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EXPERIMENTS ON SMOKE DETECTION
PART 1 : FLAMMABLE LIQUID FIRES

by

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SUMMARY

Experiments are described on the detection of the smoke emitted from fires in mixtures of alcohol and benzene. A room of volume 153 m^3 (5400 ft^3) was used, of height 2.46 m (8 ft 1 in), with the fires at distances of up to 6.10 m (20 ft) from the detection and measuring equipment. The rate of smoke emission was varied by changing the percentage of benzene in the mixtures, and measurements were made of the detection times of two proprietary smoke detectors, the optical density of the smoke and the rise in air temperature at ceiling level.

KEY WORDS: Investigation, smoke, detector, fire, flammable liquid.

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JOINT FIRE RESEARCH ORGANIZATION

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INTRODUCTION

The detection of fires in buildings by smoke, whether by detectors based on ionisation chambers or optical means, is dependent on the mass concentration of the smoke present, and on the physical properties of the smoke particles, such as size, shape, density, refractive index, etc.[1]. The problem of detection is complicated by the wide variety of smokes which may be produced from materials in protected premises, and by the physically unstable nature of smoke. The latter problem is brought about by processes of coagulation, sedimentation and condensation which are continuously taking place, and by dilution with air as the smoke rises with the hot gas stream from the fire and spreads laterally across the ceiling of the enclosure in which the fire is developing. These factors contribute to a dynamic process which may continuously modify the physical properties of the smoke during the growth of a fire. As a first step to obtaining background information on the detection of smoke, experiments were carried out to determine the effect of the rate of emission of a given type of smoke on the optical density and on the response of two proprietary detectors, while keeping the thermal output of the fire approximately constant. The experiments were conducted in a relatively small draught-free room having a volume of 153 m^3 (5400 ft^3).

Future work will cover a variety of fires, including cellulosic materials, rubber, plastic foams, and flammable liquids such as petrol and diesel oil. Experiments will also be performed in larger enclosures to examine the problems of smoke detection in large buildings, with particular regard to the effect of ceiling height on the rapidity of response.

EXPERIMENTAL

The experiments were performed in a room of lateral dimensions 8.84 m (29 ft) by 8.03 m (26 ft 4 in) and 2.46 m (8 ft 1 in) in height. The ceiling of the room was divided into three bays, the location and dimensions of which are shown in Fig.1. Two detectors were used in the work, an ionisation chamber type (detector A) and a light scattering type (detector B), which were mounted in the central bay at 1.68 m (5 ft 6 in) from one side of the room. A light source and photocell (Mullard ORP 60 - cadmium sulphide) were mounted in close proximity to the detectors in order to obtain a continuous measure of the optical density of smoke produced by the experimental fires. Details of the mounting of the detectors and optical density measuring device are shown in Fig.2. Measurements of the air temperature were made by a 121 µm (40 SWG) chromel/alumel thermocouple mounted between the two detectors at 102 mm (4 in) below the ceiling. The room was draught-proofed and blacked-out during the course of the experiments so as to eliminate the effect of extraneous draughts on smoke movement, and the effect of changes in the light intensity outside the room on the photocell output. The latter precaution will be unnecessary in later experiments for which the use of a compensating beam is envisaged.

Smoke was produced by steadily burning fires consisting of mixtures of benzene and industrial spirit. By varying the percentage of benzene in the mixture, the rate of smoke emission could be conveniently altered without changing the convective heat output by more than about 20 per cent. The mixtures were burnt in a circular tray of 102 mm (4 in) diameter, containing 500 cm^3 (0.88 pt) of fuel, and four fuel mixtures were used, containing 5, 10, 15 and 20 per cent of benzene.

The position of the fires relative to the detectors was varied along a line at floor level vertically beneath the centre line of the bay in which the detectors were mounted. The fires were mounted at distances of 0, 1.52, 3.05 and 6.10 m (0, 5, 10 and 20 ft) from a point immediately below the detectors.

In each experiment, the fire was ignited and the operating times of the two detectors from the moment of ignition were recorded. The air temperature rise at the point mid-way between the detectors was also measured, and the optical density of the smoke was continuously recorded. Two replications were made for each combination of the experimental variables, making a total of 32 experiments.

The detectors were connected to their normal control equipment, which gave an alarm indication at operation. Detector A was as originally set by the manufacturer, and detector B was set by the procedure specified by the manufacturer.

The thermocouple output was recorded continuously during the experiments so that a measure of the air temperature rise was obtained. In all the experiments the rise in air temperature was only a few degrees Celsius, because of the relatively low heat outputs of the fires. A heat-sensitive detector mounted on the ceiling would not have been raised to a sufficient temperature to give a fire alarm.

MEASUREMENTS OF OPTICAL DENSITY

The optical density of the smoke was obtained by recording the current through the photocell, which is proportional to the intensity of light falling on its sensitive surface. The optical density D of the air between the light source and the photocell is defined as[2]:

$$D = \log_{10} \frac{I_o}{I} \qquad (1)$$

where I_o is the intensity of light falling on the photocell in the absence of smoke

and I is the corresponding intensity when smoke is present.

The optical density at any time is obtained from the ratio of the photocell current in the absence of smoke to that at the particular time under consideration (equation 1). Some representative curves of the variation of optical density with time are given in Fig.3; the values of optical density quoted in this report are applicable to an effective optical path length of 0.508 m (1 ft 8 in).

The optical density of the smoke was found to increase almost linearly with time for all the experiments, as can be seen from Fig.3. In a number of cases there was evidence that a 'plateau' value was attained, the optical density remaining substantially constant, or falling off slightly, with time. The plateau value was reached in about 20-25 min from the start of the fire. There was considerable variability in the measurements taken immediately above the fire, where the smoke density varied rapidly with time, but from 1.52 to 6.10 m the results showed a very consistent pattern.

(a) Effect of distance from fire

The effect of distance can be studied by measuring the optical density of the smoke at a particular time after ignition of the fire. Some typical results are shown in Fig.4 for various percentages of benzene. The curves show clearly that there was a reduction in the optical density of the smoke with increasing horizontal distance from the fire upt to a distance of 3.05 m, but beyond this distance the optical density remained practically constant. The relationship was observed for all the rates of smoke evolution, and for all times during the experiments.

(b) Effect of rate of smoke evolution

The optical density increased with the percentage of benzene, and the form of the relationship is shown in Fig.5. These curves were obtained by taking the optical density at a particular time after the start of the fire, for a given horizontal distance from the fire. The optical density generally increased by a factor of 3 to 4 over the range of benzene percentages examined.

RESULTS FOR DETECTOR A

The operating times of the detector showed very good agreement between the two replications. There was only one unrepresentative result, which occurred for the 10 per cent benzene fire with the detector mounted immediately above it, and here the response time was very long. A repeat of this test, however, resulted in a response time which was of similar magnitude to the second replicate (see Table 1).

The most interesting feature of the results was that there was no operation of the detector in any of the tests in which the minimum concentration of 5 per cent benzene was employed, even when the fire was situated immediately below the detector. In these tests, however, the evolution and build-up of smoke was such as to be easily evident visually.

(a) Effect of distance from fire

The effect of the distance of the detector from the fire is shown in Fig.6 for different rates of smoke evolution, as determined by the concentration of benzene in the fire. The operating time was almost constant when the detector was immediately above the fire (about 11 s) for the fires with benzene concentrations in the range 10 to 20 per cent, but there was no response for the 5 per cent concentration over a period of 32-35 minutes.

The effect of distance from the fire was to increase the response time, and the increase was particularly marked for the 10 per cent benzene fire, rising to about 20 min at 1.52 m from the fire. The response time at this benzene concentration showed a decrease as the distance from the fire increased further, falling to about $15\frac{3}{4}$ min at 6.10 m. For the fires with 15 and 20 per cent benzene, the response times were markedly shorter at all distances up to 6.10 m. Thus at 20 per cent concentration, the maximum response time was approximately $1\frac{1}{4}$ minutes.

Although response time increased with distance from the fire in each case, reaching its maximum at 3.4-3.7 m (11-12 ft), the effect was relatively unimportant from a practical viewpoint over the range 1.52 m to 6.10 m.

