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FIRE DETECTION SYSTEMS USING LASER BEAMS

by

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SUMMARY

An analytical treatment is given of the sensitivity of an interferometric fire detector using laser beams. It is shown that the system would probably give false alarms due to building distortions.

An alternative system is discussed, depending on the bending of laser beams in the space above a fire due to changes in the refractive index of the atmosphere.

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

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INTERFEROMETRIC SYSTEM

A laser has the property of producing coherent monochromatic radiation. It thus enables a highly collimated beam to be produced which, when divided by an optical system, may be made to travel over different paths and then be recombined to exhibit interference (Fig. 1).

If S is a laser source and the beam is split by the mirror system, M_1 M_2, and recombined by M_3 M_4 (Fig. 1), so that the beams travel over paths A and B, then the beams will cancel or reinforce accordingly as path A and path B differ by $(2n+1)\frac{\lambda}{2}$ or $n\lambda$, λ being the wavelength of the laser beam.

If the path difference is continuously changing with time, then the photo-electric cell P will receive a flickering light.

The optical path lengths A and B will change in a fire because of the changing refractive index of the air due to the varying temperature of the air at ceiling level and also to the presence of combustion products. A fire will therefore cause variations of light intensity at the photo-electric cell P and the corresponding alternating output from the cell may be used to operate an alarm. Of course the paths A and B need not be in one straight line, the beams may be reflected by means of mirrors to criss-cross an area and so give area protection.

SENSITIVITY

If the source of light is monochromatic and has a frequency n, a path length ℓ will contain N waves where

$$N = \frac{n\ell\mu}{c_0} \qquad \text{.............} (1)$$

where μ is the refractive index of the medium,
and c_0 is the velocity of light in vacuo.

If the two paths A and B (Fig. 1) are separated by a distance Δh in the vertical plane, the difference in the number of waves between the two paths, due to varying refractive index, will be

$$dN = \frac{n\ell}{c_0} \frac{d\mu}{dh} \Delta h \qquad \text{............. (2)}$$

As the path difference changes between an odd number and an even number of wavelengths, the light falling on the photo-electric cell P will vary from a minimum to a maximum. This will mean that the frequency of the output of the photo-electric cell $\nu = \frac{dN}{dt}$ will be given by

$$\nu = \frac{n\ell}{c_0} \frac{d^2\mu}{dh\,dt} \Delta h \qquad \text{............. (3)}$$

The variation of the refractive index μ could be due either to changes in the temperature of the gases above a fire or to their composition. It may be shown (Appendix I) that the change in refractive index due to change in the composition of the atmosphere above a fire, is entirely outweighed by the effect of temperature and it is only necessary to consider the latter.

EFFECT OF TEMPERATURE CHANGES ON REFRACTIVE INDEX

Biot and Arago derived an expression for the variation of refractive index μ with the absolute temperature T

$$(\mu - 1) \propto \frac{p}{T}$$

where p is the pressure.

As the pressure differences above fires are small compared with the changes in temperature,

$$(\mu - 1) \propto \frac{1}{T} = \frac{k}{T}$$

and therefore

$$\frac{d\mu}{dh} = -\frac{k}{T^2} \frac{dT}{dh} \qquad \text{............. (4)}$$

On substituting (4) in (3)

$$\nu = \frac{n\ell}{c_0}\,\frac{k}{T^2}\,\frac{d^2T}{dh\,dt}\,\Delta h$$

Putting $k = (\mu_0 - 1)T_0$ where the values with subscripts o refer to $^\circ$C and the wavelength of laser light $\lambda = c_0/n$

$$\nu = \frac{\ell}{\lambda}(\mu_0 - 1)\frac{T_0}{T^2}\,\frac{d^2T}{dh\,dt}\,\Delta h \qquad \ldots\ldots\ldots\ldots\ldots (5)$$

Taking a path length of 100 m and $\lambda = 6943 \times 10^{-8}$ cm (ruby laser).

