressed as

$$\theta \simeq \alpha\,(t - \tau) \qquad (4)$$

If T_s is the setting of the detector (i.e. the temperature at which it will operate), and T_A is the ambient temperature, then the operating time, t_o, can be expressed as:

$$t_o = \frac{T_s - T_A}{\alpha} + \tau \qquad (5)$$

$$\text{since} \quad \theta = T_s - T_A$$

Therefore if a detector was positioned where the air temperature rose linearly at a rate of 10 deg C/min from an ambient temperature of 20°C, the time of response for a setting of 50°C, assuming a time constant of 0.5 min, would be

$$t_o = \frac{50 - 20}{10} + 0.5 = 3.5 \text{ min.}$$

In many practical situations, however, the f (t) is not a linear function of time, the coefficient of convective heat transfer varies during the fire development, and the detector may be of the rate-of-rise type, which makes the analysis more complex.

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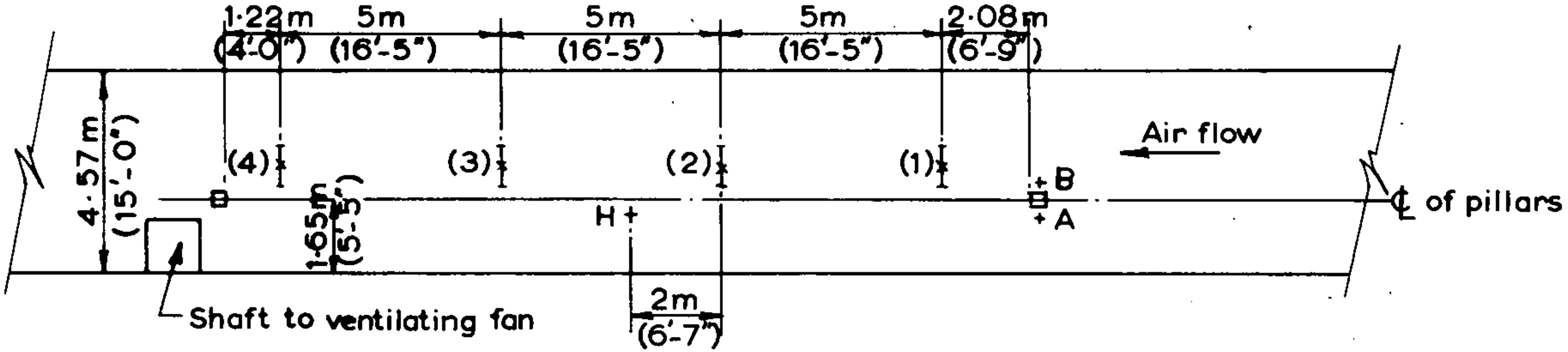
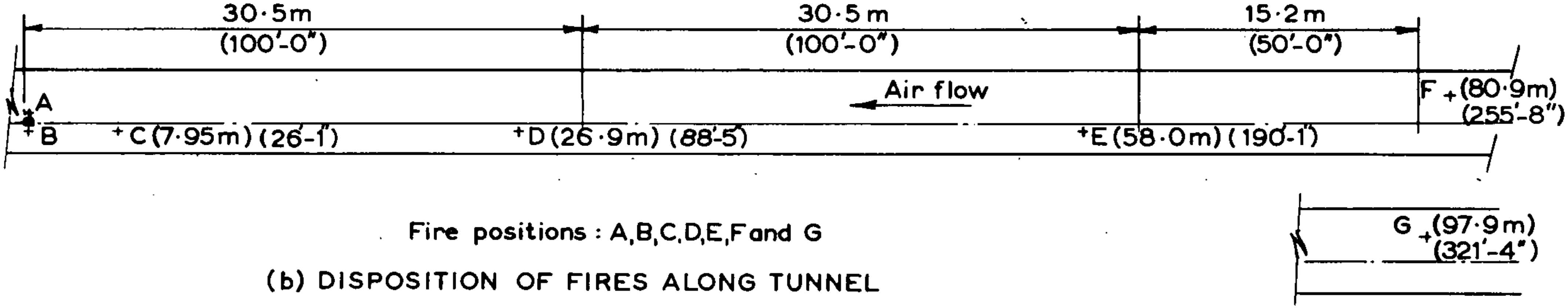