(b) Effect of rate of smoke evolution

The rate of smoke evolution from the fire had a pronounced effect on the response time of detector A, giving a marked increase as the percentage of benzene was reduced below 15 per cent. The curves given in Fig.7 show the relationships between response time and percentage benzene at various distances from the fire. These are consistent with the fact that no response was observed for 5 per cent benzene at any distance, since the rate of increase of response time with reducing percentage benzene in the vicinity of the 10 per cent mixture is very high, tending to an asymptotic value of about 8 per cent. The curves show a progressive 'flattening-out' towards the 20 per cent benzene concentration, and show that for higher rates of smoke evolution than that represented by this fire, the reduction in response time, both proportional and actual, will be small.

The curve for the fires immediately under the detector differs in form from the other three curves, in that the response time was very little affected by the rate of smoke evolution over the range 10-20 per cent benzene. This is probably because the detector is mounted in the smoke plume, and the smoke conditions in the detector reach the critical level for operation very early in the fire growth. Nevertheless, the minimum benzene concentration for operation is above 5 per cent.

RESULTS FOR DETECTOR B

This detector operated in only 8 out of the 32 experiments. The majority of the responses were for the 20 per cent benzene fire, and no general effects of the variables can be ascertained. Where the detector did operate, the response times were much longer than those for detector A. For example, at 1.52 m from the fire, for the 20 per cent benzene fire, the response time had a mean value of about $18\frac{1}{2}$ min, compared with 38 s for detector A (see Table 1).

OPERATION OF AN OPTICAL DENSITY DETECTOR

The times required to reach a particular optical density represent the operating times of a detector 'set' at that optical density, if the measuring equipment were employed as a detecting device. The variation in operating time with setting is shown in Figs 8 and 9 for the 10 per cent and 20 per cent benzene fires. At the lower rate of smoke evolution, the detector would not respond for some of the higher settings. This results in the curves becoming asymptotic to the limiting value of optical density, as can be seen from Fig.8. The effect arises because the setting represents a higher optical density than the 'plateau' value attained during the experiment, e.g. at more than 3.05 m from the fire the detector is unlikely to operate if set at an optical density of 0.065 or more, for the 10 per cent benzene fire. The results show clearly that unless the detector is sufficiently sensitive, it is unlikely to operate, even though the fire emits smoke continuously. The lower the rate of smoke evolution and the farther the detector from the fire, the greater the sensitivity required to ensure operation. In Fig.10, the maximum values of optical density are plotted against distance from the fire for all the fires. From this figure, the requisite settings of optical detectors necessary for operation under the conditions of the experiment can be obtained. For example, operation at distances up to 6.10 m from the 5 per cent benzene fire would require an operating optical density setting of not more than 0.03. For the 20 per cent benzene fire, however, an optical density setting of not more than 0.10 would permit operation.

(a) Effect of distance from fire

The effect of the distance of the detector from the fire is dependent on the operational level of optical density. In general, the operating time increased with distance, but there was a 'flattening out' of the curves beyond 3.05 m with comparatively little increase in the time required for operation beyond this distance. Some typical results are shown in Fig.11. At higher levels of setting, the detector would not have operated at the lower rates of smoke evolution, or operation would have been restricted to a detector sited relatively close to the fire (Fig.8). An optical density of 0.02 was necessary to ensure operation for the range of experimental conditions examined; for a setting of optical density equal to 0.06 there would have been no operation of a detector for the 5 per cent benzene fire.

(b) Effect of rate of smoke evolution

As the rate of smoke evolution increased, the operating time of the detector decreased rapidly. Typical results are shown in Fig.12. If the setting was increased, the response times became longer, increasing rapidly for the fires with the lower rates of smoke evolution. Above a particular density (corresponding to the plateau values) there would be no response of the detector. This is shown in Fig.12 where for fires at more than 3.05 m from the detector the curves are asymptotic to a critical value of percentage benzene, below which there would be no response to the smoke produced.

COMPARISON OF DETECTORS

The curves in Fig.13 compare the relative operating times of two types of detector, for different response settings of the optical density type, and one setting of detector A, at a distance of 6.10 m from the fire. For example, if both detectors operated in the same time under all conditions, the locus of the comparative curve of operating times would be a straight line at 45 degrees to each axis, passing through the origin. For an optical density type operating at D = 0.03, the locus of the comparative curve, for the rates of smoke evolution of the fires used, is shown by the curve labelled 'D = 0.03'. This curve shows that atrelatively high smoke densities, the detector A would be quicker to respond than would the optical density type. As the actual smoke level is reduced, the performance of the optical density detector overtakes that of detector A. Similar curves are shown for optical density settings of 0.01, 0.02, 0.04, 0.05, 0.06 and the relative positions of these curves show that at the higher optical density settings, detector A is quicker over a greater range of smoke evolution rates than for the 0.03 setting, and vice versa. To obtain a comparable or better performance over the whole range of rates of smoke evolution, an optical density type would need to be set to operate at a level of D= 0.01, and at this level it would be superior to type A except at the highest rate of smoke evolution used. As the rate of smoke evolution falls, it would become progressively more effective than detector A. A setting of D = 0.01, however, is probably too sensitive for the general protection of fire risks in buildings, since it represents an obscuration of only 2.4 per cent over an optical path of 0.508 m.

At higher settings of optical density the results show detector A to be more sensitive, except for fires with the lower rates of smoke emission (Fig.13). At a setting of D = 0.03, for example, detector A was more sensitive with the exception of fires with rates of smoke evolution below that represented by the 10 per cent benzene fire.

DISCUSSION AND CONCLUSIONS

The experiments show that consistent smoke measurements can be obtained using flammable liquid fires in a relatively small room (having a volume of 153 m^3 (5400 ft^3)).

The optical density of the smoke was found to increase linearly with time during the fires, reaching a plateau value after 20-25 minutes. It has been shown that the optical density of wood and coal smokes is proportional to the mass concentration of smoke[4,5], so that the optical density measurements can be used as a convenient measure of the way in which the mass concentration of the smoke increases with time. The importance of the plateau value of optical density is that it shows that operation of a detector dependent on this parameter will not occur if the setting of the device is higher than the plateau value applicable to such steadily burning fires.

Detector A was found to have a rapid response to the fires with the higher rates of smoke evolution, but the response times increased rapidly at lower rates of evolution, and the detector did not operate for the fire having the lowest rate of smoke production. A detector depending on changes in optical density in the atmosphere could respond more rapidly than detector A at relatively low rates of smoke emission, providing the operating level is suitably chosen. More information on the effect of changes in the setting of detector A, however, is required to provide a comprehensive comparison with the optical density device, and in practice similar sensitivities may be necessary to avoid the occurrence of false alarms.

Detector B was found to be relatively insensitive to this type of fire, in that it operated only intermittently, and its response times on operation were comparatively long.

The effect of distance from the fire was similar for detector A and for a detector using the optical density principle. There was an increase in response time up to about 3.05 m from the fire, but beyond this distance there was little practical change in response. This result is reflected in the constant value of optical density (and presumably mass concentration) beyond 3.05 m from the fire.

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Table 1

Operating times of detectors A and B

Distance from fire (ft)	Operating time (min - s)							
	5 per cent benzene		10 per cent benzene		15 per cent benzene		20 per cent benzene	
	A	B	A	B	A	B	A	B
0	- -	- 27-50	19-55 0-15 0-10 (1)	- -	0-10 0-10	- 4-32	0-09 0-12	16-32 11-55
5	- -	- -	18-32 21-20	- -	3-15 3-11	- -	0-40 0-35	20-40 16-28
10	- -	- -	17-16 18-15	35-32 -	4-40 4-00	- -	1-23 - 1-08 (1)	19-28 -
20	- -	- -	14-42 16-40	- -	3-20 3-25	- -	0-47 0-38	- -

(1) Third replication carried out.

No entry in the table indicates that the detector failed to operate during the experiment.

