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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

THE THERMAL TESTING OF HEAT-SENSITIVE FIRE DETECTORS

by

R. W. Pickard, D. Hird and P. Nash

SUMMARY

The thermal conditions to which heat-sensitive fire detectors must respond when a fire occurs have been investigated. The resulting knowledge of the air temperatures and velocities beneath the ceiling of the room involved, has been used in suggesting a test procedure for the performance of heat-sensitive detectors.

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1. INTRODUCTION

A test procedure for heat-sensitive fire detectors is specified in British Standard Code of Practice C.P. 327.404/402.301. These tests were to be revised in the light of an investigation now being made at the Joint Fire Research Organization. This note describes the work which has been carried out to determine the conditions to which a heat-sensitive detector should respond.

2. DETERMINATION OF AIR VELOCITY AND TEMPERATURE DISTRIBUTIONS NEAR A FLAT CEILING

2.1 Experimental fires

The time for a detector to operate is largely governed by the temperature and velocity of the air which flows past it. In order to reproduce these temperatures and velocities, different-sized trays of methylated spirit, each having a heat output (Table 1) equivalent to that of a particular stage in the development of a fire, were burnt beneath a ceiling.

TABLE 1

Heat output from burning methylated spirit

Diameter of tray ft.	in.	Heat Output kcal/sec.
0	6	1.16
1	0	6.39
2	0	30.90
3	0	89.60

Typical values of heat output during the development of a fire were obtained from measurements of the rate of loss of weight during the burning of 1/10th scale furnished model rooms. Models with both combustible and incombustible linings were used, flashover occurring at $5\frac{1}{2}$ and $13\frac{1}{2}$ minutes respectively. These results were compared with those for a full-scale room(1) in which flashover occurred at approximately the same time, and there was found to be a close agreement. Further results were computed from measurements taken during a full-scale slowly-developing fire. Fig. 1 shows the relation between heat output and time for these fires.

2.2 Temperature distribution beneath a ceiling

The temperature distribution of air close to a ceiling due to a fire beneath has been discussed theoretically elsewhere(2) but there are few experimental results available. For the present investigation, a flat ceiling 24 ft. x 20 ft., unrestricted at its edges and mounted 10 ft. above the floor of a substantially draught-free room, was used. The trays of methylated spirit were supported with their liquid surfaces 8 ft. below the ceiling (Fig. 2).

The air temperature was measured by a comb of thirteen 40 s.w.g. chromel/alumel thermocouples set vertically at 1 in. intervals, the top thermocouple being $\frac{1}{2}$ in. below the surface of the ceiling. The thermocouples were placed at a known distance from the vertical axis of the fire, which was allowed to burn for 2 minutes to obtain stable conditions before any measurements were taken. The output from the thermocouples was recorded automatically, a typical trace being shown in Fig. 3. Owing to the large fluctuations in air temperature, a mean value over $1\frac{1}{2}$ minutes was taken. This procedure was repeated for distances up to 15 ft. from the vertical axis of the fire, for each of the four sizes of tray.

Considering first the temperature distribution perpendicular to the ceiling, the results showed that while there was no marked temperature gradient over the $12\frac{1}{2}$ inches covered by the thermocouples, temperatures close to the ceiling were slightly lower than those at greater distances. Fig. 4 shows the temperature $\frac{1}{2}$ in. below the ceiling as compared with the mean temperature between $1\frac{1}{2}$ and $3\frac{1}{2}$ in., for distances up to 15 feet from a fire in a 2 ft. diameter tray. The lower temperature close to the ceiling is probably due to heat losses to it.

The radial temperature distribution was then examined. Since there was no marked temperature gradient at distances greater than $1\frac{1}{2}$ in. below the ceiling, it was assumed that the sensitive element would be subjected to an air temperature represented by the mean value between $1\frac{1}{2}$ and $3\frac{1}{2}$ ins.

Fig. 5 shows, for the four sizes of tray, how the mean temperature rise of the air within this band varies with the distance from the fire.

Fig. 6 shows that the temperature rise can be related to the distance from the fire by an equation of the form

$$\Theta = \frac{A}{\sqrt{R}}$$

where Θ is the temperature rise
R is the distance from the fire
A is a constant dependent on the size of the fire.

Experiments were also made using the 1 ft. and 2 ft. diameter trays mounted with their liquid surface 4 ft. below the ceiling and showed that there was a marked temperature gradient perpendicular to the ceiling, as can be seen in Fig. 7.

Fig. 8 compares the radial distribution of temperature, $\frac{1}{2}$ in. below the ceiling, with the fires mounted 4 ft. and 8 ft. below it. It can be seen that, close to the ceiling, higher values of temperature rise are obtained as the distance between the fire and ceiling is decreased.

Fig. 9 shows the radial distribution of temperature 3 in. below the ceiling and it can be seen that with the fire 4 ft. below the ceiling the temperature rise is again governed by the approximate relation

$$\Theta = \frac{A'}{\sqrt{R}}$$

2.3 Discussion of temperature distribution

The air temperature rise at a point near a ceiling due to a fire beneath it is governed by the following factors:-

(1) The size of the fire.
(2) The distance from the axis of the fire.
(3) The distance between the fire and ceiling.
(4) The depth below the ceiling at which the temperature is measured.

These factors will govern the placing of detectors. Since there is likely to be a marked temperature gradient perpendicular to the ceiling if the fire is close to it, it appears to be advisable to mount detectors so that the sensitive element is not less than 1 inch and not more than about 3 in. below the ceiling.

The rate of temperature rise to which a detector may be subjected, will depend on the rate of development of a fire and the distance of the detector from the fire. Fig. 10 shows the rate of rise of temperature which might occur at various distances from the most rapidly developing fire shown in Fig. 1. Here it has been assumed that the detector is mounted 3 in. below the ceiling, and that the fire originated 8 ft. below the ceiling. It may be seen that the temperature rise with time for the early stages of this fire is approximately linear.

2.4 Velocity distribution

The velocity measurements were made by means of a thermocouple anemometer(3). The instrument was calibrated with air flows at room temperature and 200°C. The output for a given mass flow was found to be almost independent of temperature over this range. Since there was considerable variation in the temperature of the air of which the velocity was measured, the mass flow readings obtained from the instrument have been reduced to an equivalent velocity at room temperature (15°C), and this is the velocity referred to in this note.

The distribution was first measured with the fires 8 ft. below the ceiling. As with the temperature measurements, a mean value over $1\frac{1}{2}$ minutes at each position was taken.

In Fig. 11 the velocity distribution is plotted for depths of $\frac{3}{4}$ in., 3 in. and 6 in. below the ceiling, for a 3 ft. diameter fire. The figure shows that, close to the fire, a marked velocity gradient exists perpendicular to the ceiling. The air velocity 3 in. below the ceiling has been plotted in Fig. 12 for 1 ft., 2 ft., and 3 ft. diameter trays. It can be seen that the velocity decreases with distance from the fire.

Fig. 13 shows that at distances greater than about two diameters from the fire, an approximate relation of the form $V = \frac{B}{R}$ holds where

V is the velocity of the air.
R is the distance from the fire.
B is a constant dependent on the size of fire.

The lower velocities recorded close to the fire are probably due to the fact that the anemometer only measured that component of velocity parallel to the ceiling and close to the fire the air rises nearly vertically.

Experiments were also carried out with the 1 ft. and 2 ft. diameter trays placed 4 ft. below the ceiling. It was found that velocities close to the ceiling were lower than the corresponding values for the fires 8 ft. below the ceiling, and that velocities 6 in. below the ceiling were too low for any reliable measurements to be taken with the anemometer used. This indicates a reduction in the thickness of the heated air layer.

Fig. 14 shows the radial distribution of velocity $\frac{3}{4}$ in. below the ceiling for the two fires. It can be seen that the distribution is again governed by an approximate relation of the form $V = \frac{B'}{R}$ though the low velocities encountered with the 1 ft. fire made reliable measurement difficult at distances greater than 10 ft. from the fire.

Fig. 15 shows the variation in velocity with time which might be expected from the most rapidly developing fire of Fig. 1. An approximate relation between velocity and time is, $V = ct^3$.

2.5 Discussion of velocity distribution

As a fire develops a detector will be subjected to an air stream of increasing velocity. The rate of rise of velocity will depend on the distance of the detector from the fire and the time for which the fire has been developing (Fig. 15).

The smaller the distance between the fire and the ceiling, the less the thickness of the layer of heated air will be. This was also suggested by the temperature measurements and will similarly govern the siting of detectors with respect to the ceiling.

3. TEST CONDITIONS

The test apparatus should reproduce conditions which are representative of those which occur in practice. It has been shown that in general these consist of an air flow with a uniformly-rising temperature and a rising velocity.

The sensitive elements of detectors are generally protected by shields which have a screening effect and result in the detector operating at different times under the same temperature conditions, for different directions of air flow. The air flow in the test apparatus must therefore be directional.

The choice of velocity conditions is important since the operating time of a detector will depend on the heat transfer to the sensitive element (Appendix I) which in turn is a function of velocity. Comparison of the temperature and velocity distributions show that it is not possible to associate a fixed velocity variation with a given rate of rise of air temperature. However, it can be shown (Appendix II) that the sensitivity of detectors can be adequately assessed by testing them in a directional air flow with a constant velocity of 80 cm/sec. and with a linearly rising air temperature.

4. CONCLUSIONS

The conditions of air flow to which a heat sensitive detector will be subjected, are those of an increasing temperature and velocity, the values of which depend on the nature of the fire and the position of the detector with respect to the fire and the ceiling. These conditions can be simulated in a laboratory test by an air flow having an increasing temperature and a velocity of 80 cm/sec. The air flow must be directional since the operating time of a detector may vary with the direction of the air stream.

5. ACKNOWLEDGEMENT

Mr. W. Ross assisted in the experimental work.

6. REFERENCES

(1) Tests carried out at the Building Research Station - unpublished.

(2) Thomas, P.H. - The distribution of temperature and velocity due to fires beneath ceilings. F.R. Note No. 141/1955.

(3) Benseman, R. F. and Hart, H. R. - A thermocouple anemometer, J. Scientific Instruments, April 1955, Vol. 32. No. 4.

(4) McAdams, W.H. - Heat Transmission. McGraw Hill Publishing Co. Ltd.

APPENDIX I

The temperature rise of an element subject to an air flow of increasing temperature and constant velocity

Assuming no heat losses, the temperature rise θ of an element at any time t subject to a constant velocity air flow with a linearly-increasing temperature of α °C per second is given by

$$HA(\alpha t - \theta) = C\frac{d\theta}{dt} \quad \text{.....(1)}$$

where H is the convective heat transfer coefficient to the element.

A is the area of the element.

C is the thermal capacity of the element.