Measuring positions :(1),(2),(3) and (4)
Fire positions : A,B and H

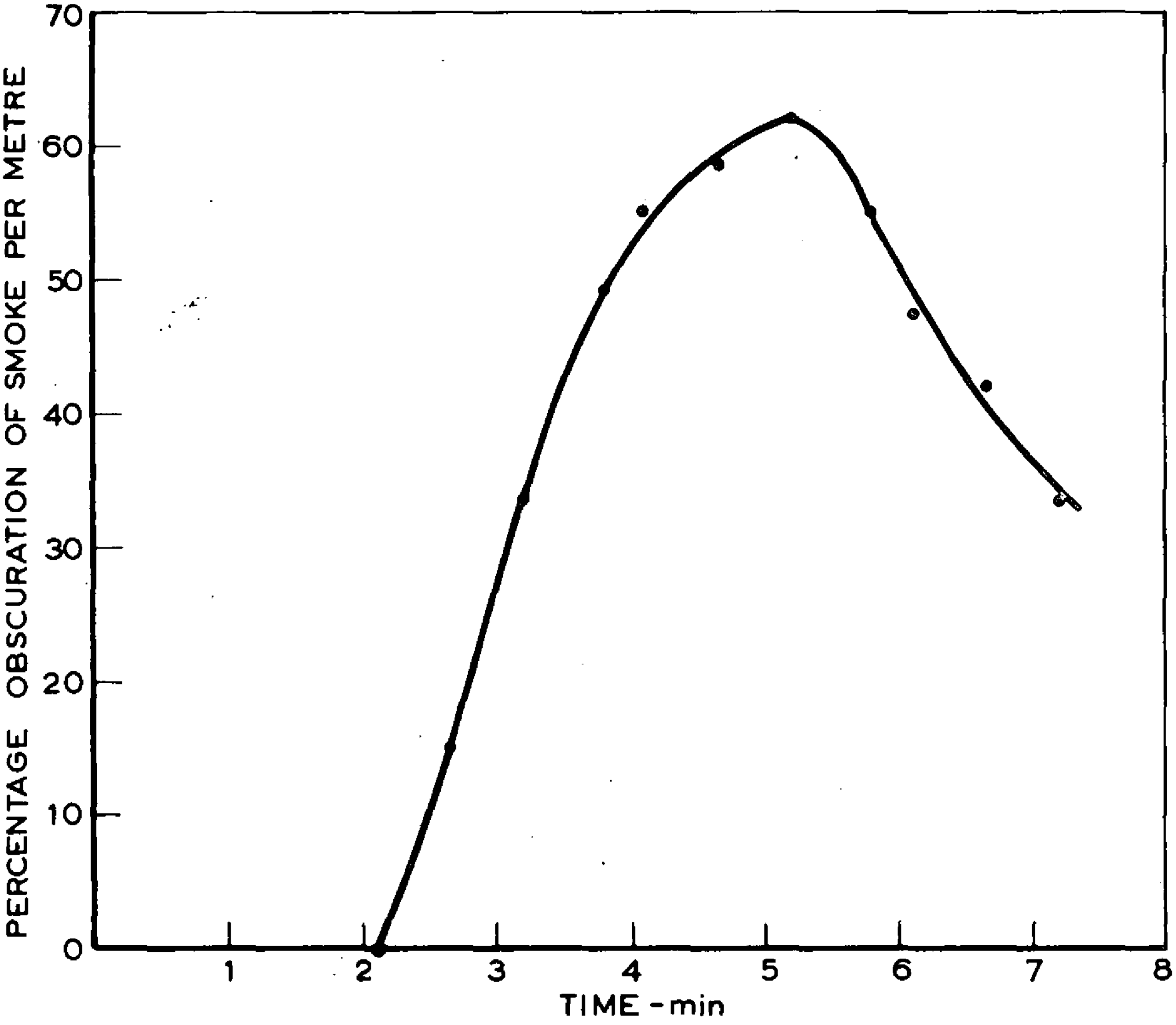
(a) ARRANGEMENT OF MEASURING POSITIONS



Fire positions : A,B,C,D,E,F and G

(b) DISPOSITION OF FIRES ALONG TUNNEL

FIG.1. PLAN VIEW OF TUNNEL SHOWING FIRE AND MEASURING POSITIONS



Fire area = 0·37m² (4ft²)
Distance from fire = 95·2m (312 ft)
Tunnel ventilated