$$(\mu_0 - 1)_{air} = 3 \times 10^{-4}$$
$$T_0 = 273^\circ K$$
$$T = 300^\circ K$$

Δh the beam separation = 30.5 cm (1 ft)

$$\frac{d^2T}{dh\,dt} = 0.002 \text{ deg C cm}^{-1}\text{ s}^{-1}$$

then $$\nu = \frac{10^4 \times 3 \times 10^{-4} \times 273}{6.943 \times 10^{-5} \times (300)^2} \times 0.002 \times 30.5$$

$$\simeq 8 \text{ c/s.}$$

This is produced by a heat release of 100 Btu/s, equivalent to burning 6 g fuel per second, i.e. a fire the size of a waste-paper basket.

The system, therefore, is not very sensitive and it is possible that perturbations of the path caused by perturbations in the building due to, say, a gusty wind could be of this order.

BEAM DEFLECTION SYSTEM

A fire detector could be constructed by using the fact that a beam of light will be refracted when passing through a medium of varying refractive index such as would occur over a fire. A laser beam has the advantage that it is closely collimated so that the undeflected beam could be masked and a photo-electric cell arranged to receive light only when the beam is deflected, as when a fire occurs.

From Fig. 2, consider the wave front AC traversing a path in a medium in which the velocity of propagation along AB is V + dV and along CD is V. The wavefront will arrive at BD after traversing a circular path such that

$$\frac{V + dV}{V} = \frac{R + dR}{R}$$

or

$$\frac{V}{R} = \frac{dV}{dR} \qquad \text{............. (6)}$$

The velocity of light V in a medium of refractive index is $V = \frac{C_o}{\mu}$

Whence from (6)

$$\frac{C_o}{\mu R} = -\frac{C_o}{\mu^2}\frac{d\mu}{dR}$$

or

$$\frac{1}{R} = -\frac{1}{\mu}\frac{d\mu}{dR} \qquad \text{............. (7)}$$

Since R is always large, the deflection d of the light beam from a straight path may be obtained from the geometry of the circle as

$$d = \frac{\ell^2}{2R} \qquad \text{............. (8)}$$

where ℓ is the length of path traversed by the light beam.

Substituting (8) in (7) gives

$$d = -\frac{\ell^2}{2\mu}\frac{d\mu}{dR}$$

The negative sign can be dropped as this only gives the direction of the displacement.

Since R is large $\frac{d\mu}{dR} \simeq \frac{d\mu}{dh}$

also the value of μ for gases is very nearly equal to unity.

Whence

$$d = \frac{\ell^2}{2}\frac{d\mu}{dh}$$

As before, $$\frac{d\mu}{dh} = (\mu_0 - 1)\frac{T_0}{T^2}\frac{dT}{dh}$$

Thus $$d = \frac{\ell^2}{2}(\mu_0 - 1)\frac{T_0}{T^2}\frac{dT}{dh} \qquad \text{............. (9)}$$

Taking as before ℓ = 100 m (10^4 cm)

$$(\mu_0 - 1)_{air} = 3 \times 10^{-4}$$

$$T_0 = 273^{\circ}K$$

The values of $\frac{dT}{dh}$ (cf Appendix II, Figs. 3 and 4) after 1 min are 0.3 deg C/in and 0.1 deg C/in for the 12-ft and the 36-ft ceiling respectively. At this time, the thermal output from the test fire for which the figures are quoted would be only 25 Btu/s. This is a very small fire.

Translating the values of $\frac{dT}{dh}$ into metric measurement gives $\frac{0.3}{2.5}$ = 0.12 deg C/cm and 0.04 deg C/cm for the 36-ft ceiling.

Substituting these values into (9) gives for the 12-ft ceiling

$$d = \frac{10^8}{2} \; 3 \times 10^{-4} \times \left(\frac{273}{300}\right)^2 \times 0.12$$

$$= 5.5 \text{ cm.}$$

For the 36-ft high ceiling, the corresponding deflection would be 1.8 cm.