A solution of Equation 1, if $\theta = 0$ when $t = 0$, is

$$\theta = \alpha\left\{t - \frac{C}{HA}\left(1 - e^{\frac{-HAt}{C}}\right)\right\} \quad \text{.....(2)}$$

APPENDIX II

Since it is not possible to associate a fixed velocity variation with a given rate of rise of air temperature it is necessary to examine the two extreme conditions to which detectors are likely to be subjected. Insensitive detectors should be installed close together and thus being near the fire will be subjected to the most rapid rates of rise of velocity, whilst the more sensitive detectors further from the fire will be subjected to lower velocities. Assuming that the minimum spacing for detectors is that of a sprinkler, namely 10 ft, then Fig.12 shows that the detector might be subjected to a rising velocity varying between about 0 and 200 cm per second before it operates. At large distances from the fire the detector is probably subjected to a constant velocity of about 30 cm per second (Fig.12). These, then, can be taken as the extreme velocity conditions likely to occur.

The actual variation in operating time with velocity will vary with different designs of detector as illustrated in Fig.16. These results were obtained by subjecting four detectors to an air flow, the temperature of which was raised at 10°C per minute, at constant velocities varying from 60 to 240 cm per second.

It is also possible to make an estimate of a detector's performance under the extreme velocity conditions. The shape and dimensions of the sensitive elements of most heat-sensitive detectors are such that, with the velocities encountered, the maximum variation of the heat transfer coefficient H with velocity V would be given by(4)

$$H = BV^{\frac{1}{2}}$$

where B is a constant.

It has been shown in Appendix I how the temperature rise of a sensitive element depends on the value H, and this relation has been used to calculate the temperature rise of elements subjected to an air flow with a constant velocity of 30 cm per second (Fig.17) and a velocity rising from 0 to 200 cm per second in 5 minutes (Fig.18), according to the relation given in Section 2.4. The results are shown in both figures for a rate of rise of air temperature of 30°C per minute for three elements having values of $\frac{HA}{C}$ = 0.01, 0.03 and 0.10 sec.$^{-1}$ at 100 cm per second, A being the area of the element and C its thermal capacity. These values are typical for detectors with low, medium and high sensitivities.

In practice, the time for a detector to reach a given temperature rise would lie between the limits set by the above velocity conditions. The mean of the times of Figs. 17 and 18, to reach any given temperature rise between 0 and 80°C, is shown in Fig.19. Fig.20 shows the results to be expected assuming a constant velocity of 80 cm per second.

Comparison of Fig.19 and Fig.20 shows that in the case of the detectors with a high and medium sensitivity the time taken to reach any given temperature is almost the same, whilst with the low sensitivity detector the mean time is about 10 seconds longer than the time given by a constant velocity of 80 cm per second. Since, however, low-sensitivity detectors are likely to be situated close to the fire, a shorter time than the mean value would be expected in practice as the conditions here will be those of rising velocity.

It is concluded that the sensitivity of detectors can be assessed by testing them under the conditions of a directional air flow with a linearly-rising temperature, and a constant velocity of 80 cm per second.