FIG. 2. TYPICAL CURVE SHOWING VARIATION OF PERCENTAGE OBSCURATION OF SMOKE WITH TIME FROM IGNITION

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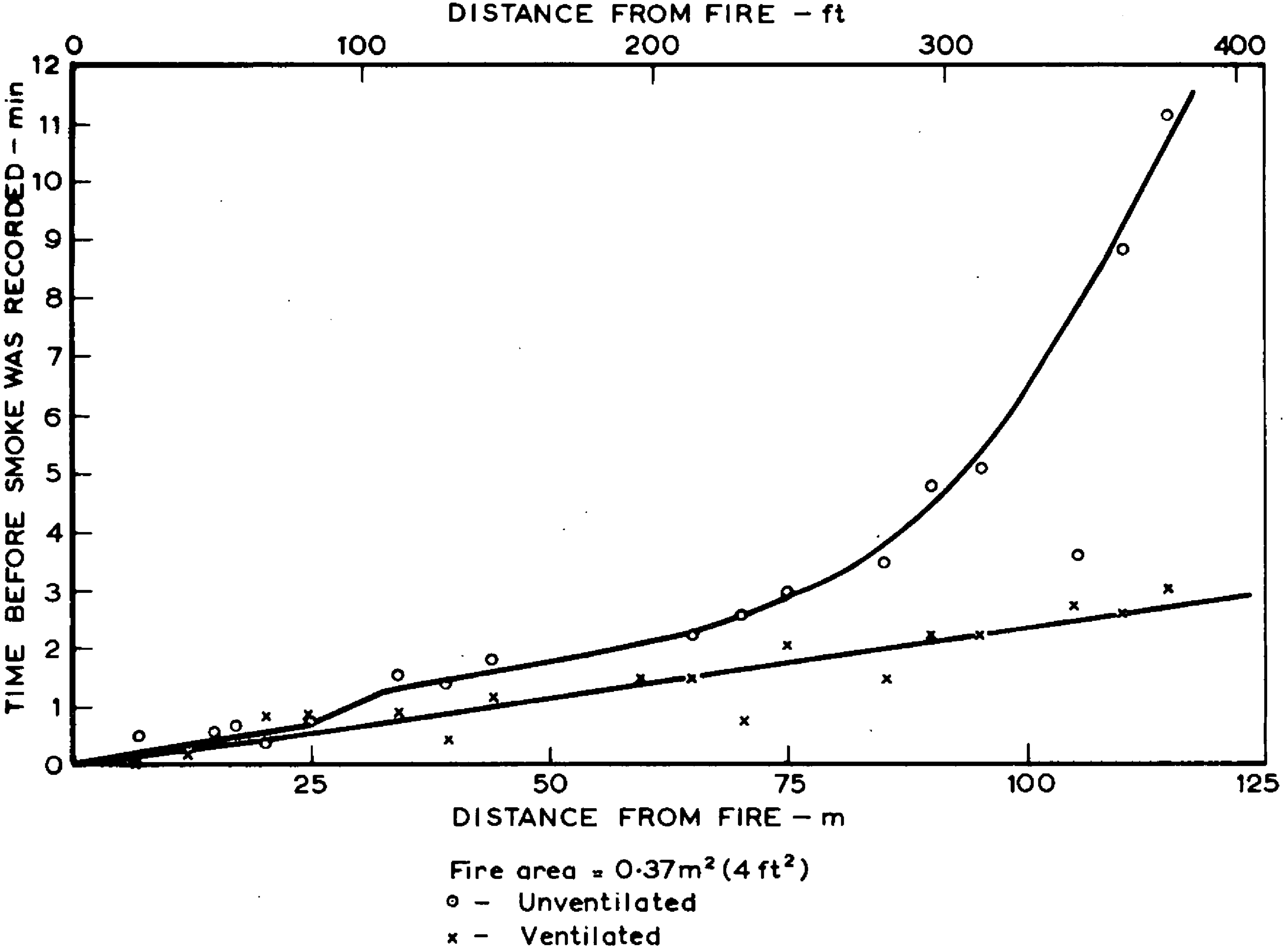
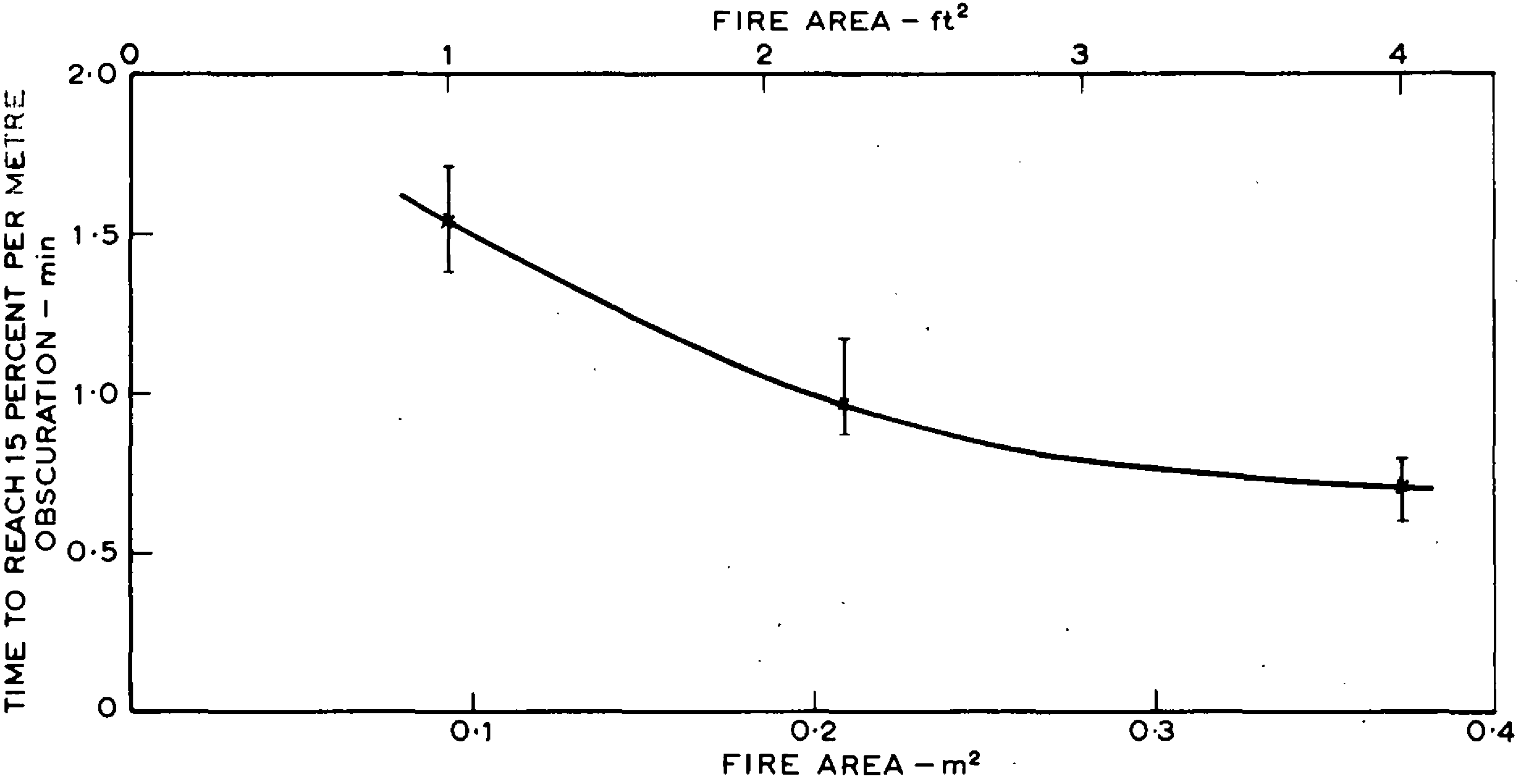


FIG.3. EFFECT OF DISTANCE FROM FIRE ON TIME TAKEN FOR SMOKE TO REACH MEASURING POSITIONS

1/8079 FR686



Distance from fire = 17·1 m (56 ft)
(Mean values for fire positions A and B
and for ventilated and unventilated conditions)