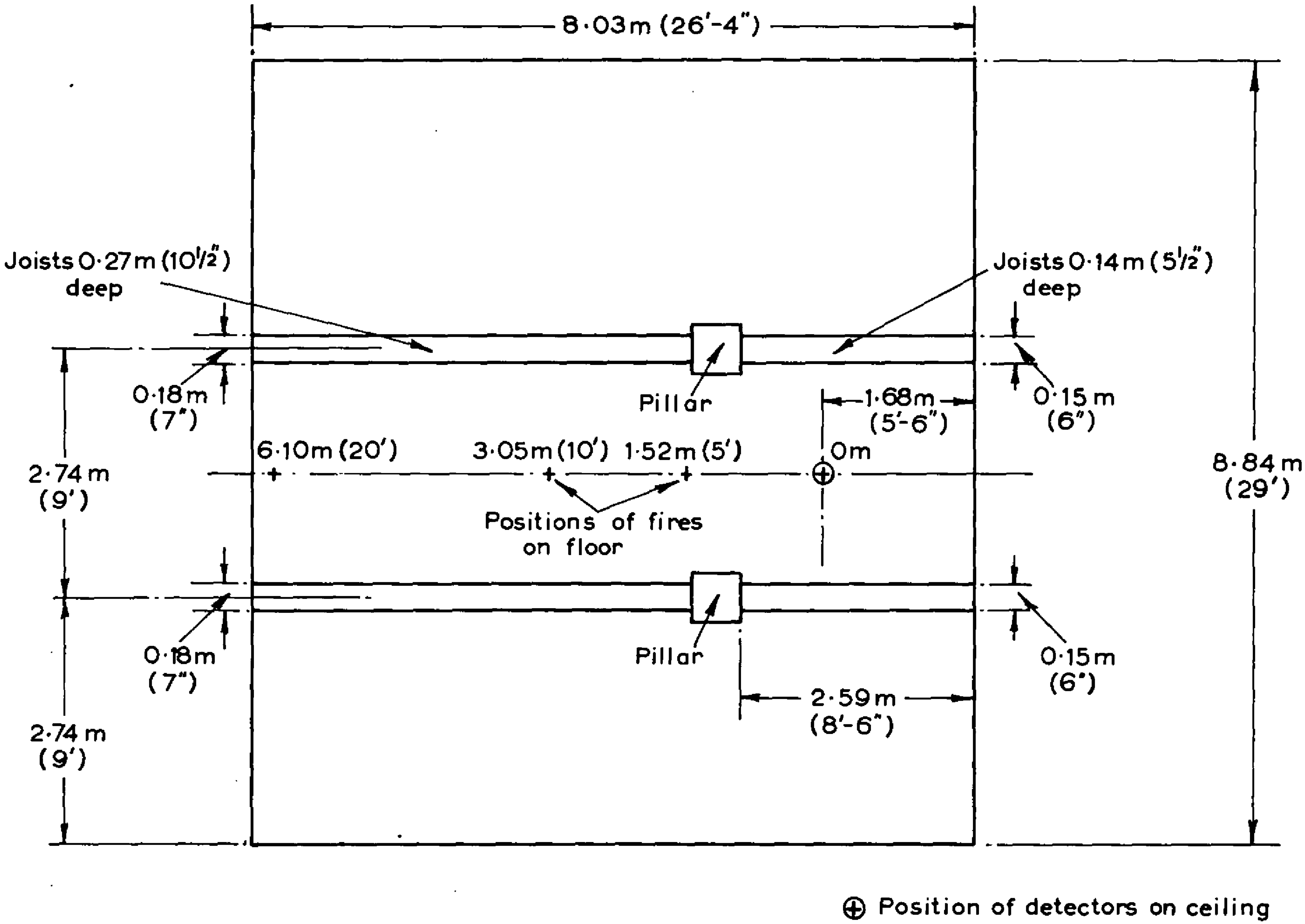

FIG.1. DIMENSIONS OF ROOM

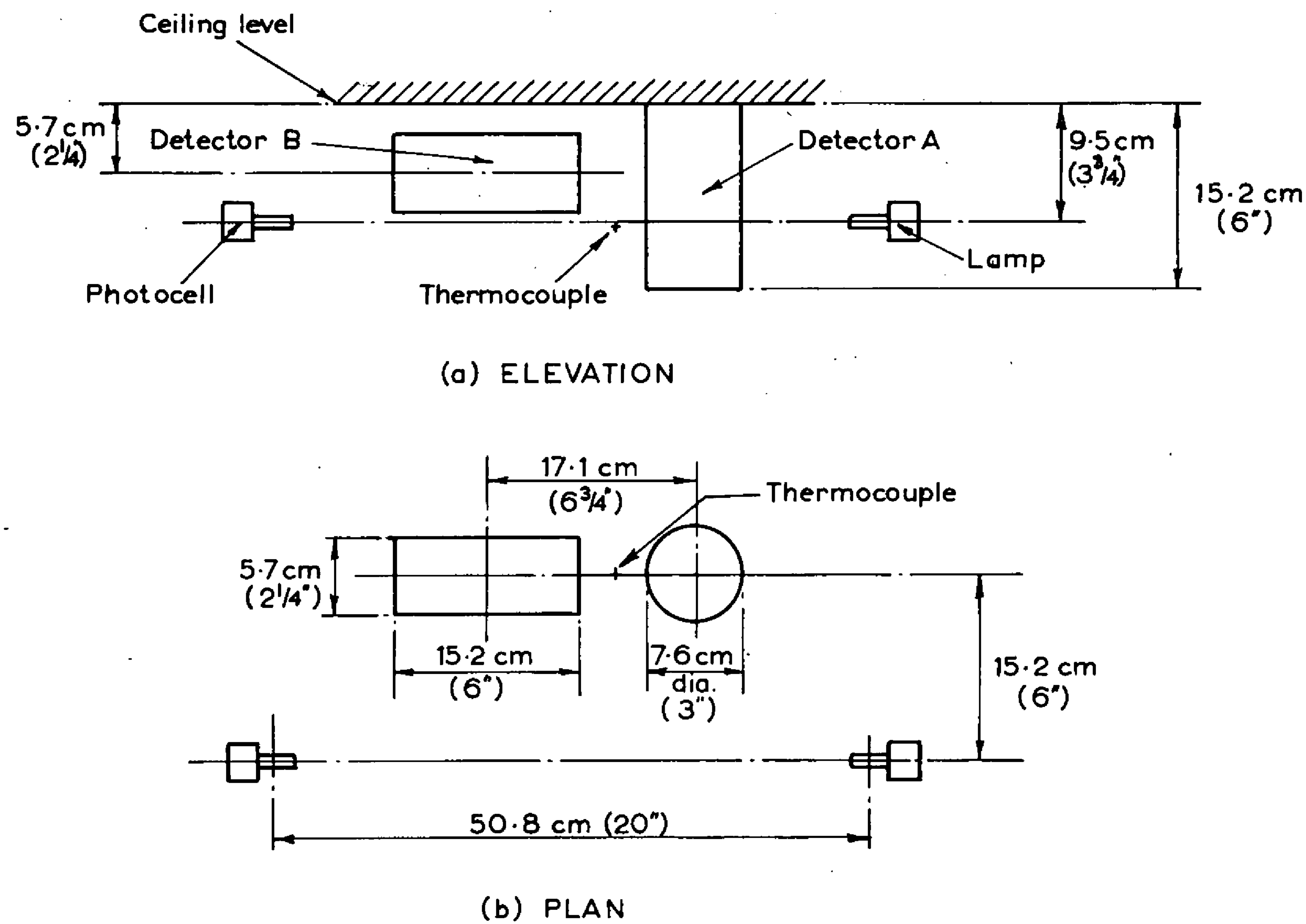

FIG. 2. ARRANGEMENT OF EQUIPMENT BELOW CEILING

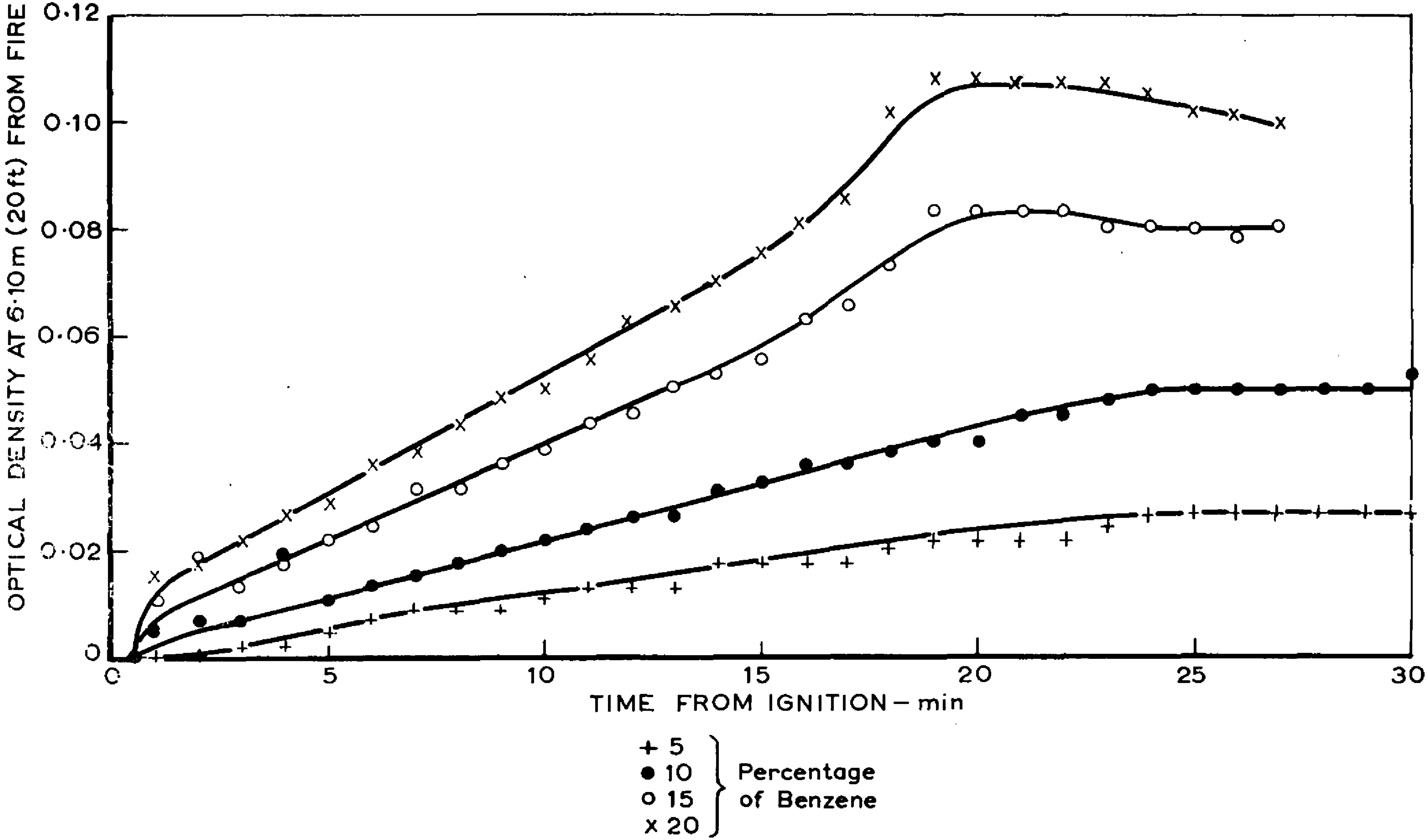

FIG. 3. VARIATION OF OPTICAL DENSITY WITH TIME