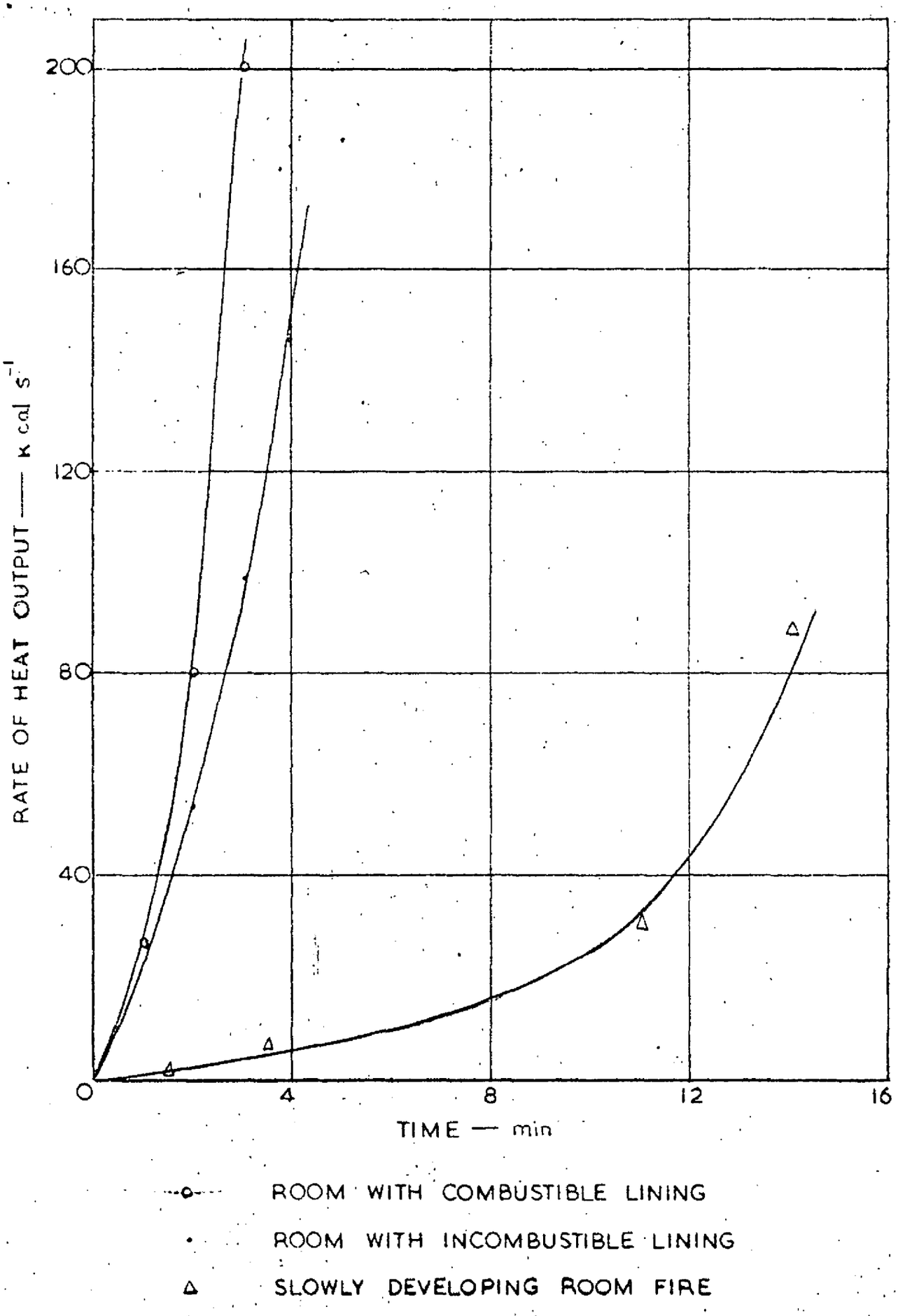

FIG. 1. HEAT OUTPUT FROM ROOM FIRES

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PLATE.2. APPARATUS FOR TAKING TEMPERATURE MEASUREMENTS

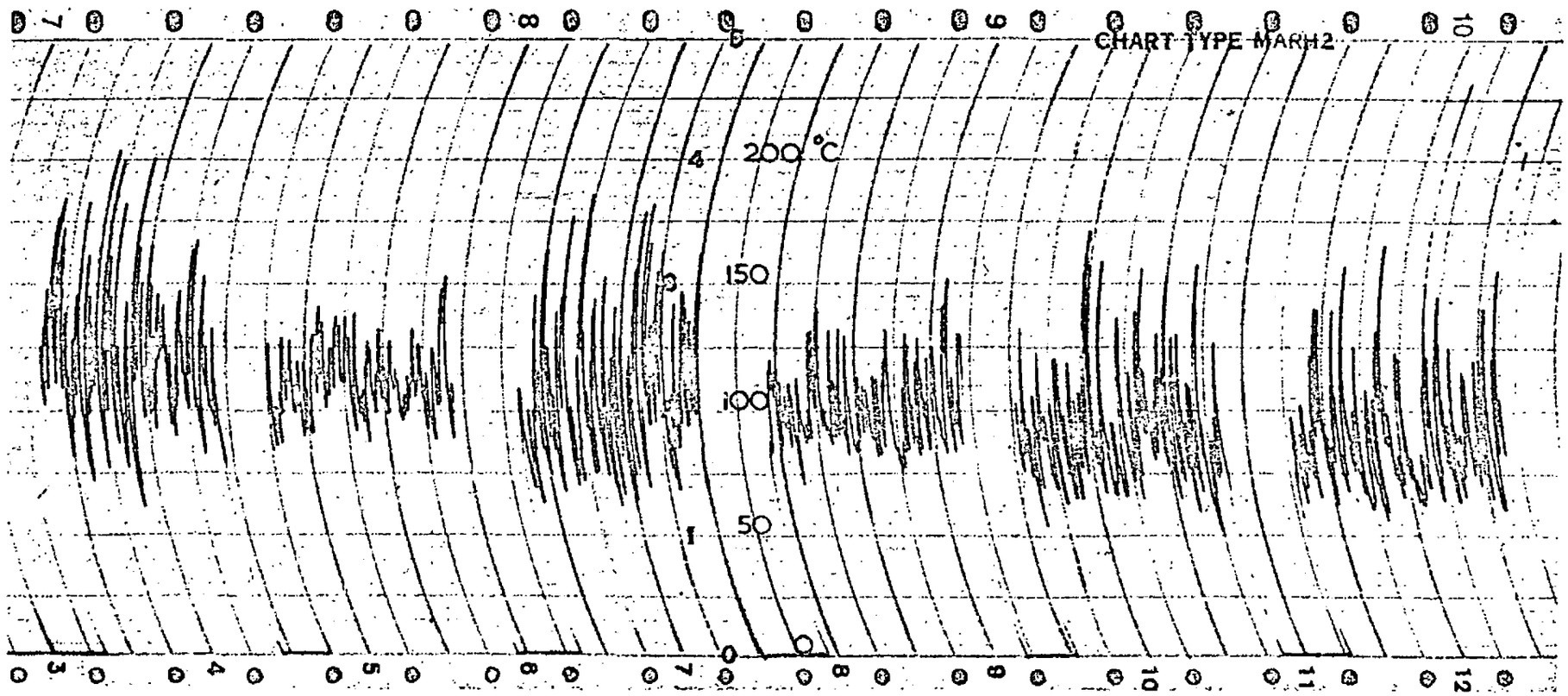


PLATE.3. A TYPICAL TEMPERATURE RECORD

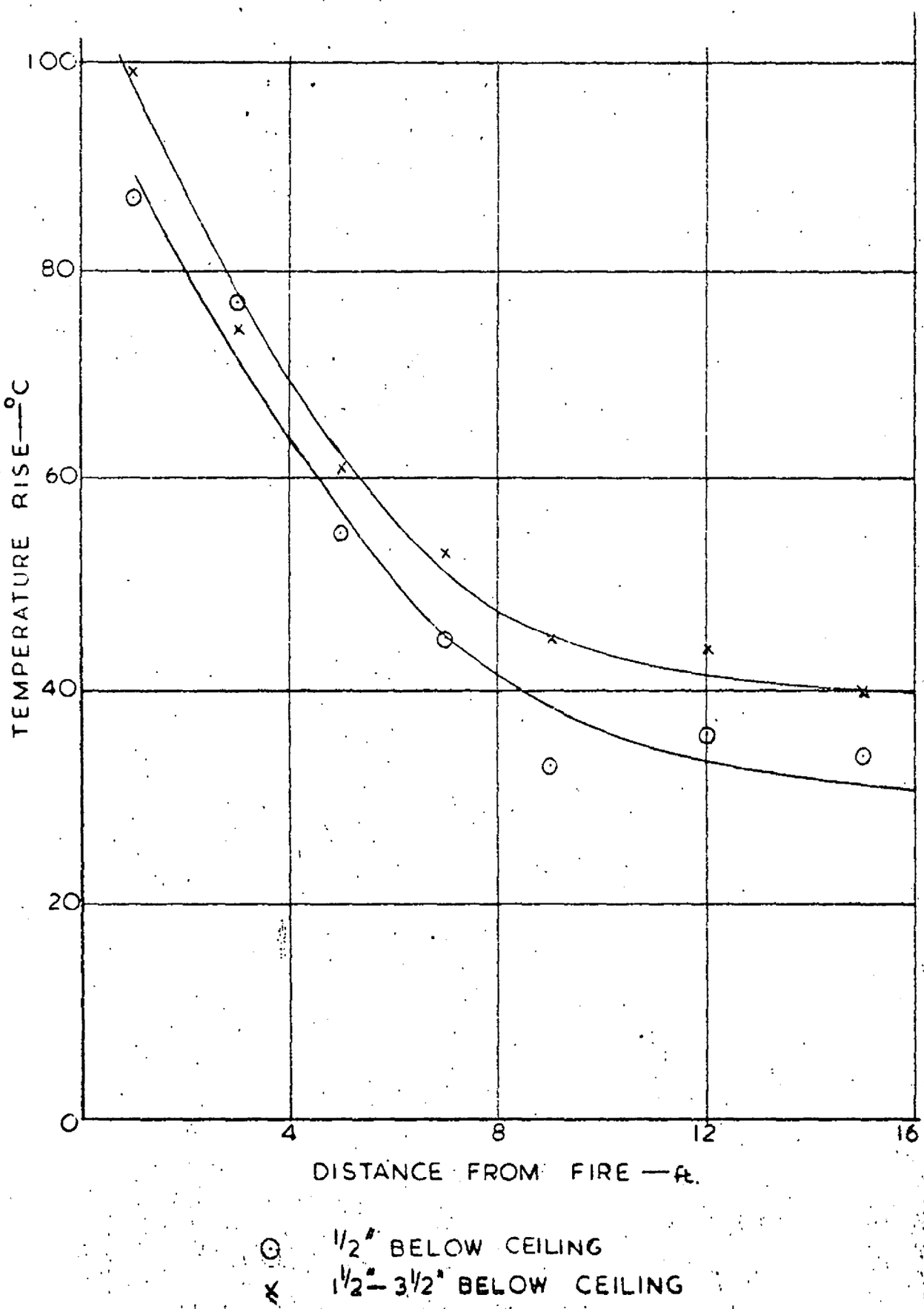


FIG 4. AIR TEMPERATURE CLOSE TO A FLAT CEILING (FIRE 8 FT BELOW CEILING)

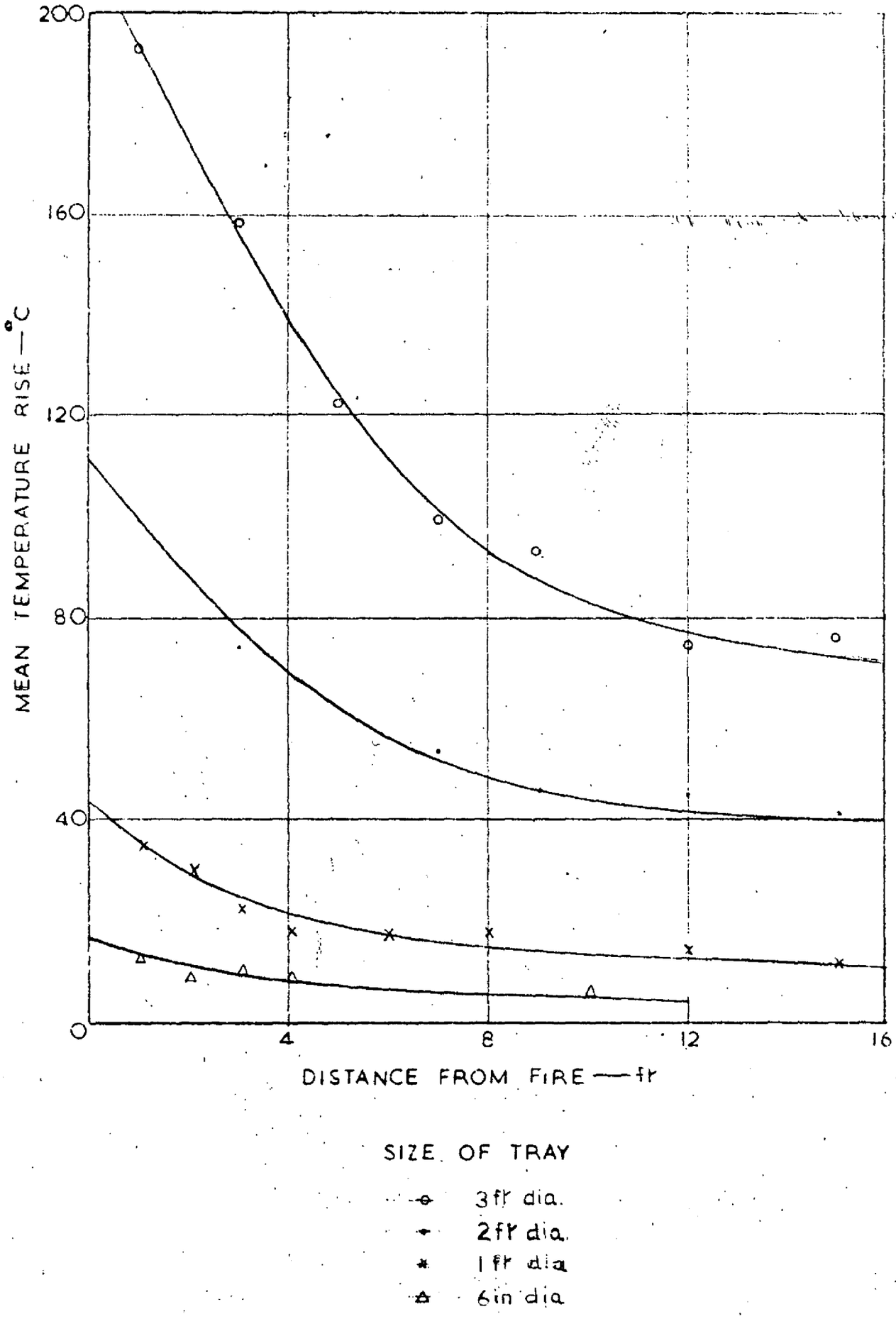


FIG. 5 RADIAL TEMPERATURE DISTRIBUTION BENEATH A FLAT CEILING (FIRE 8 FT BELOW CEILING)

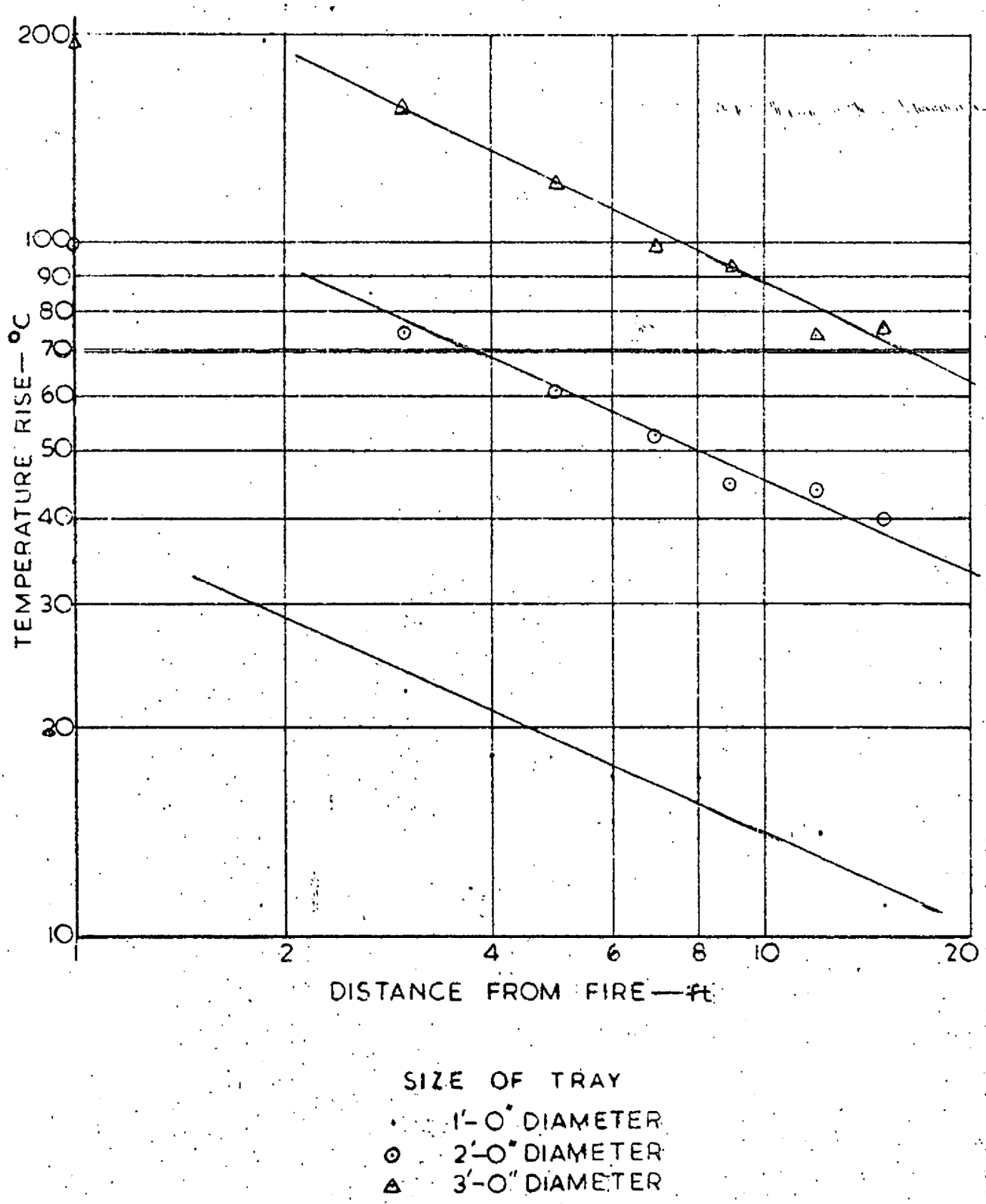


FIG. 6 RADIAL TEMPERATURE DISTRIBUTION BENEATH A FLAT CEILING
(FIRE 8 FT BELOW CEILING)