I Range of values

FIG. 4 . EFFECT OF FIRE SURFACE AREA ON TIME TO REACH 15 PERCENT PER METRE OBSCURATION

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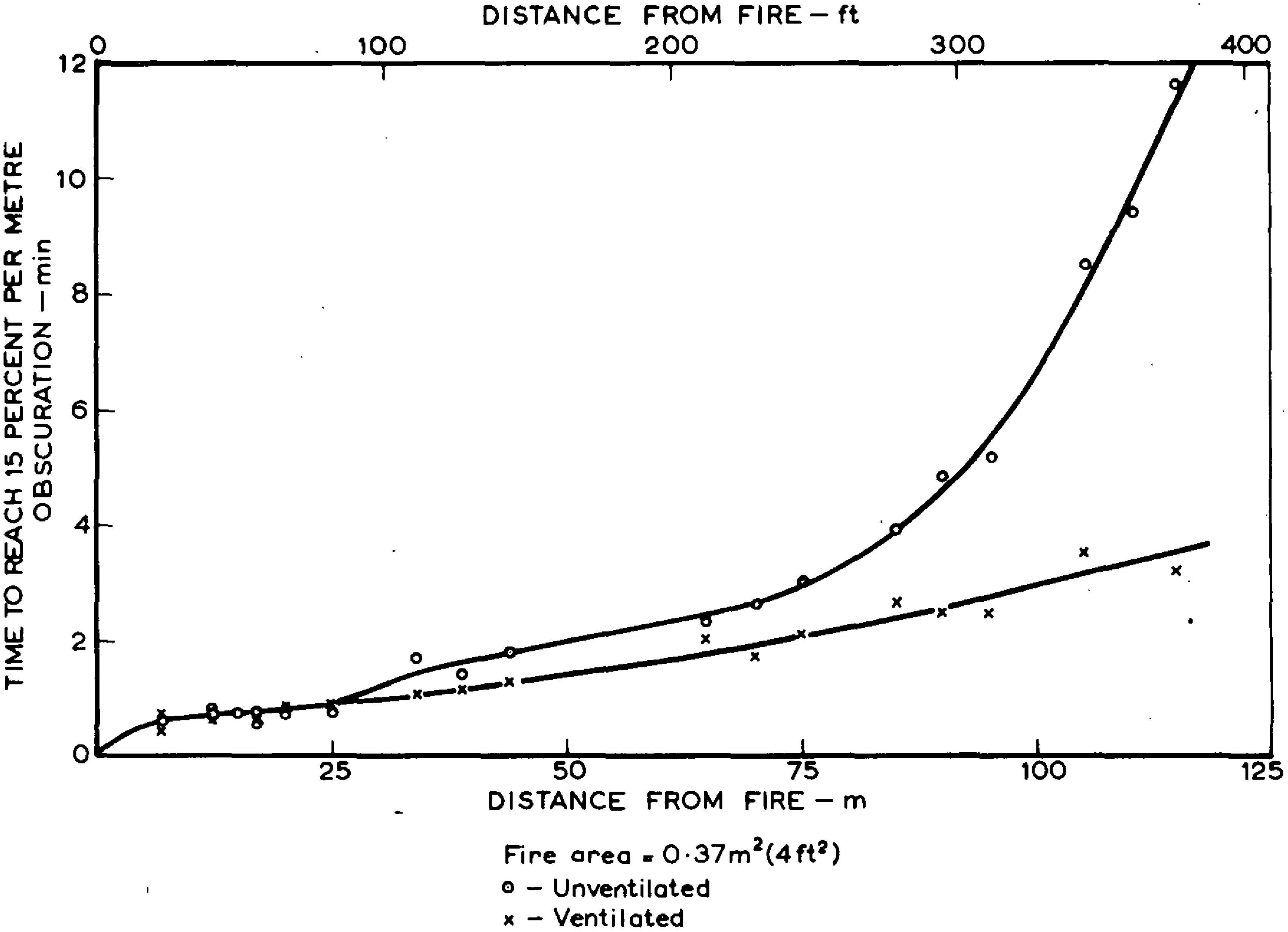
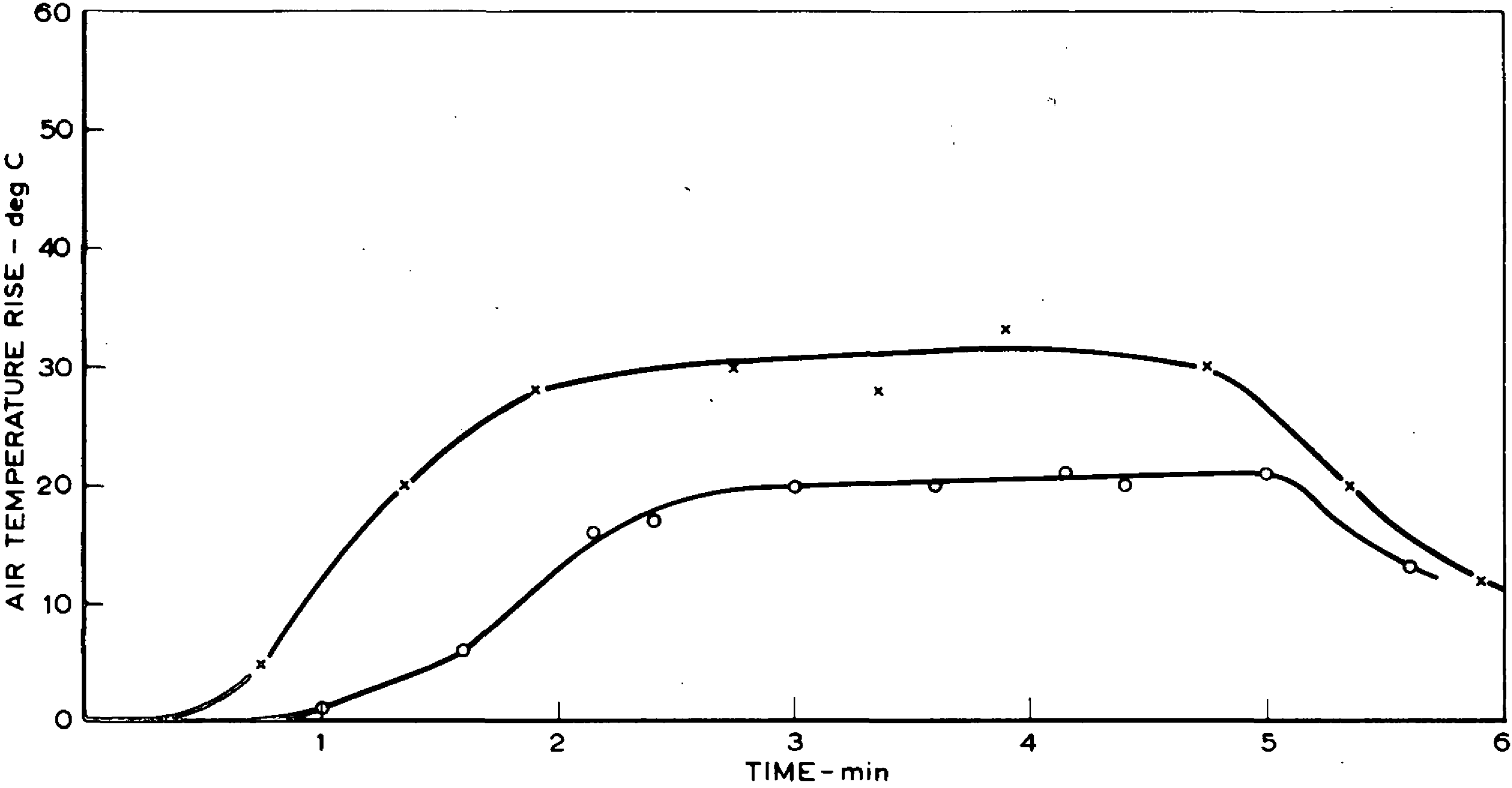