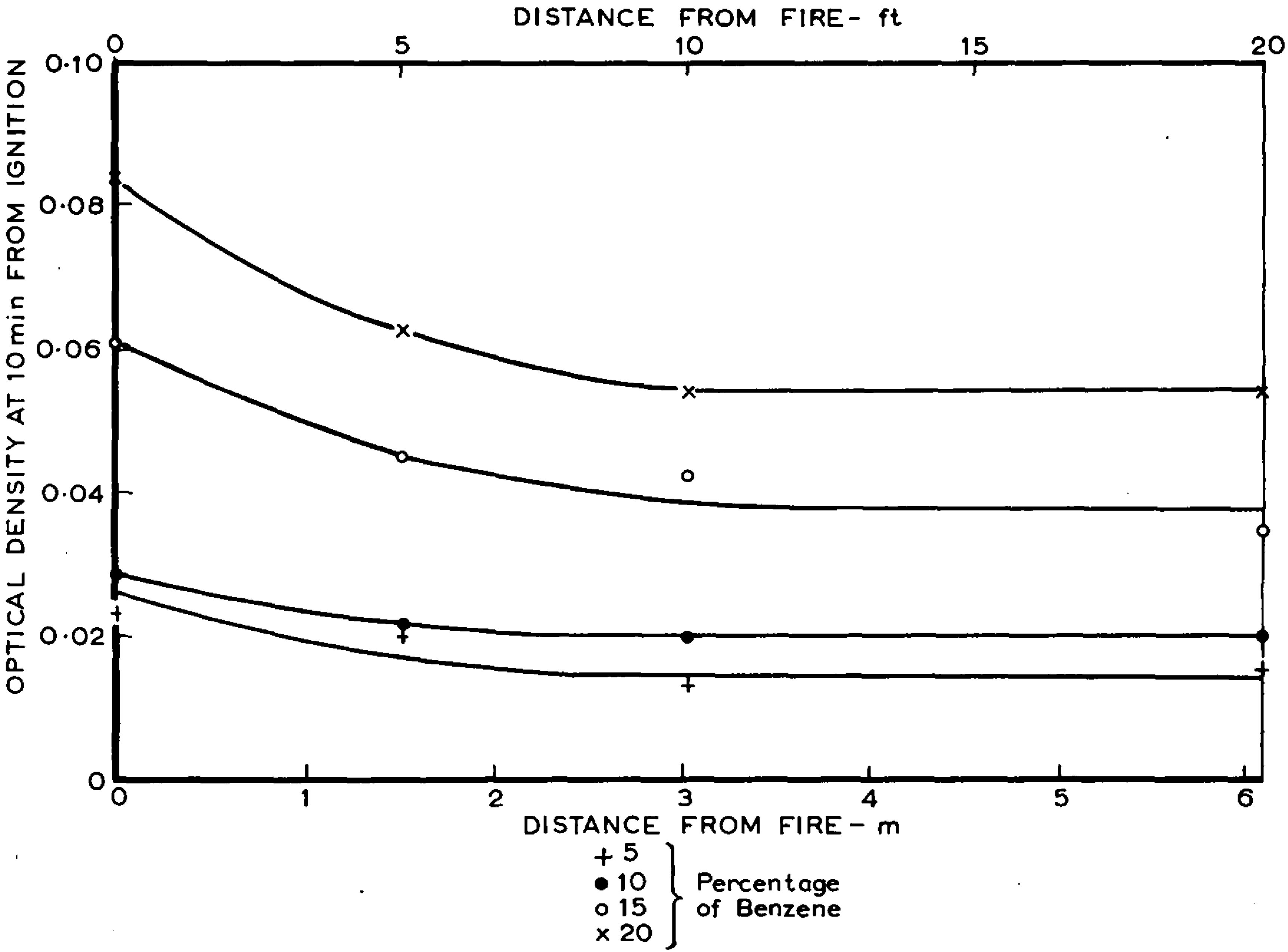

FIG. 4. VARIATION OF OPTICAL DENSITY WITH DISTANCE FROM FIRE

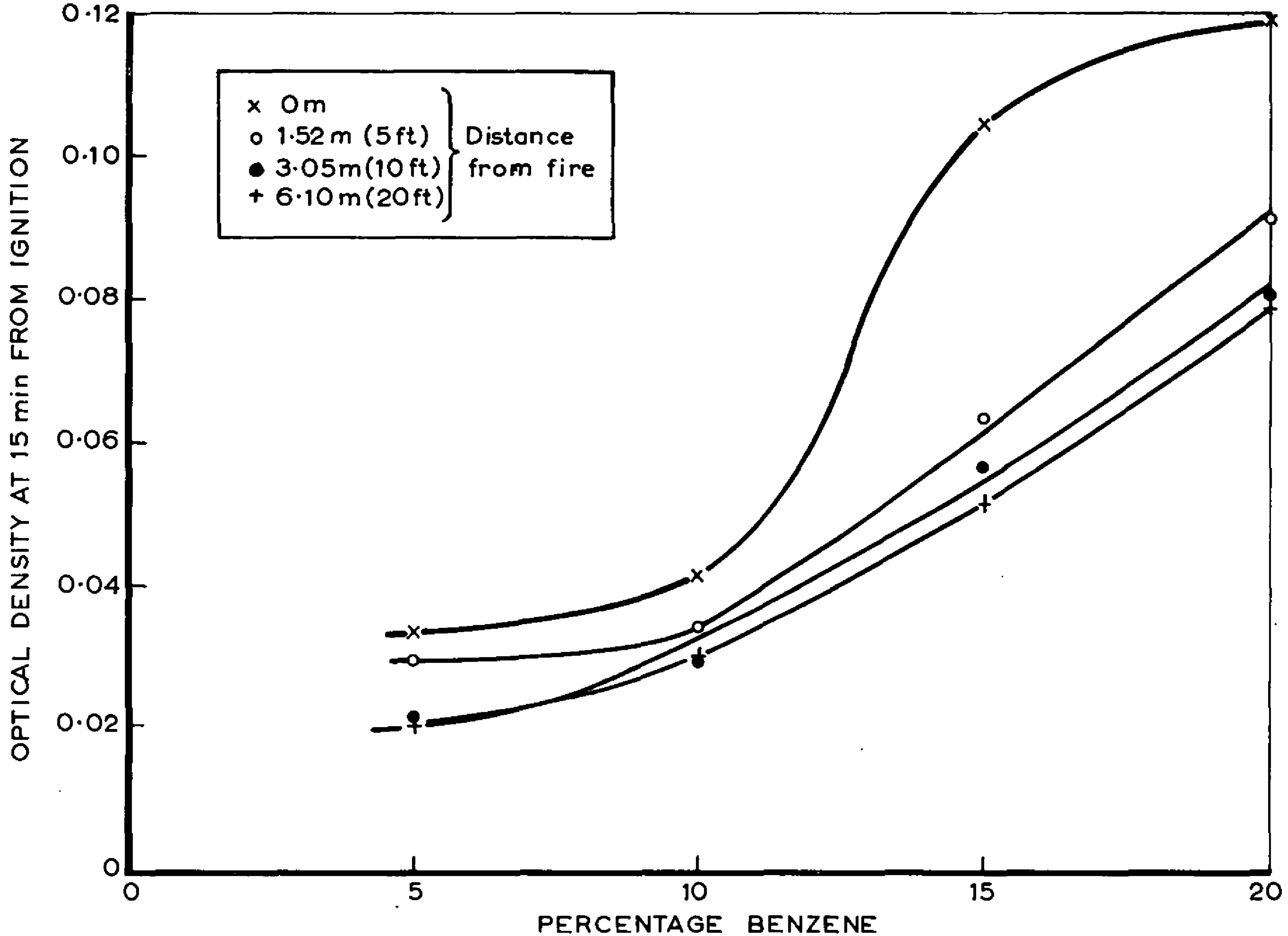

FIG. 5. VARIATION OF OPTICAL DENSITY WITH PERCENTAGE BENZENE