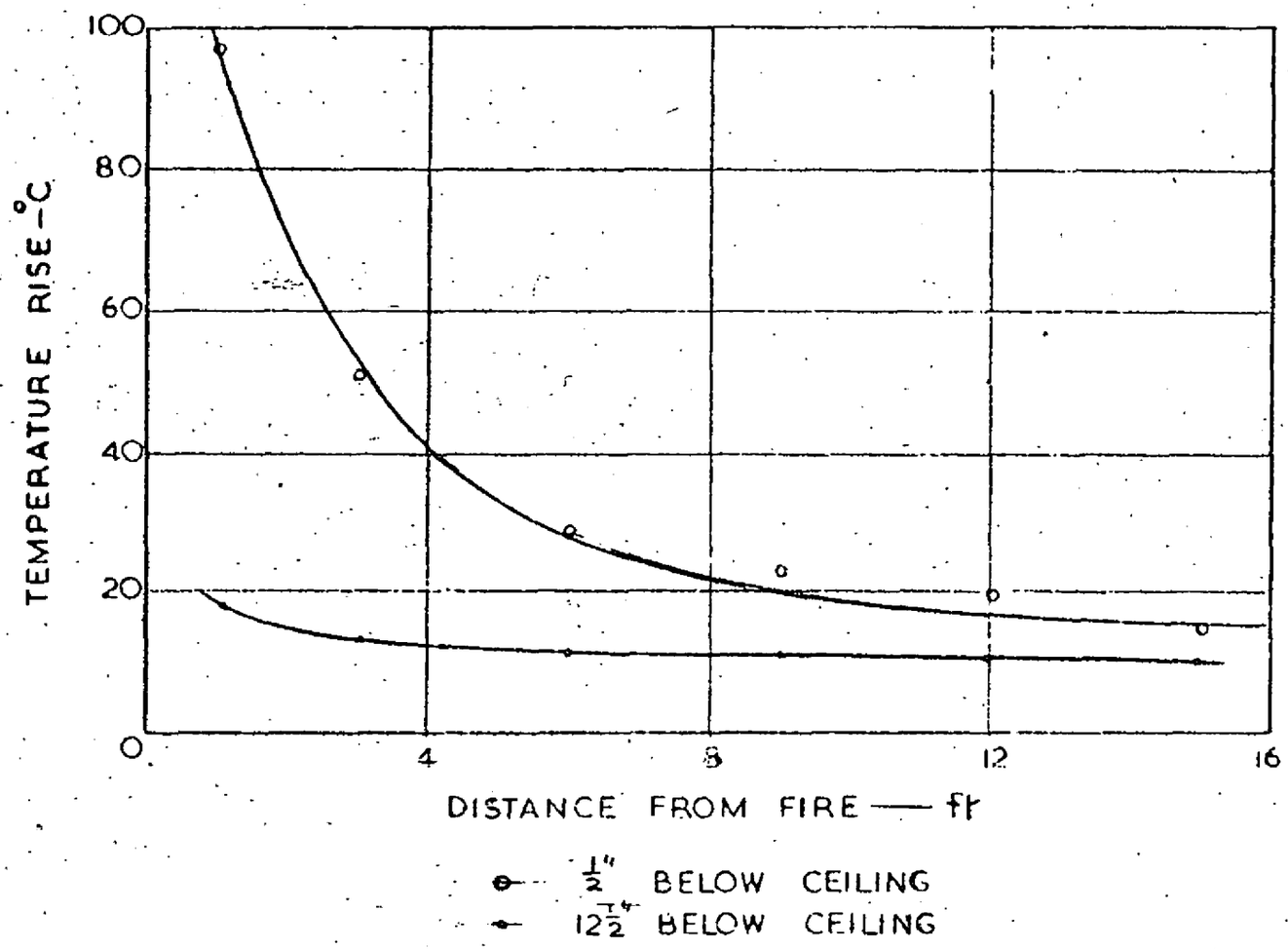
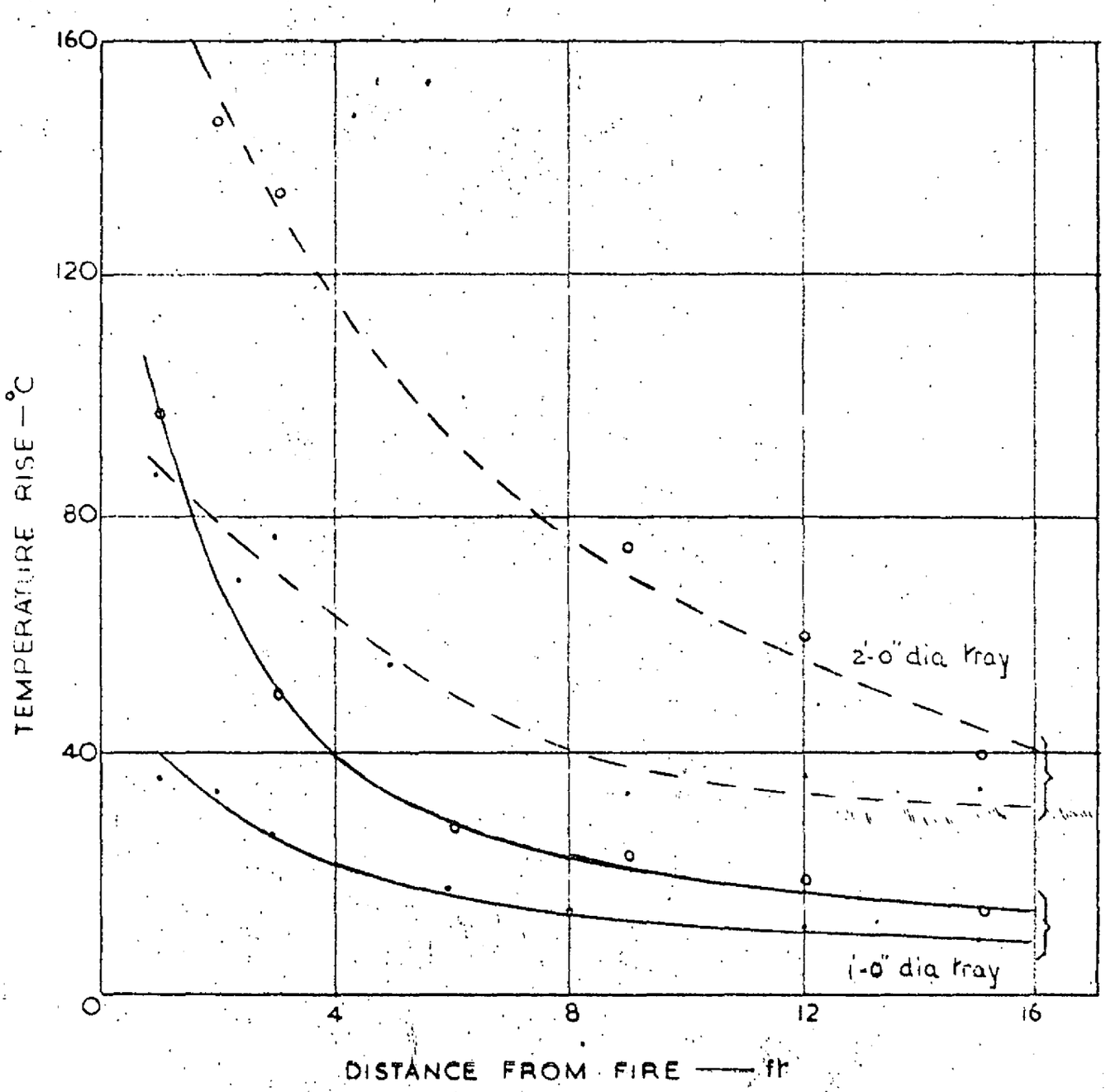


FIG. 7. TEMPERATURE GRADIENT PERPENDICULAR TO A FLAT CEILING (FIRE 4FT BELOW CEILING)



○ FIRE 4ft FROM CEILING

• FIRE 8ft FROM CEILING

FIG. 8. RADIAL DISTRIBUTION OF TEMPERATURE WITH FIRES 8ft AND 4FT BELOW A FLAT CEILING

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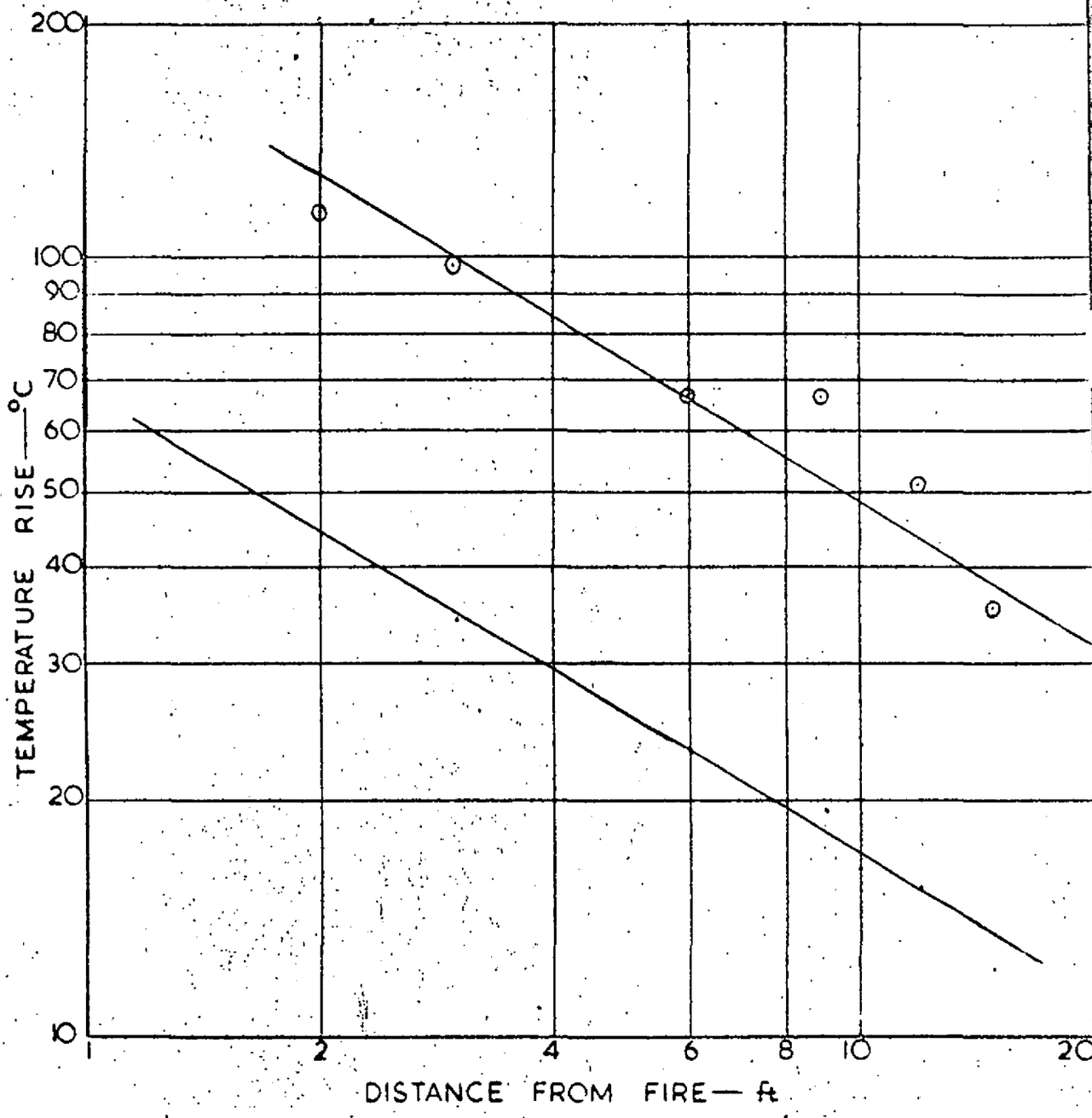