FIG.5. EFFECT OF DISTANCE FROM FIRE ON TIME FOR SMOKE CONCENTRATION TO REACH 15 PERCENT PER METRE OBSCURATION

1/8081 FR686



Fire area = 0·21 m² (2·25 ft²)
Tunnel unventilated
× - 7·1 m (23·2 ft) from fire
o - 17·1 m (56 ft) from fire

FIG. 6. TYPICAL CURVES SHOWING VARIATION IN AIR TEMPERATURE RISE WITH TIME FROM IGNITION

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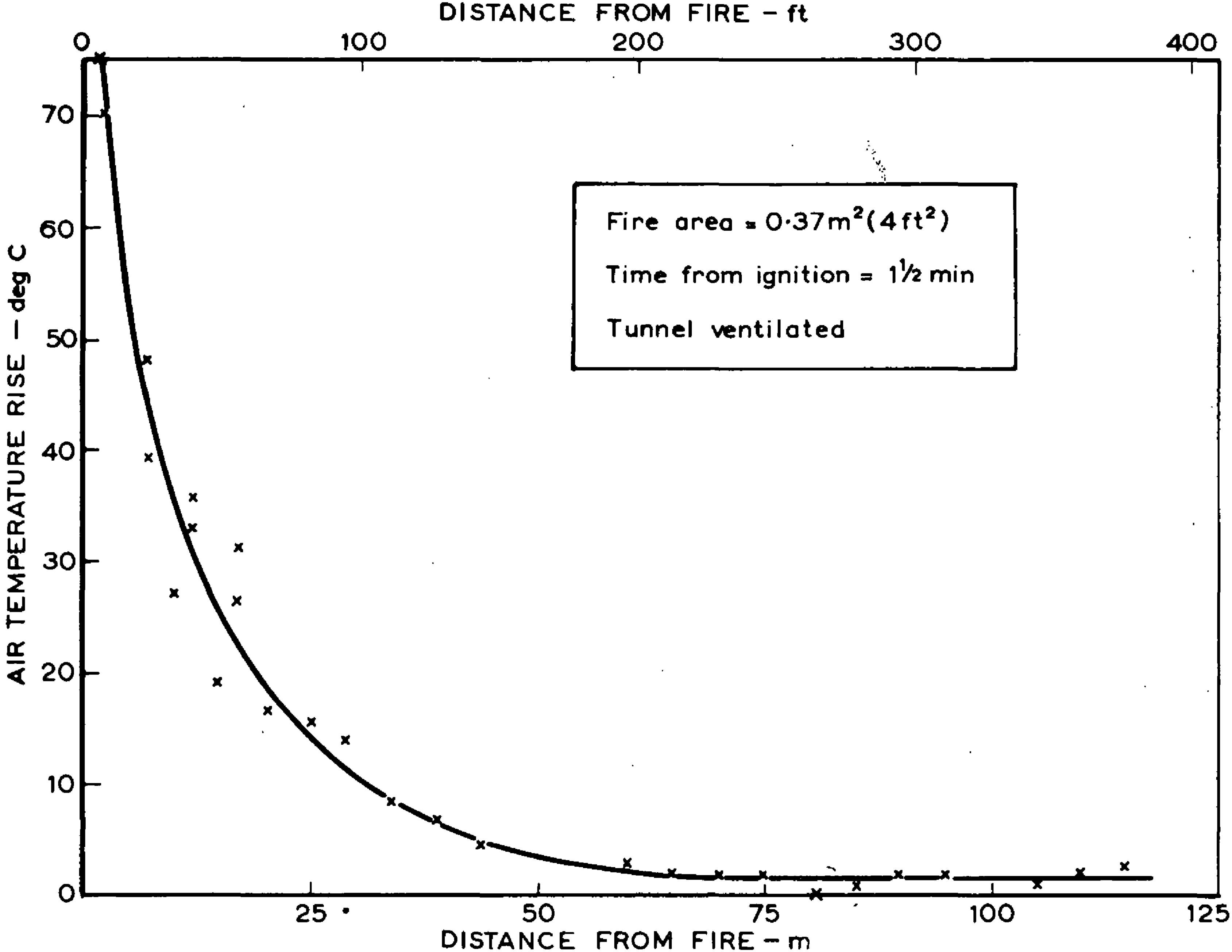