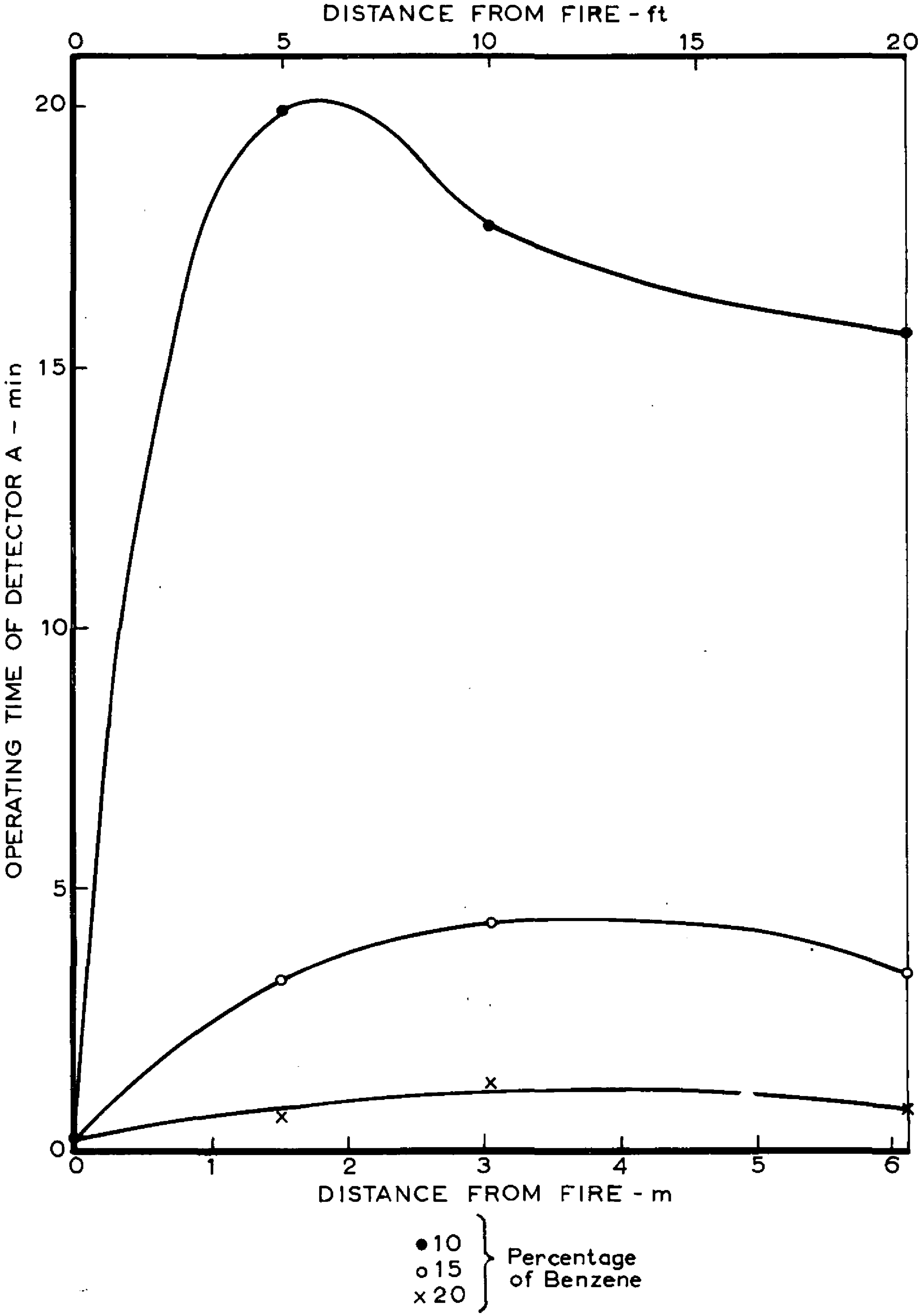

FIG. 6. VARIATION OF OPERATING TIME OF DETECTOR 'A' WITH DISTANCE FROM FIRE

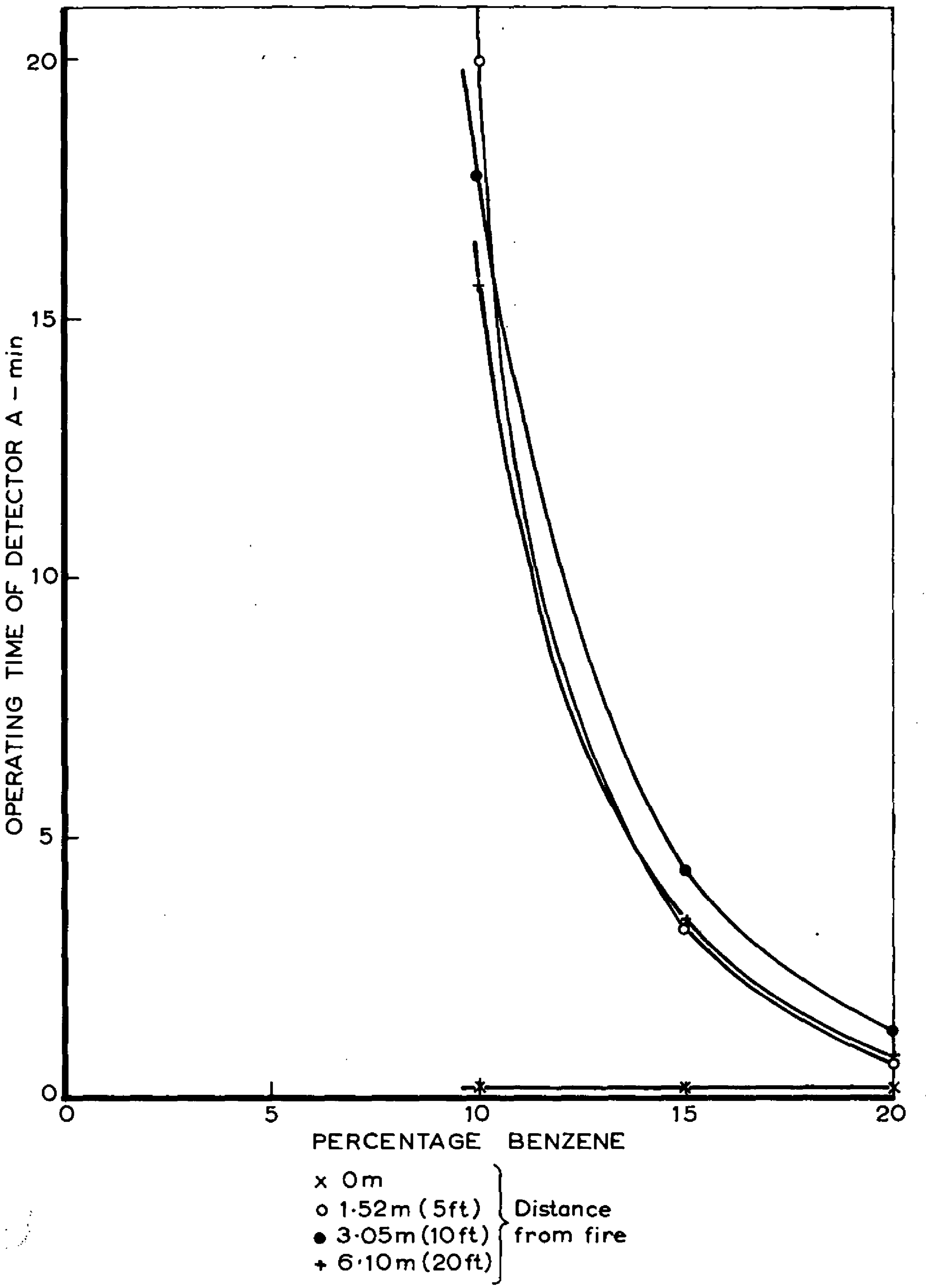

FIG. 7. VARIATION OF OPERATING TIME OF DETECTOR 'A' WITH PERCENTAGE BENZENE AT VARIOUS DISTANCES