SIZE OF TRAY

⊙ 2ft DIAMETER

• 1ft DIAMETER

FIG. 9 RADIAL DISTRIBUTION OF TEMPERATURE WITH FIRE 4FT BELOW A FLAT CEILING

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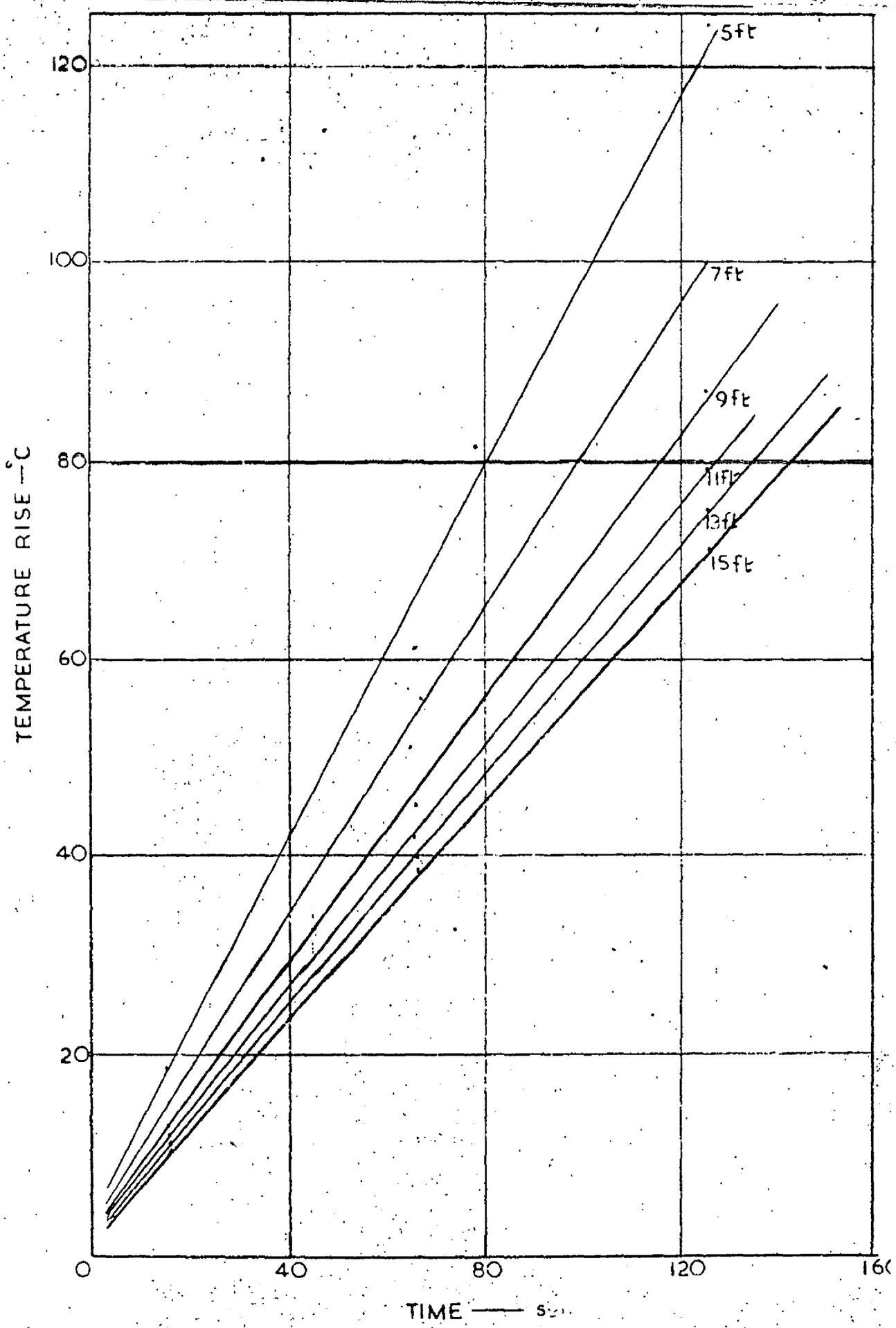

FIG. 10. RATE OF RISE OF TEMPERATURE AT VARIOUS DISTANCES FROM A RAPIDLY DEVELOPING FIRE

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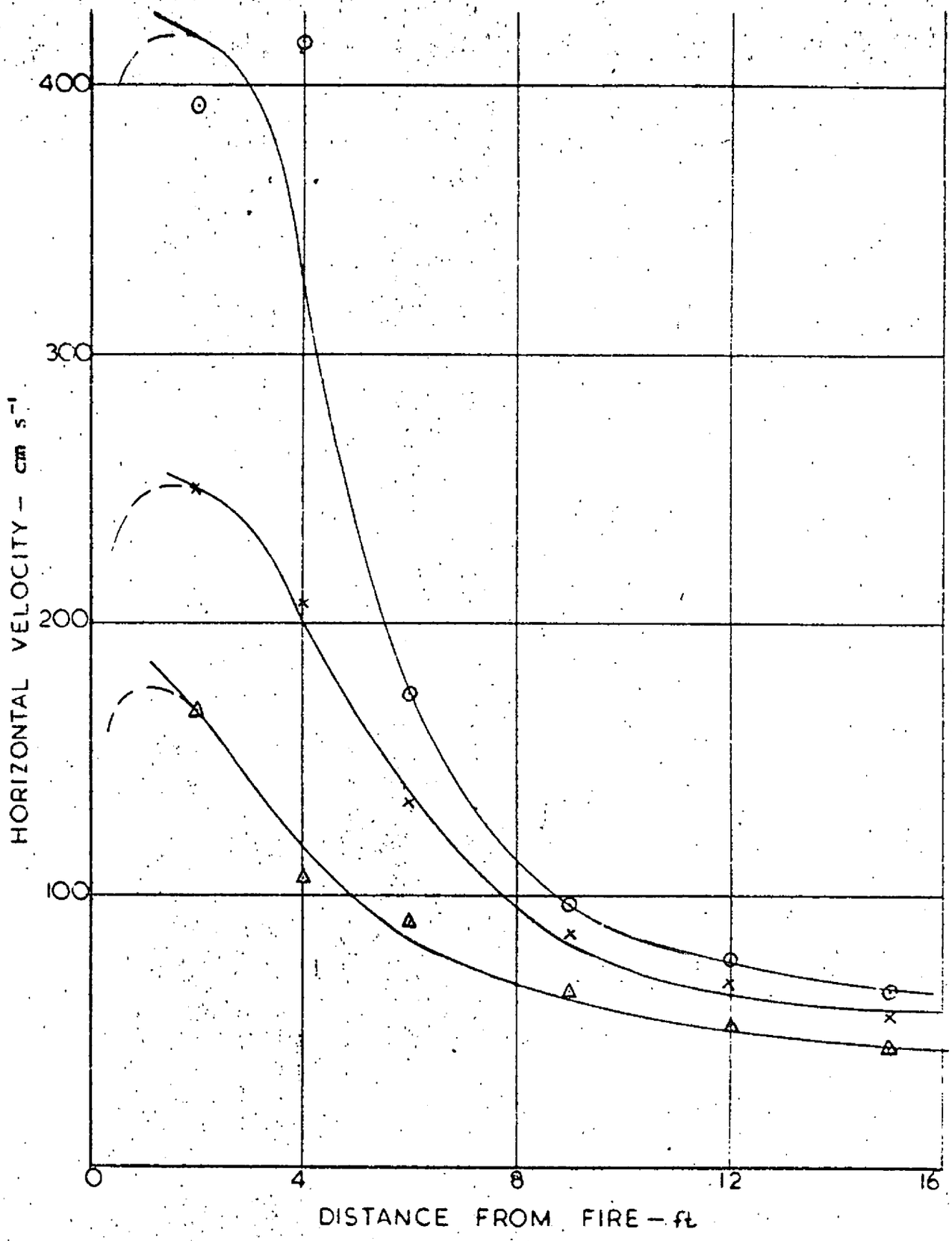

⊙ 3/4 in. BELOW CEILING
× 3 in. BELOW CEILING
△ 6 in. BELOW CEILING

FIG. 11 VELOCITY GRADIENT PERPENDICULAR TO A FLAT CEILING (FIRE 8 FT BELOW CEILING)

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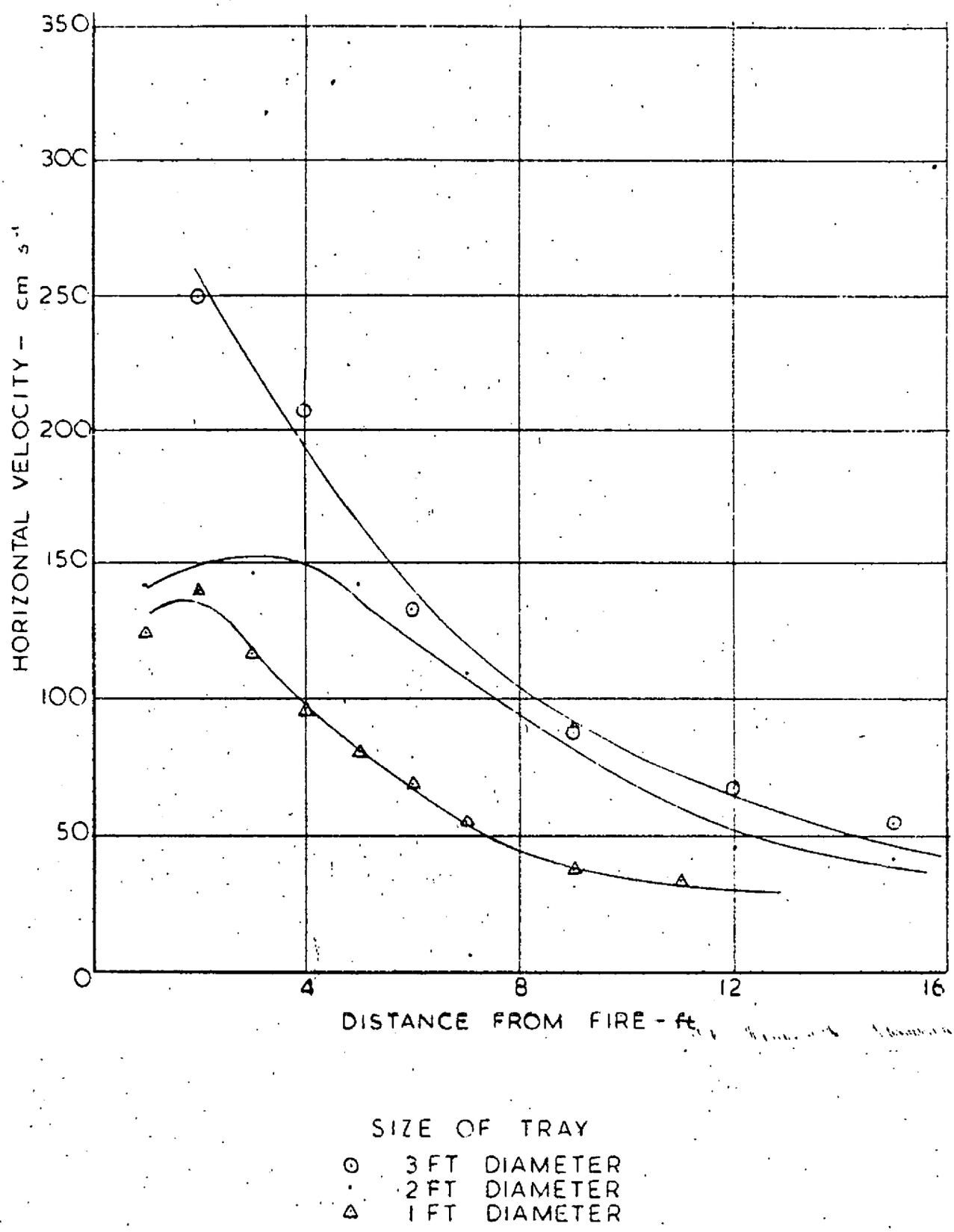