FIG. 7. EFFECT OF DISTANCE FROM FIRE ON AIR TEMPERATURE RISE

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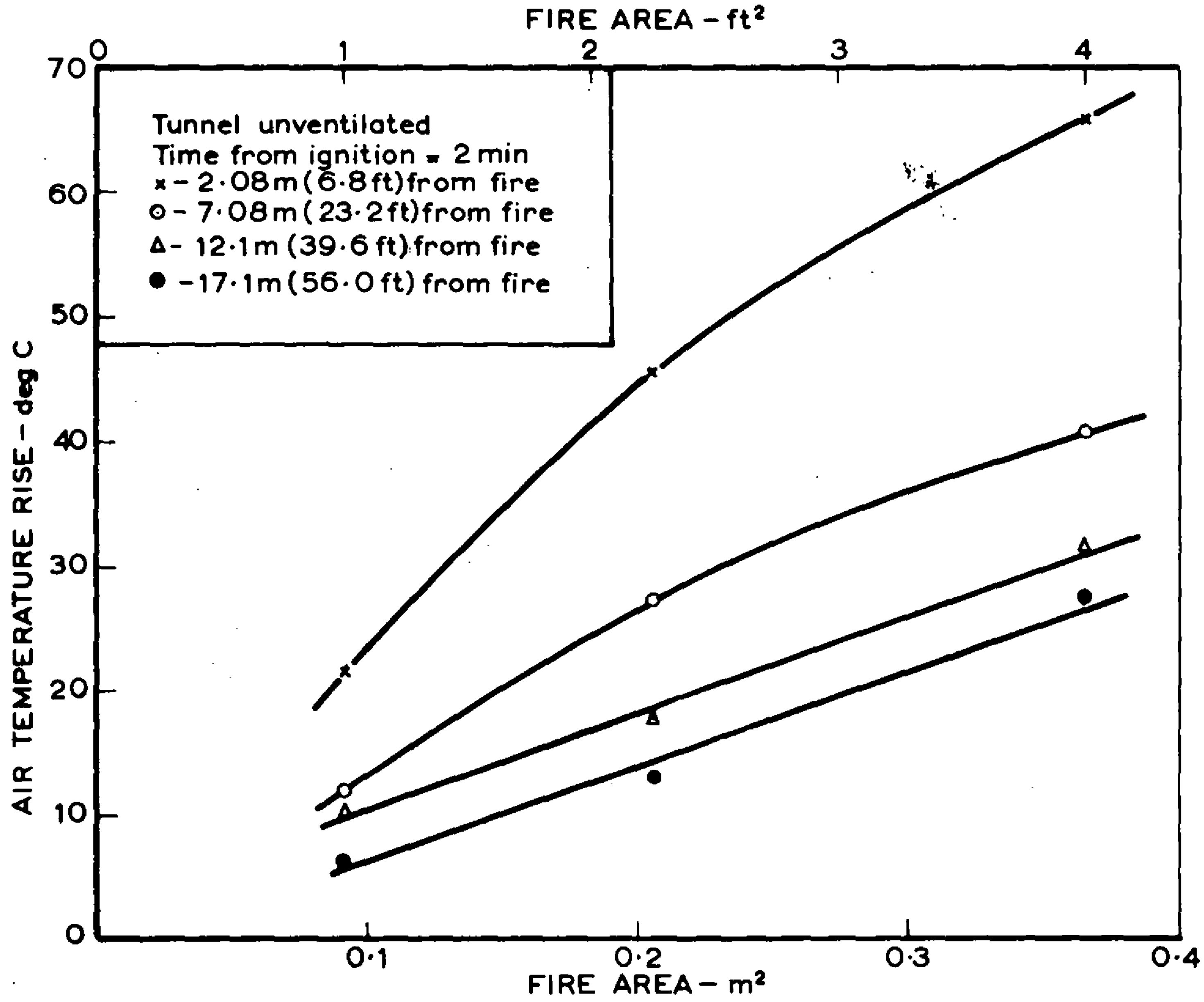