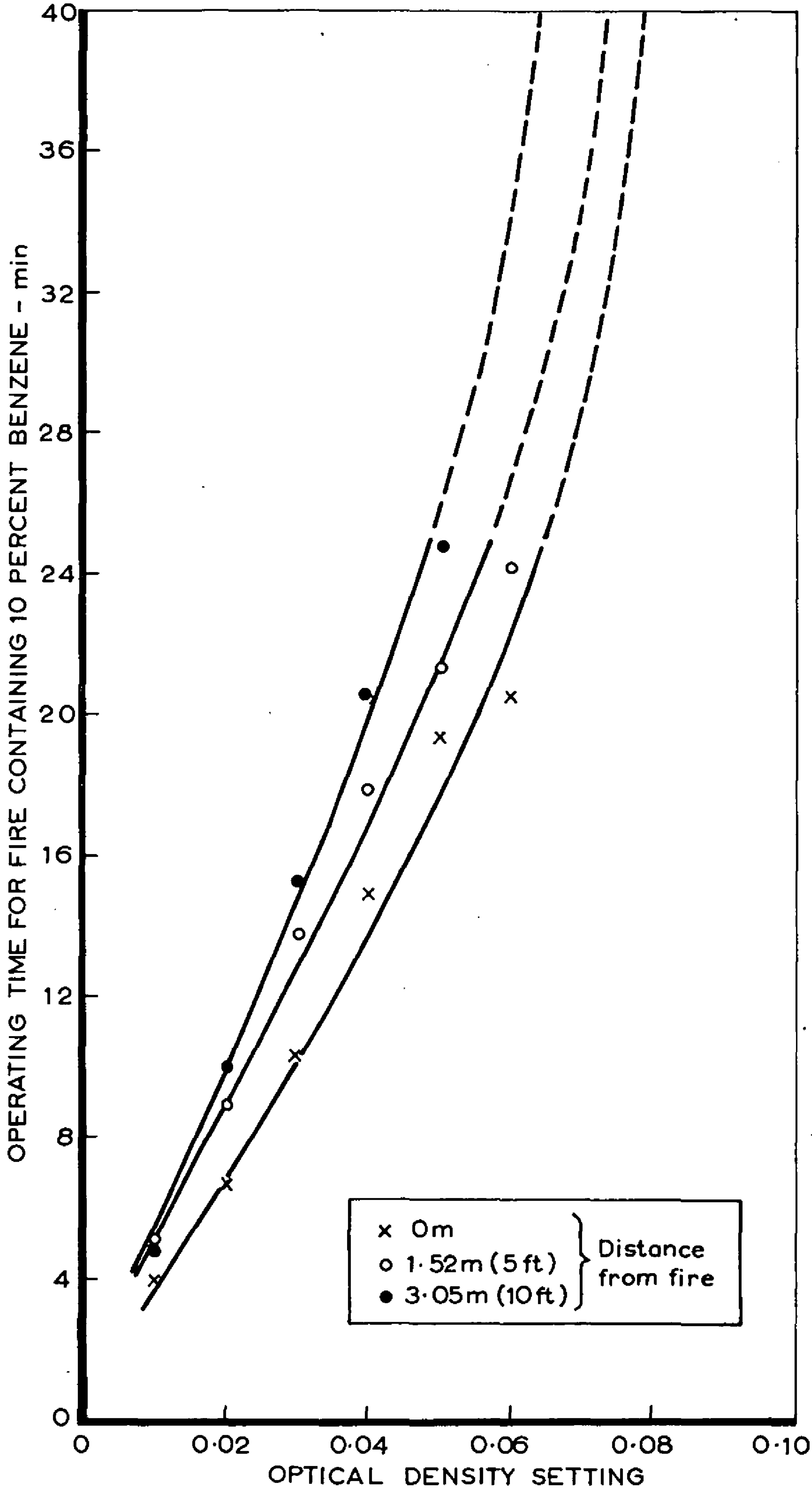

FIG. 8. VARIATION OF OPERATING TIME WITH OPTICAL DENSITY SETTING

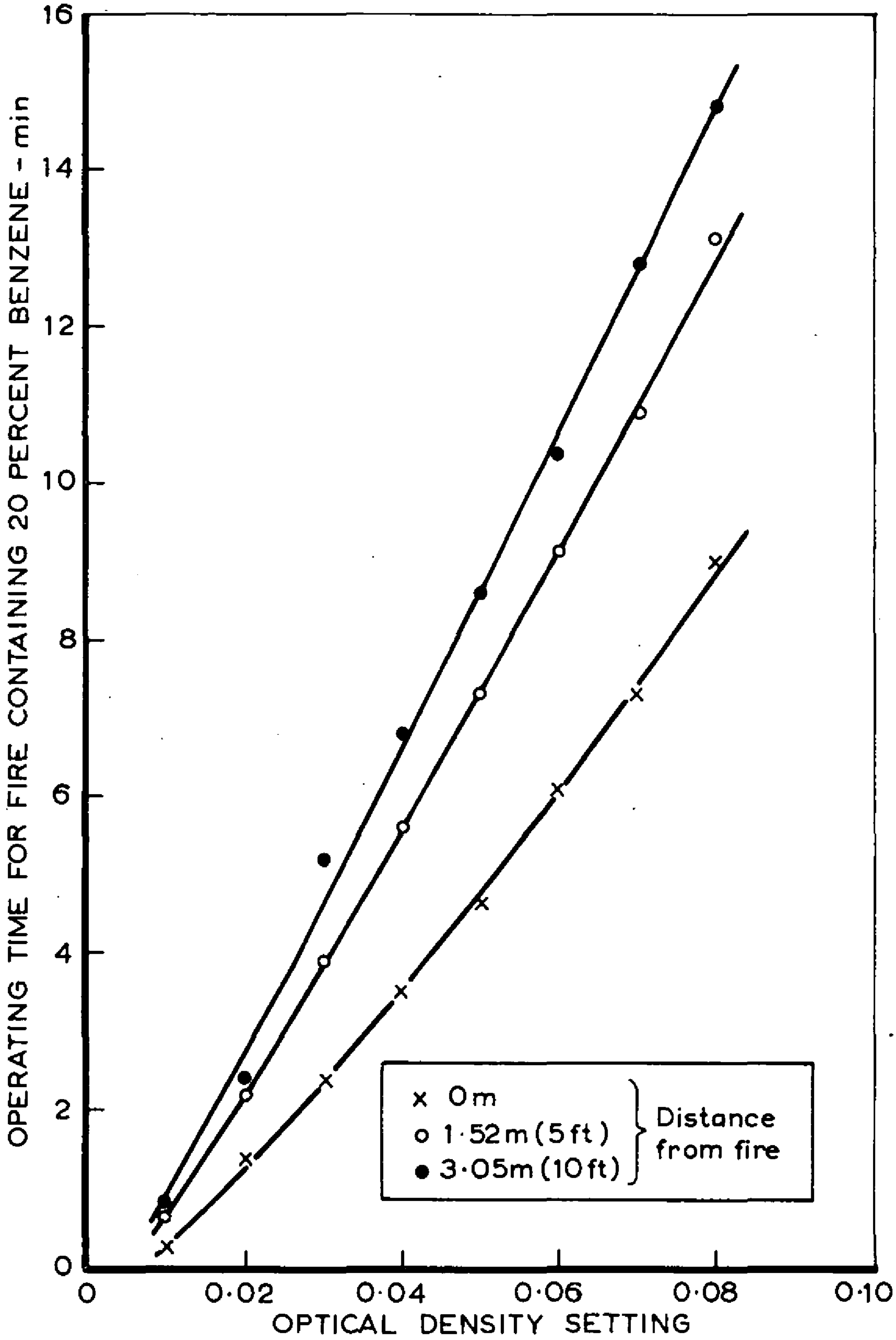

FIG. 9. VARIATION OF OPERATING TIME WITH OPTICAL DENSITY SETTING