The temperature gradient near to ceilings increases with time with a growing fire and the deflection would be correspondingly increased.

In view of the small fire used, this would seem to be a sensitive system of detecting fire and is superior to the interferometric system. A device of this kind would warrant further study.

APPENDIX I

REFRACTIVE INDICES OF GASES ABOVE FIRES

Most materials likely to be involved in fire are composed of cellulose which reacts with oxygen during combustion as follows:-

$$C_6 H_{10} O_5 + 6\ O_2 \longrightarrow 6\ CO_2 + 5\ H_2O$$

In air, the 6 moles of oxygen are accompanied by 24 moles of nitrogen and the total heat content of the combustion products is about 251 cal/deg C. The heat of combustion of cellulose is about 4,000 cal/g so that the combustion of the gram molecular weight produces 162 x 4,000 = 6.48×10^5 cal.

As something like one-third of the heat is lost by radiation, about 4.3×10^5 cal are lost in heating the combustion products above the fire. This would indicate that if the heat were used in raising the temperature of the combustion products alone, they would have a temperature of about $\frac{4.3}{251} \times 10^5 = 1700^{\circ}$ C.

Of course, the combustion gases will, when released in a compartment, entrain many times their own volume of air and the temperatures underneath ceilings will be considerably lower, but even so, it is not difficult to show that the change in refractive index due to variations in temperature are likely to far outweigh those due to changes in the composition of combustion gases so that only the former need be considered. As air entrainment will affect both the changes in the refractive index due to temperature, and changes due to the variation in composition of the combustion gases in the same way, a comparison of the two factors may be made with the undiluted combustion products.

CHANGE IN REFRACTIVE INDEX DUE TO COMPOSITION

This may be determined by proportioning. Taking the following values for sodium D light

$$\mu_{N_2} = 1.0003$$

$$\mu_{H_2O} = 1.00025$$

$$\mu_{CO_2} = 1.00045$$

The resulting refractive index for the products produced in the proportions that they appear in the combustion equation is

$$\mu = \frac{6 \times 1.00045 + 5 \times 1.00025 + 24 \times 1.0003}{35}$$

$$= 1.00032$$

It is convenient to express the change in refractive index in terms of $\delta = \mu - 1$, as this represents the difference between the refractive index concerned and that of free space. The value of δ for the combustion products may be compared with that for air, $\delta = 0.00029$, where it will be seen that the change is small and of the order of 10 per cent.

CHANGE DUE TO TEMPERATURE

Biot and Arago derived the expression $\delta \propto \frac{P}{T}$ or since the pressure changes above flames are small compared with the changes in temperature, $\delta \propto \frac{1}{T}$. From this it will be seen that the changes in δ due to temperature are likely to far outweigh those due to changes in the composition of the combustion products.

APPENDIX II

THE TEMPERATURE GRADIENTS IN BUILDINGS

I am indebted to Mr. M. J. O'Dogherty for the following unpublished information about the temperature gradients near to flat ceilings due to fires.

The air temperatures at various distances below flat ceilings were measured at different stages in the development of a crib fire. The results are shown in Figs. 3 and 4 for two ceiling heights, 3.66 m (12 ft) and 11 m (36 ft).

The rate of change of temperature with height at various times may be derived for these two ceiling heights from Figs. 3 and 4 and this is plotted in Fig. 5, from which it will be seen that the rate of change of temperature gradient with time is about 0.3 deg C in^{-1} min^{-1}. During the first 3 min with the 36-ft ceiling, the gradient is lower than this, but after that time, it approximates to the same figure as that of the 12-ft ceiling.

Thus the term in Equation (5) $\frac{d^2T}{dh\ dt}$ is 0.3 deg C in^{-1} min^{-1} or $\frac{0.3}{2.5 \times 60} = 0.002$ deg C cm^{-1} s^{-1}.