FIG. 8. EFFECT OF FIRE SURFACE AREA ON AIR TEMPERATURE RISE

1/8084 FR686

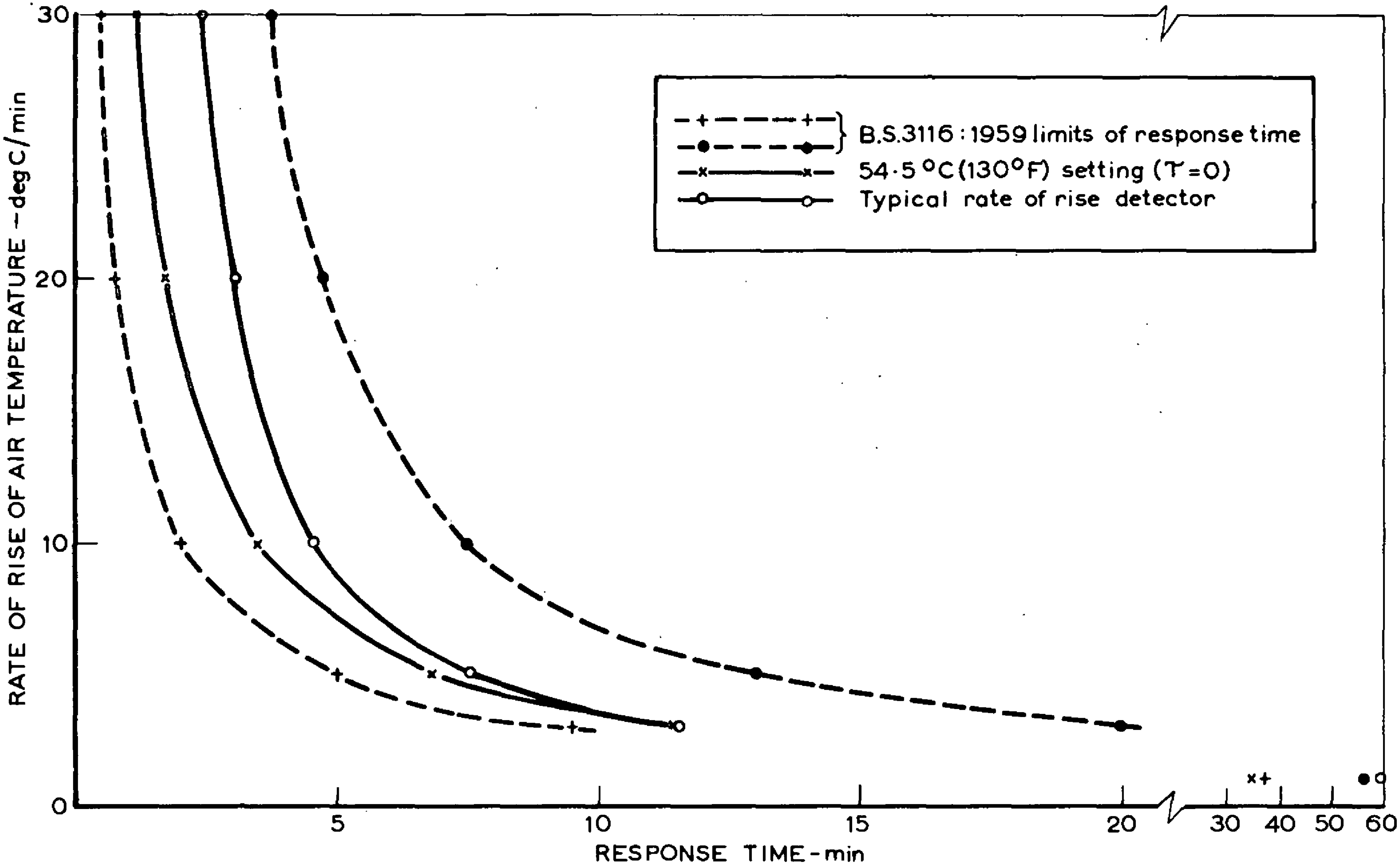
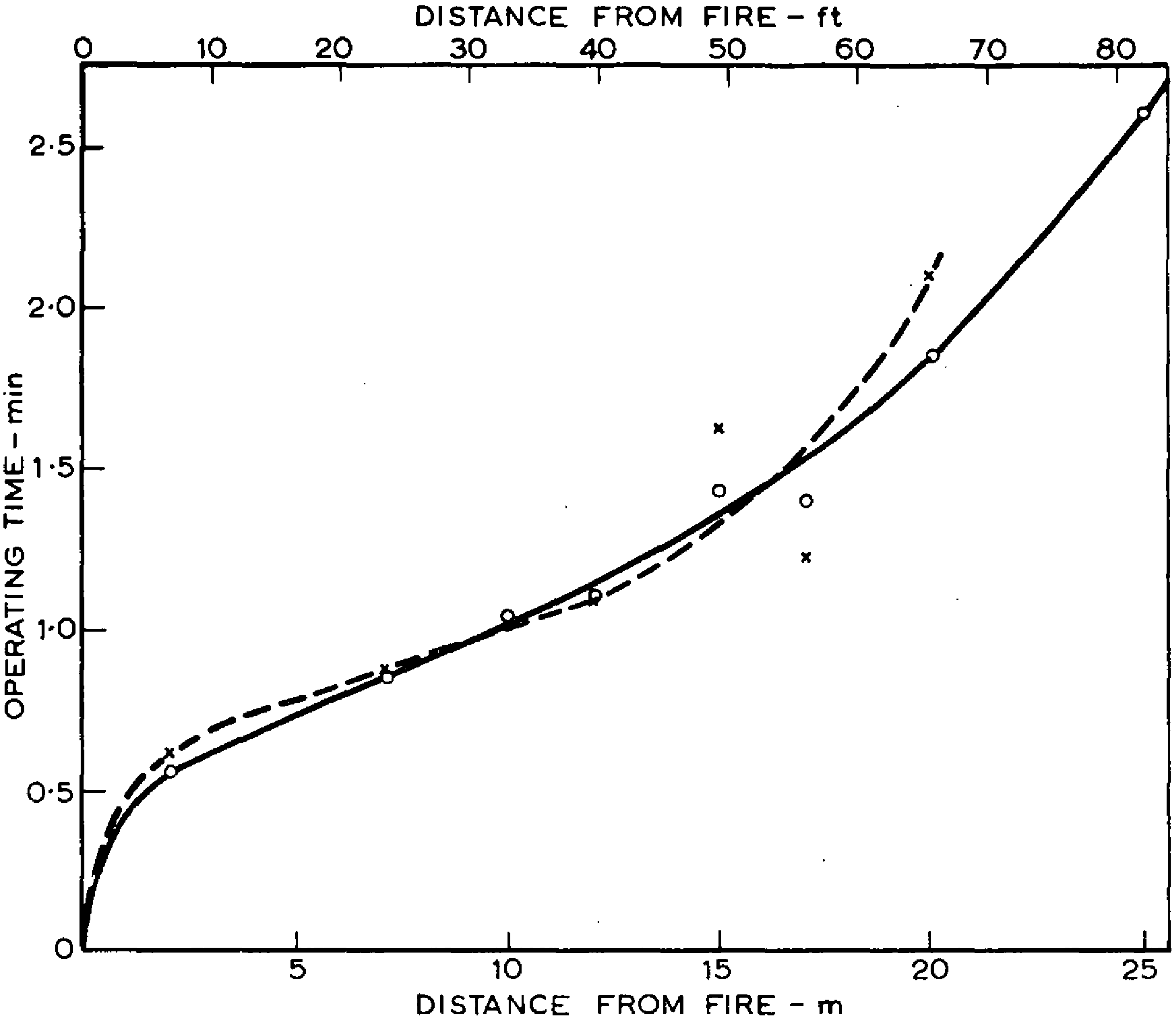