1/7191 Int Note 267 4FR770

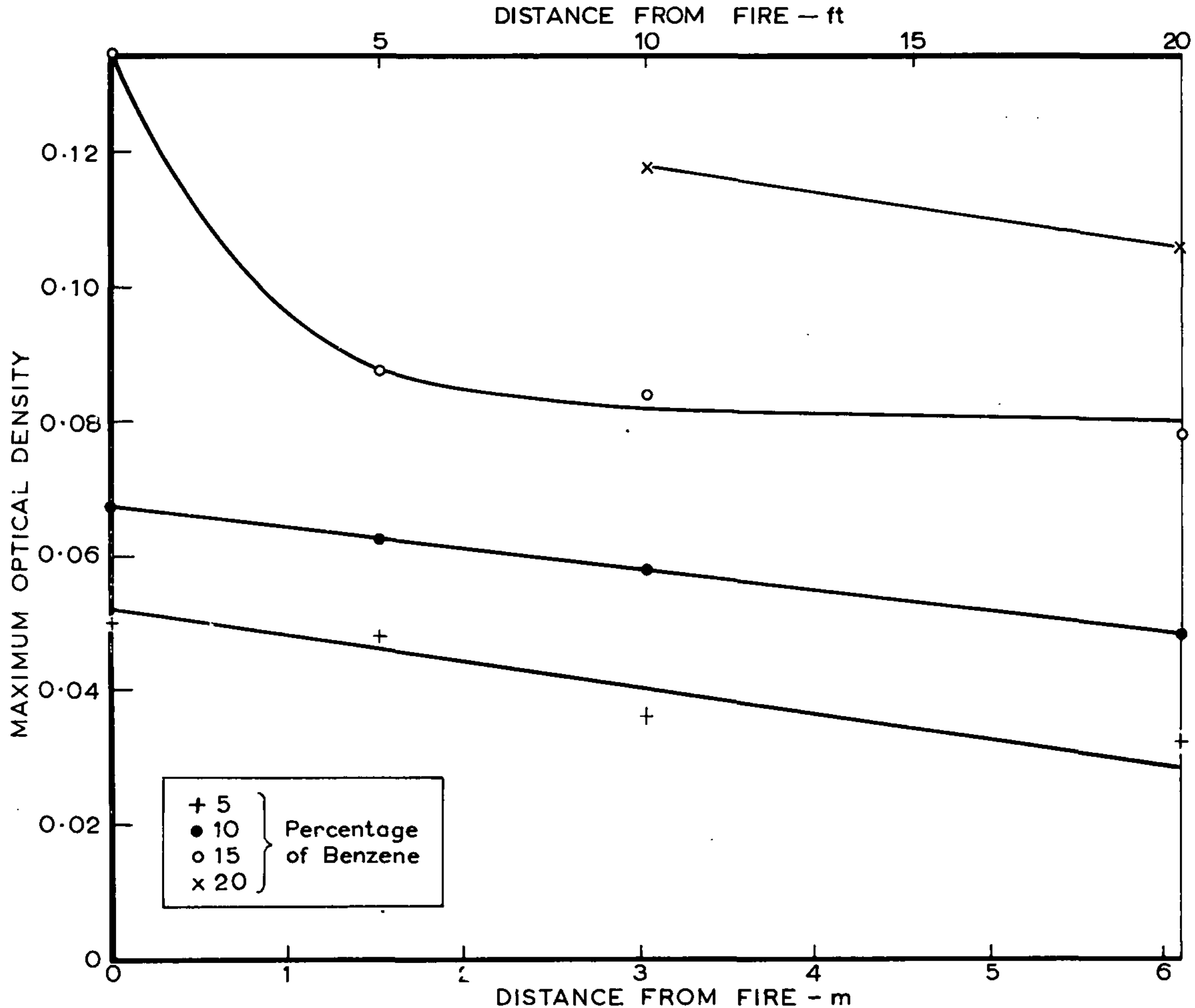

FIG. 10. VARIATION OF MAXIMUM OPTICAL DENSITY REACHED WITH DISTANCE FROM FIRE

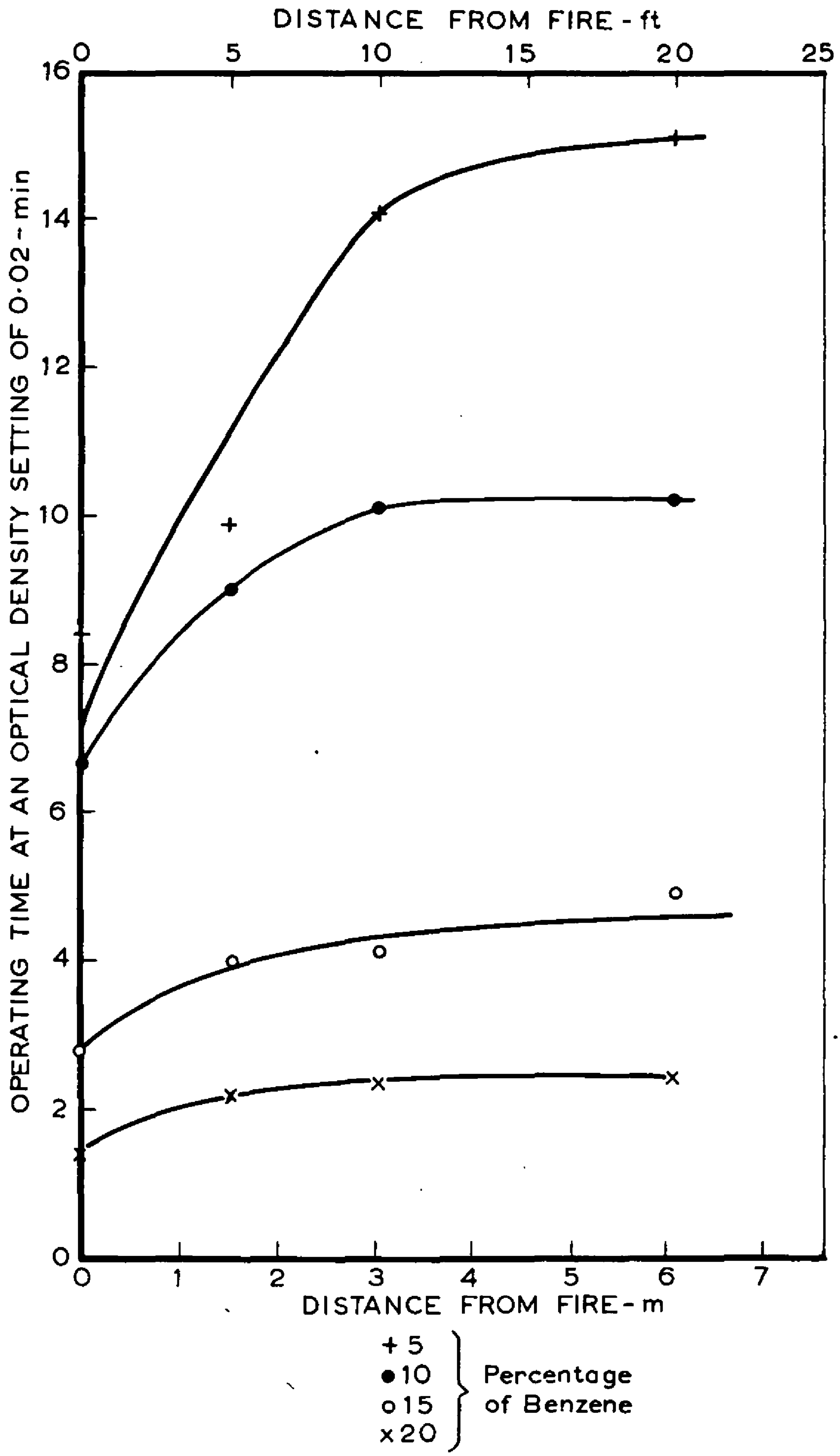

FIG. 11. VARIATION OF OPERATING TIME WITH DISTANCE FROM FIRE