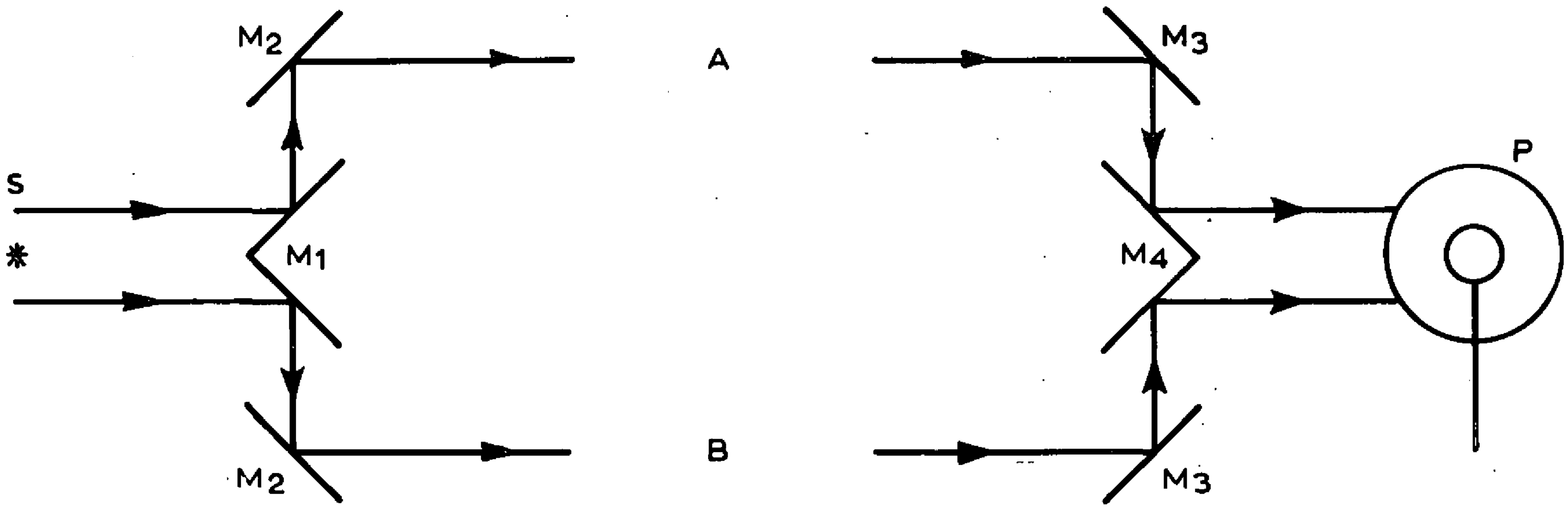


FIG. 1. A FIRE DETECTION SYSTEM USING THE PRINCIPLE OF THE