FIG. 9. RESPONSE TIMES OF HEAT DETECTORS IN THERMAL TESTS OF B.S. 3116 : 1959



Detector setting = 54·5 °C (130 °F) ($\tau = 0$)
Ambient temperature = 32 °C (90 °F)
Fire area = 0·37 m² (4 ft²)
Mean of positions A and B where appropriate
o – Unventilated tunnel
x – Ventilated tunnel

FIG. 10. VARIATION OF HEAT DETECTOR OPERATING TIME WITH DISTANCE FROM FIRE

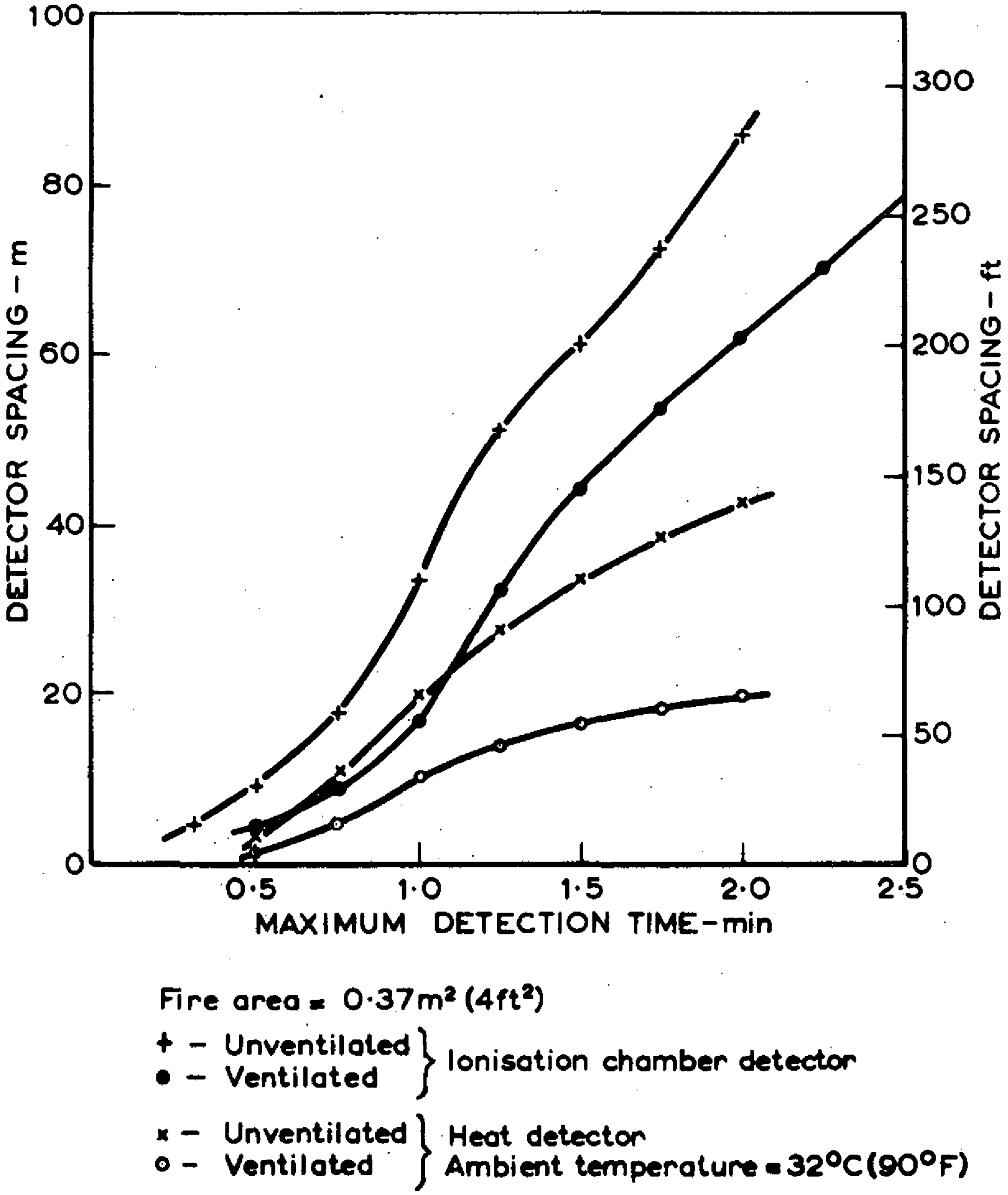


FIG. 11. VARIATION OF MAXIMUM DETECTION TIME WITH DETECTOR SPACING