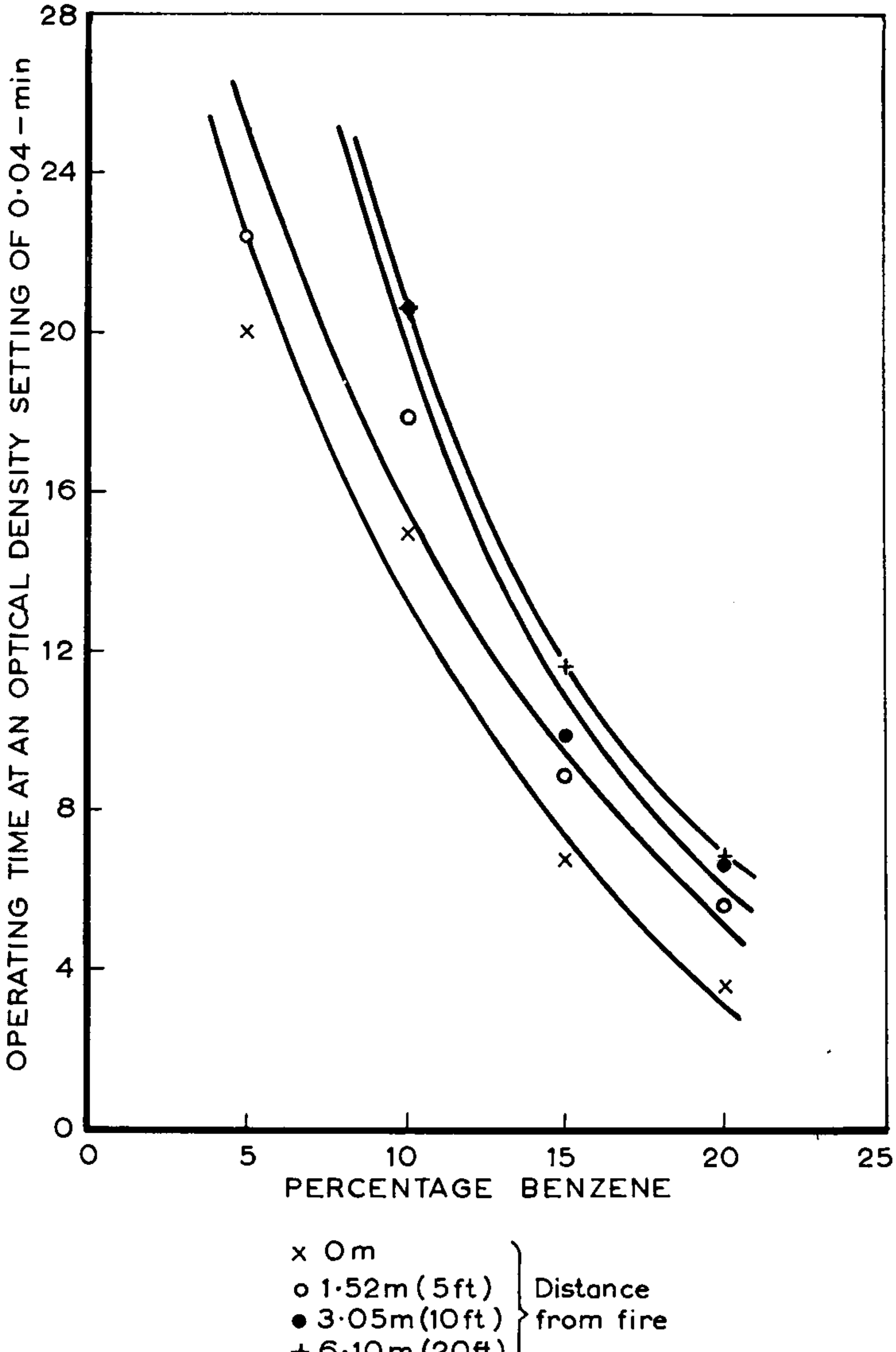

FIG. 12. VARIATION OF OPERATING TIME WITH PERCENTAGE BENZENE

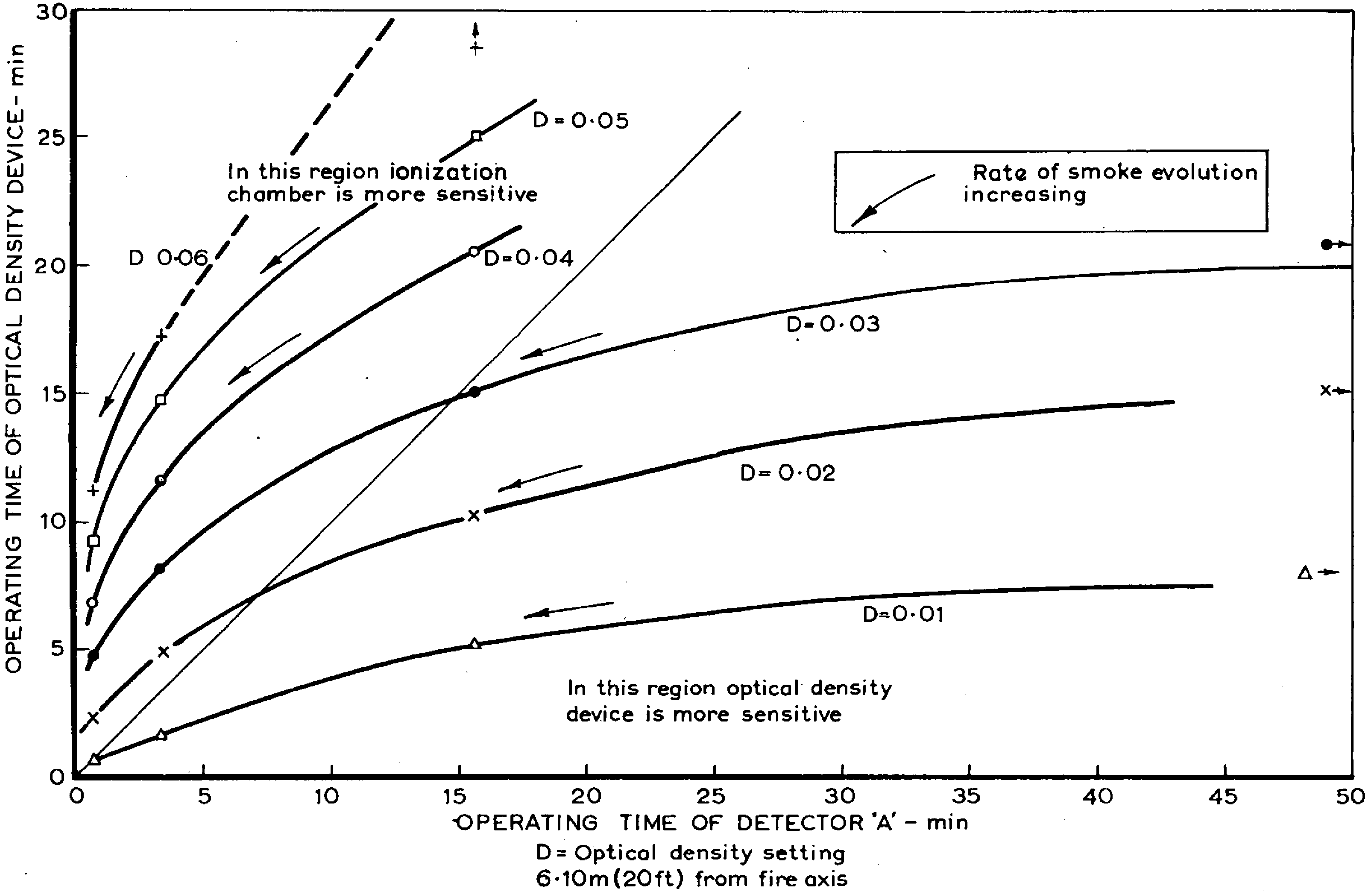

FIG.13. COMPARISON OF OPERATING TIMES OF DIFFERENT SMOKE DETECTORS