FIG 12 RADIAL VELOCITY DISTRIBUTION 3 IN BENEATH A FLAT CEILING (FIRE 8 FT BELOW CEILING)

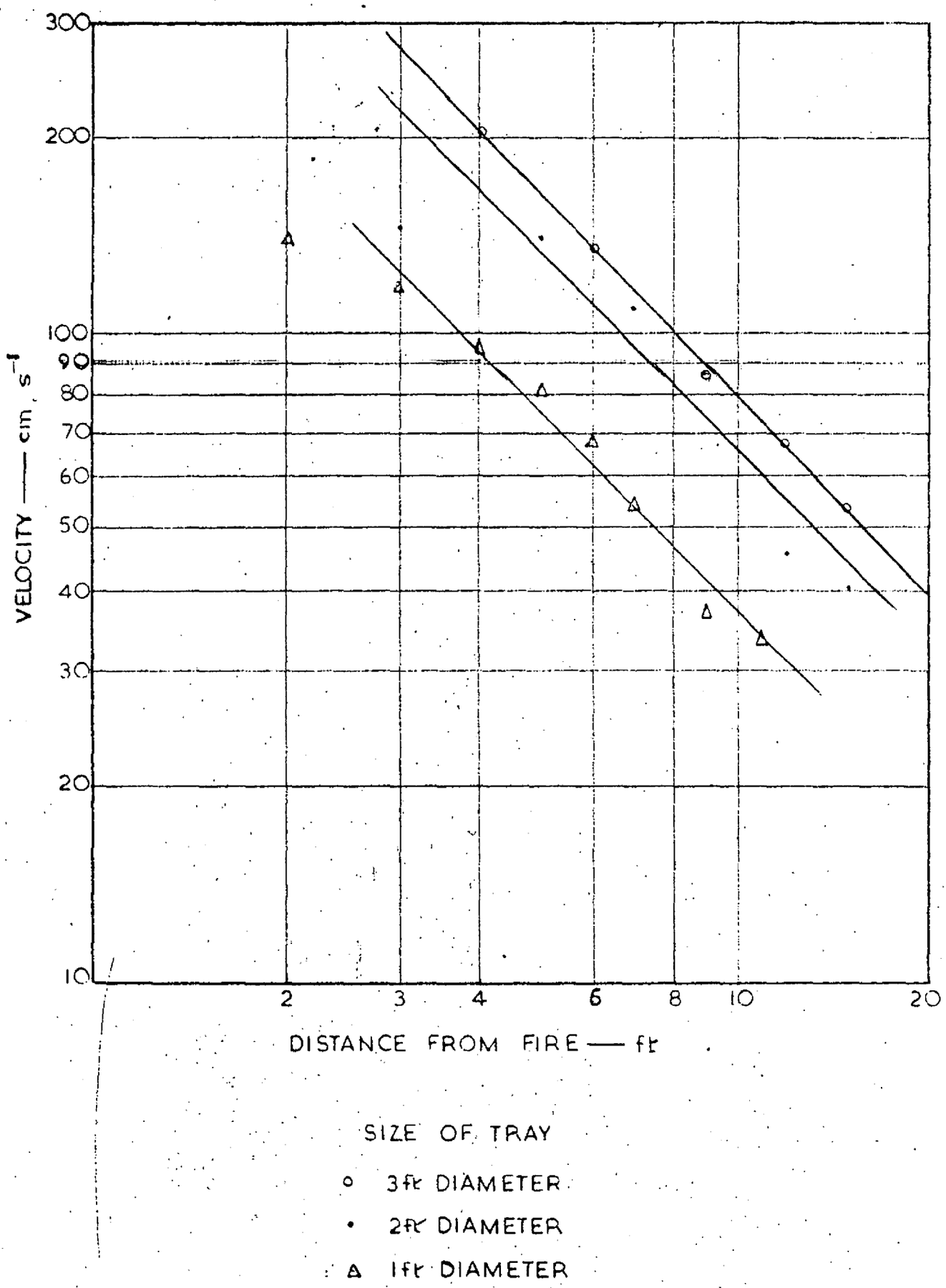

FIG. 13. RADIAL VELOCITY DISTRIBUTION BENEATH A FLAT CEILING (FIRE 8FT BELOW CEILING)

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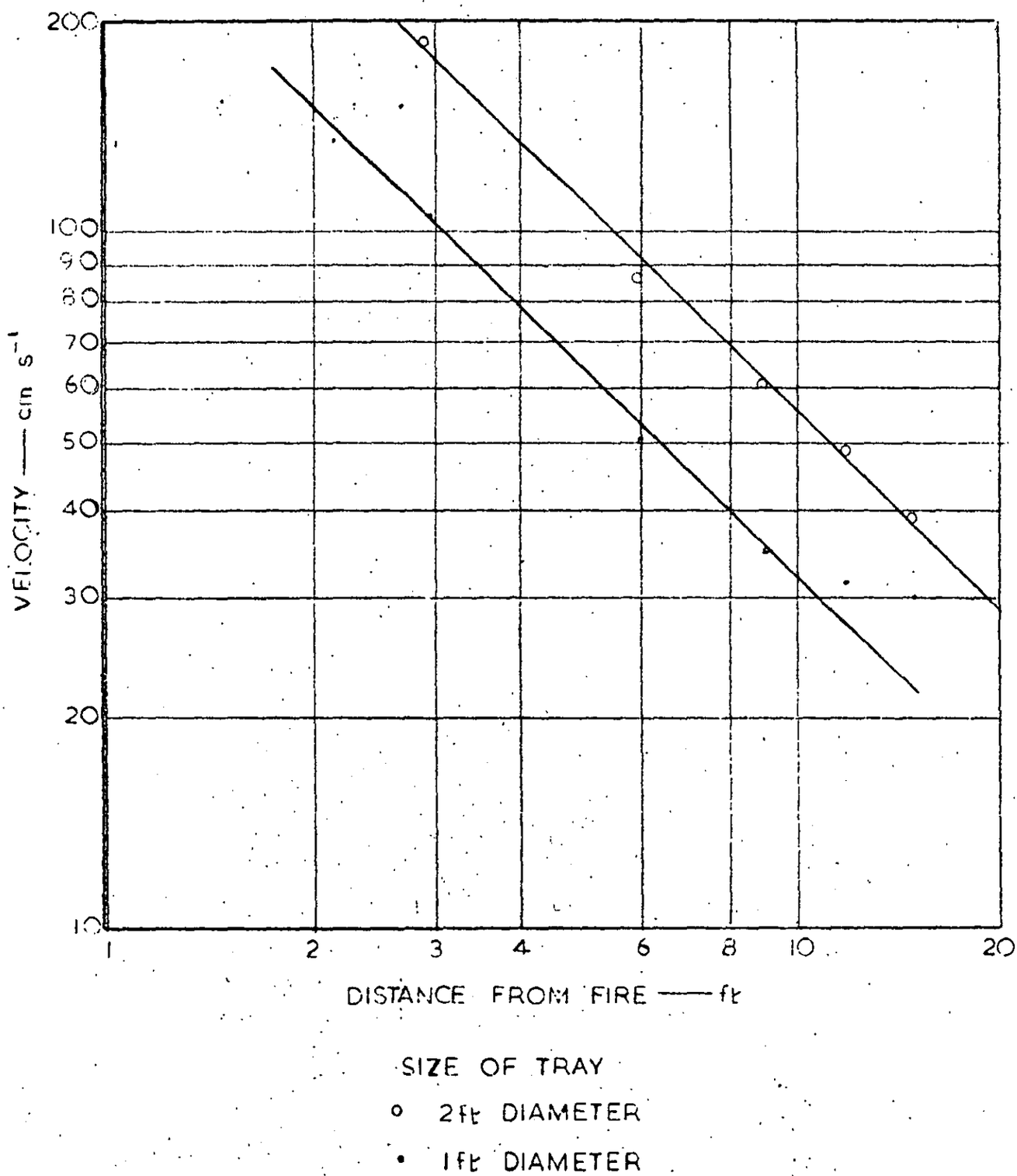