INTERFEROMETER

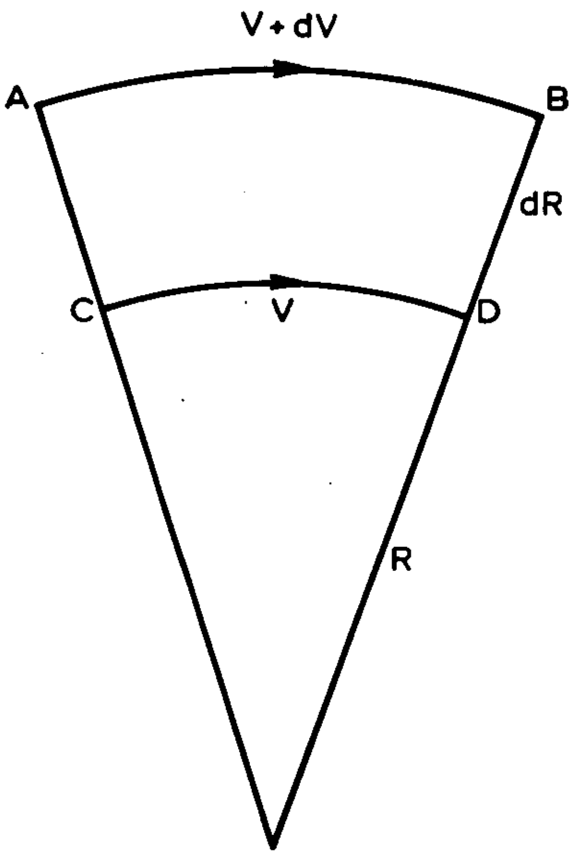
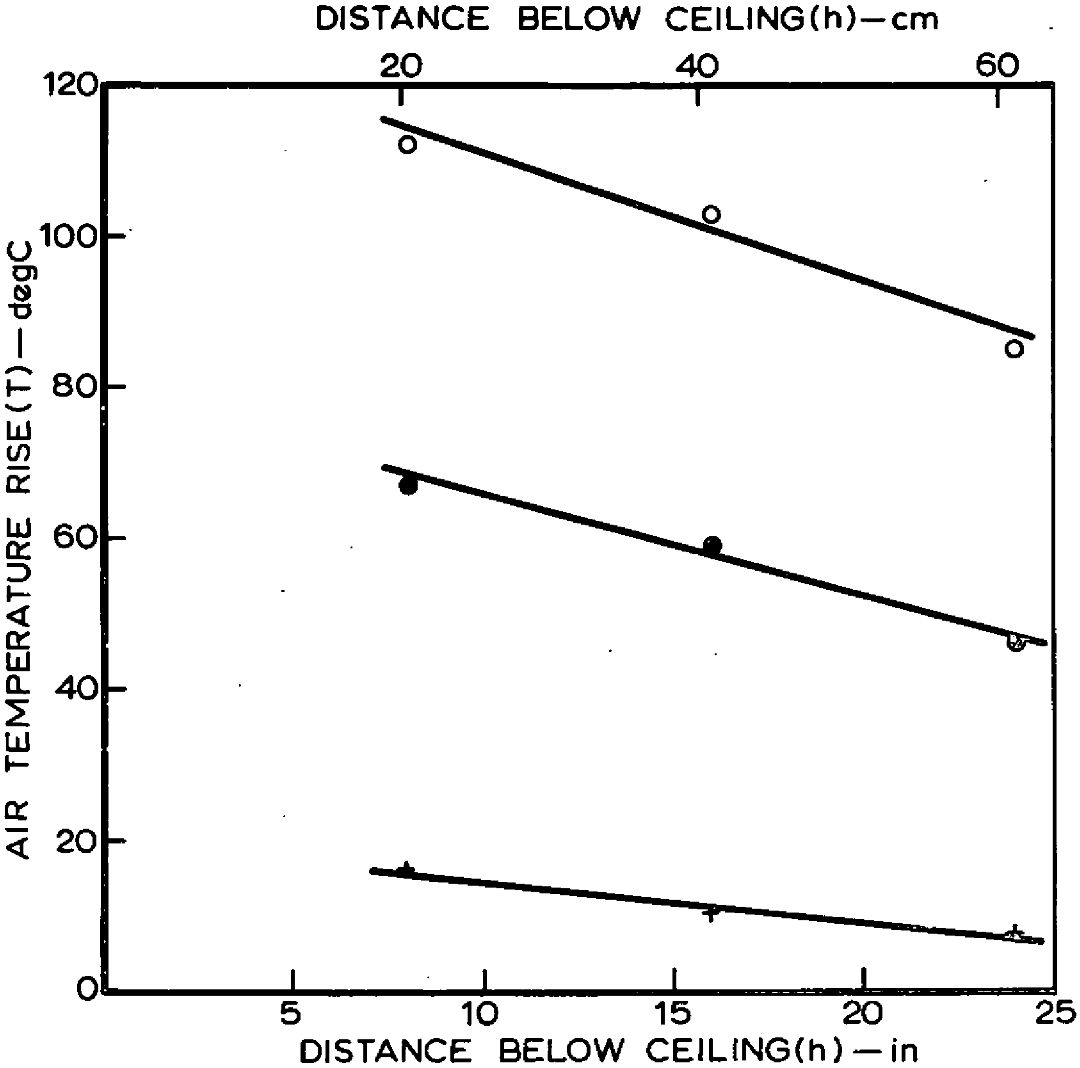