FIG. 14. RADIAL VELOCITY DISTRIBUTION WITH FIRE 4FT BELOW A FLAT CEILING

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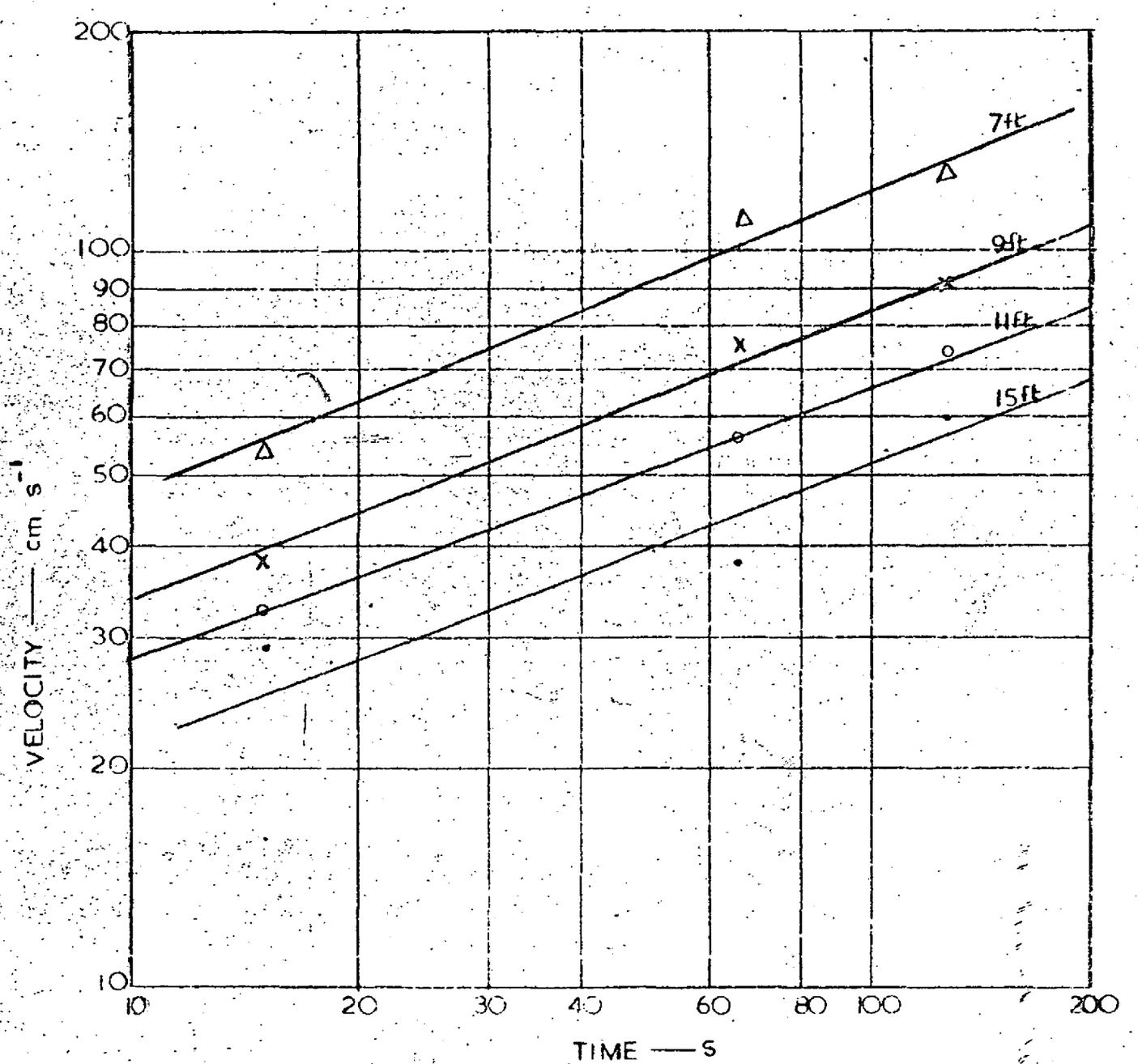

FIG.15. VARIATION OF VELOCITY WITH TIME. (FIRE 8FT BELOW CEILING)

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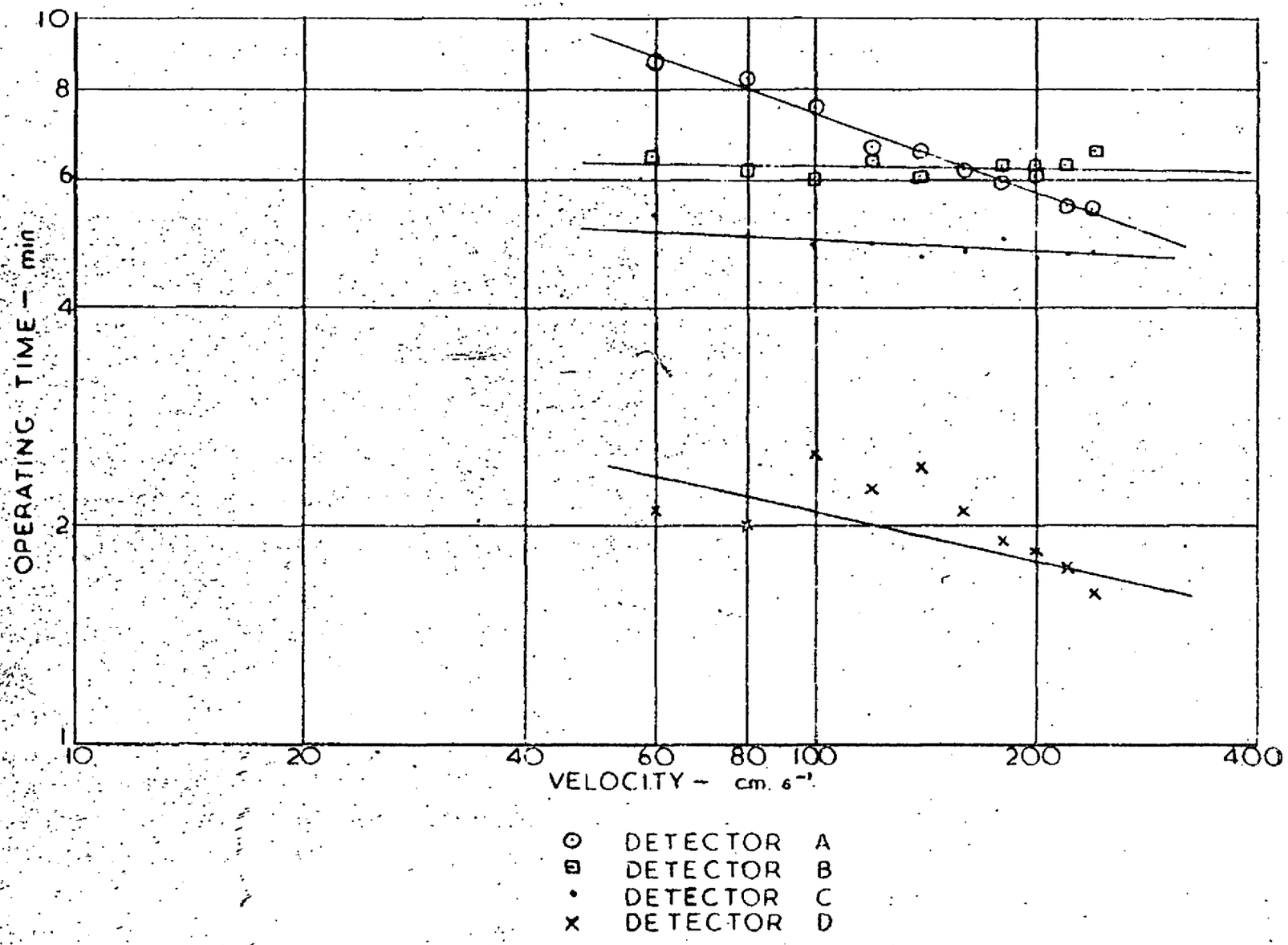

FIG. 16 VARIATION IN OPERATING TIME OF DETECTORS WITH VELOCITY

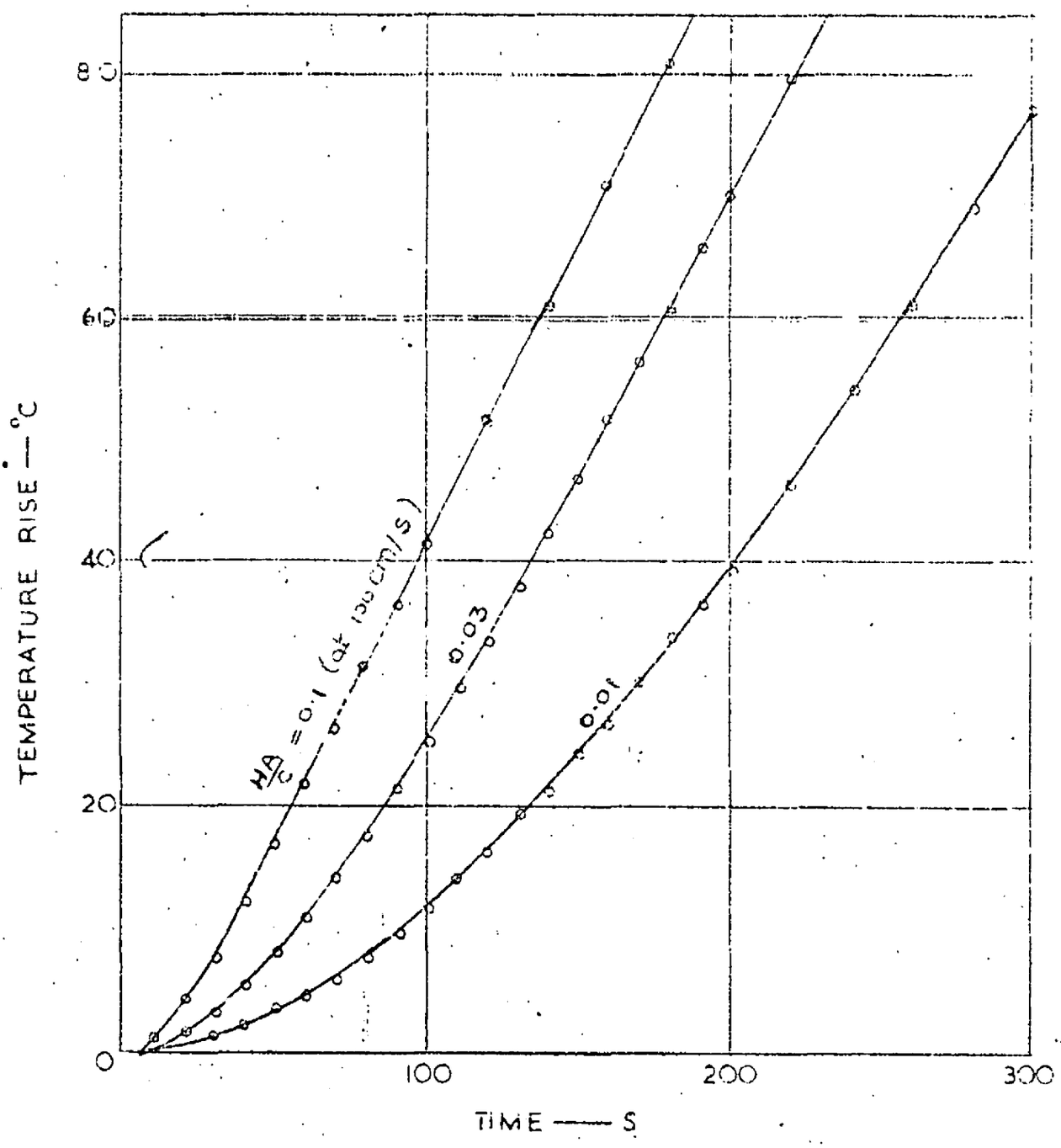

FIG. 17. TEMPERATURE RISE OF HEATED ELEMENTS SUBJECTED TO A CONSTANT VELOCITY OF 30 cm/s

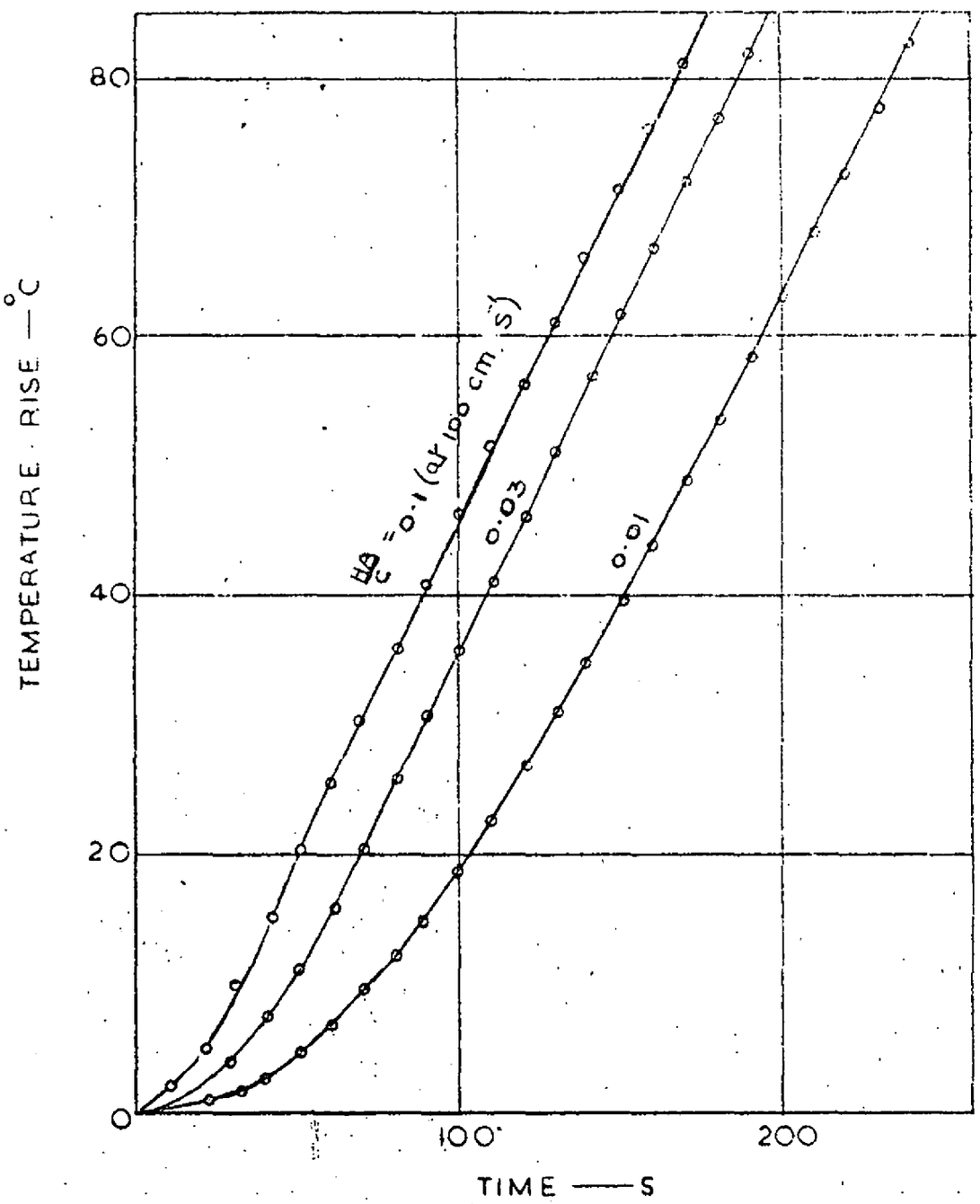

FIG. 18. TEMPERATURE RISE OF HEATED ELEMENTS SUBJECTED TO A VELOCITY RISING FROM 0-200 cm/s IN 5 MINUTES

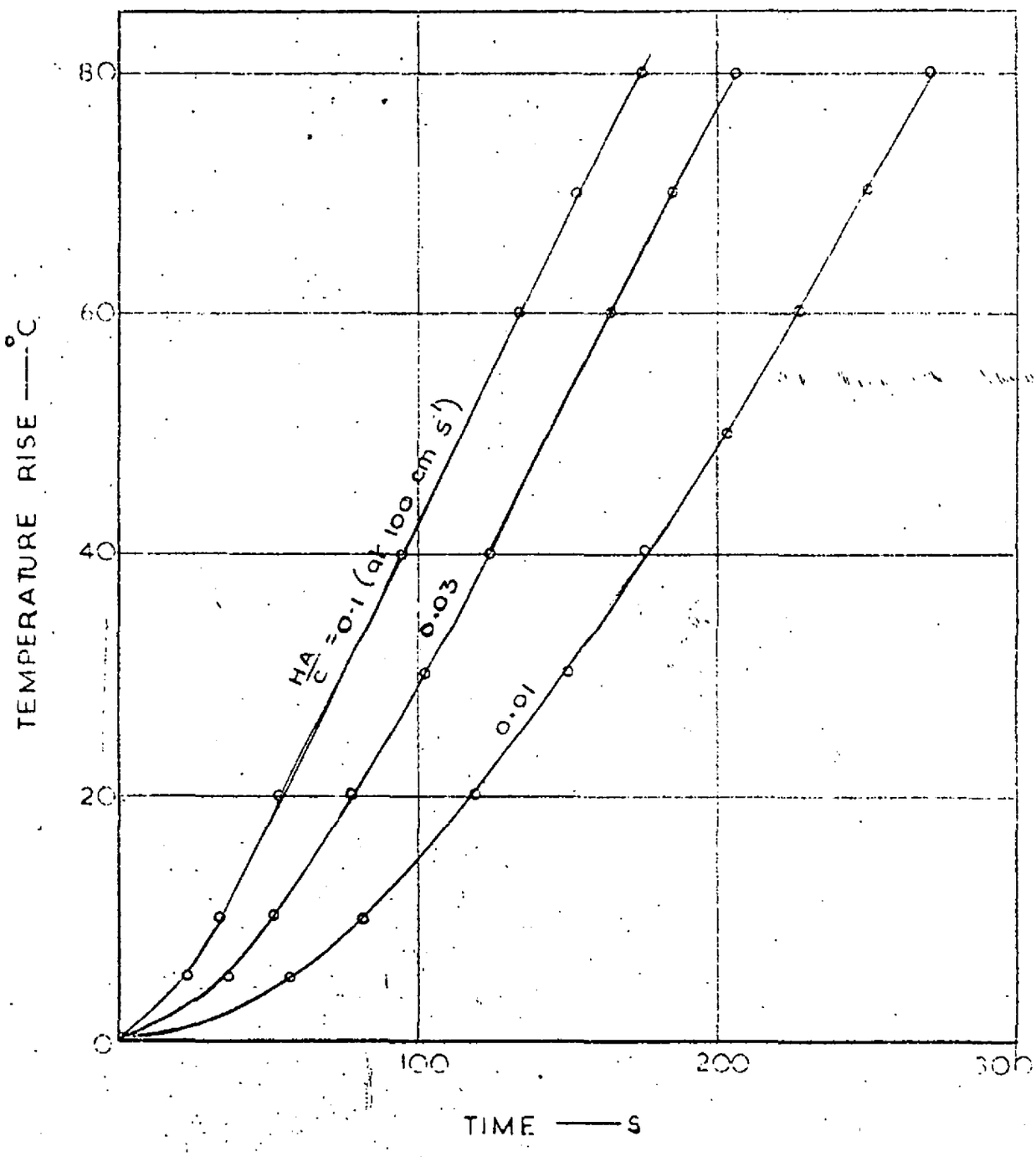

FIG. 19. AVERAGE TEMPERATURE RISE OF HEATED ELEMENTS

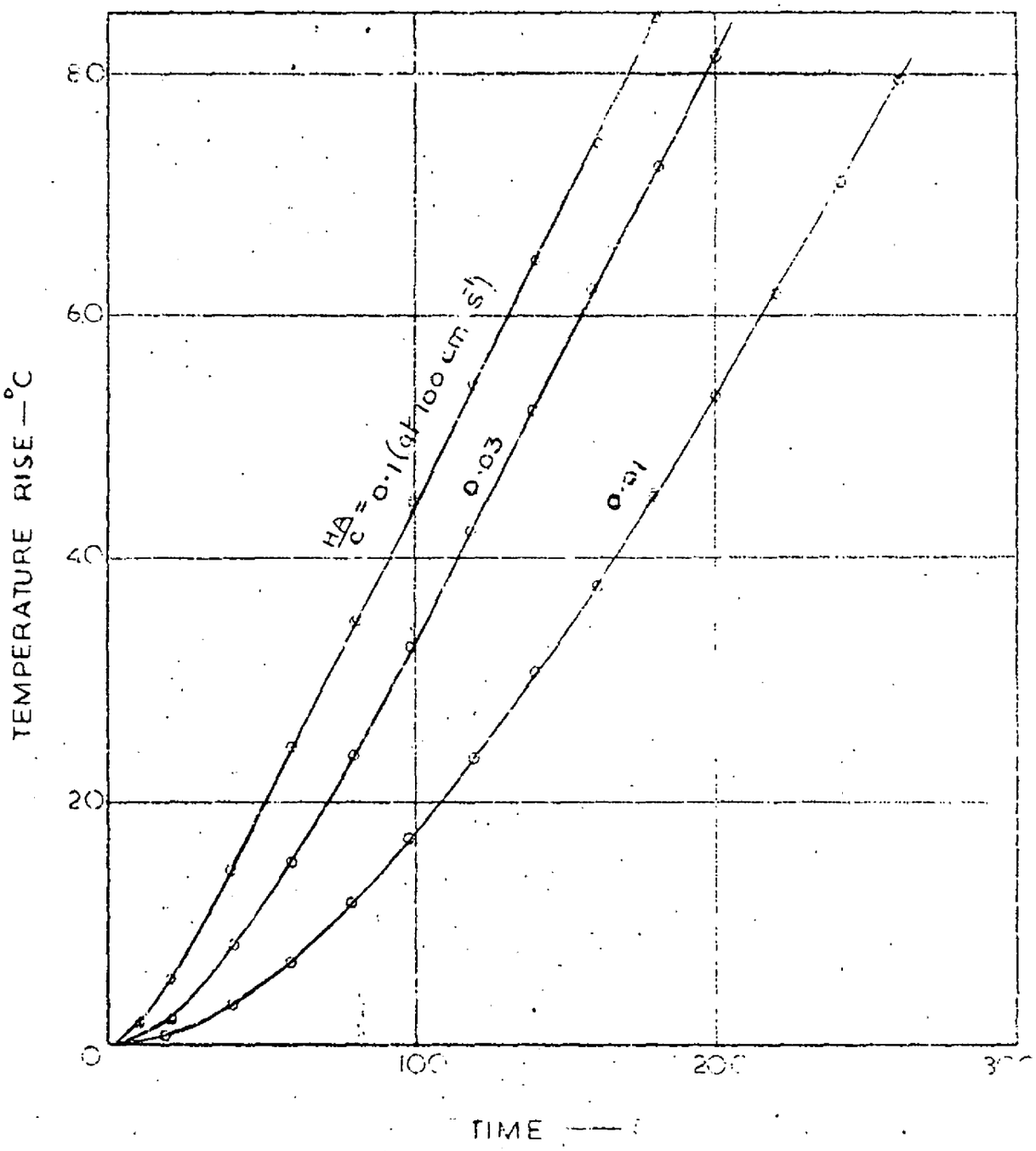

FIG. 20. TEMPERATURE RISE OF HEATED ELEMENTS SUBJECTED TO A CONSTANT VELOCITY OF 80 cm/s