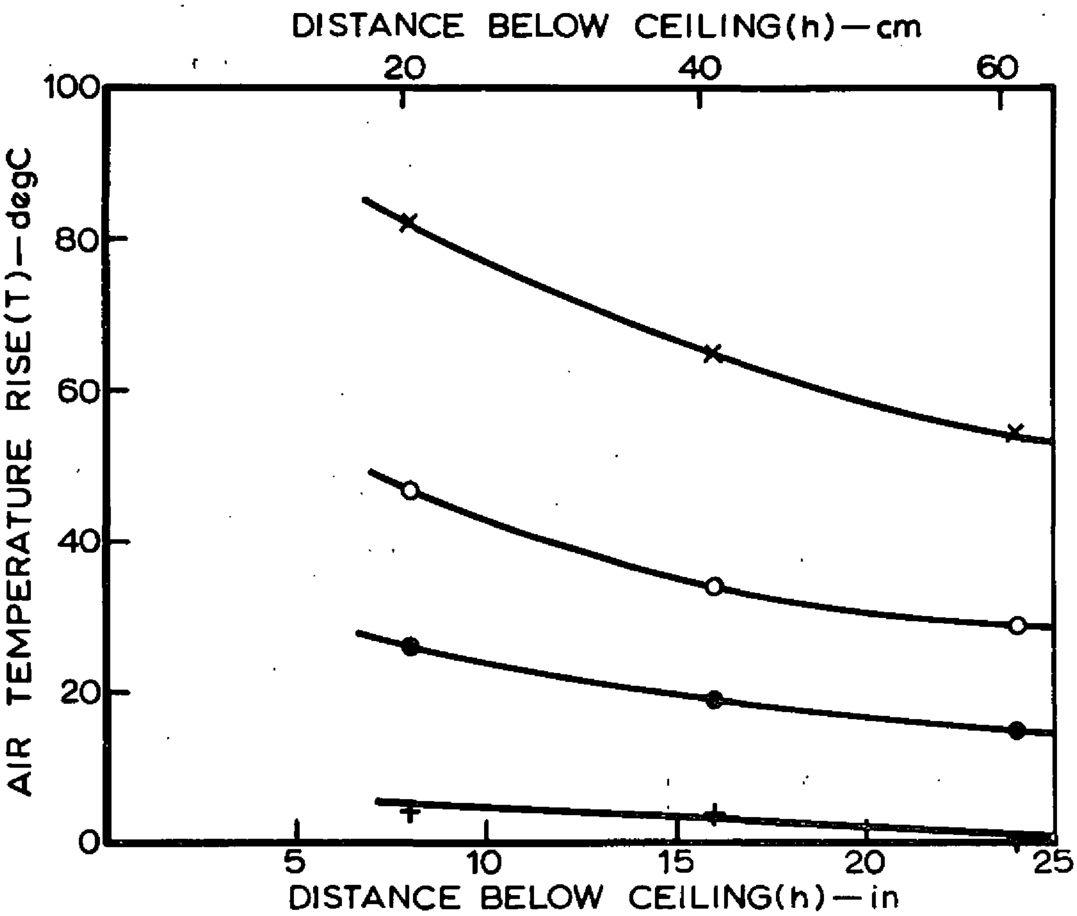
FIG. 2. THE TRANSMISSION OF LIGHT IN A MEDIUM OF VARYING REFRACTIVE INDEX



Symbol	Heat output of fire Btu/s	kcal/s	Time min
o	1000	252	5·7
●	500	126	4·4
+	100	25	2·2

Air temperature measured 10 ft (3·05 m) from axis of fire

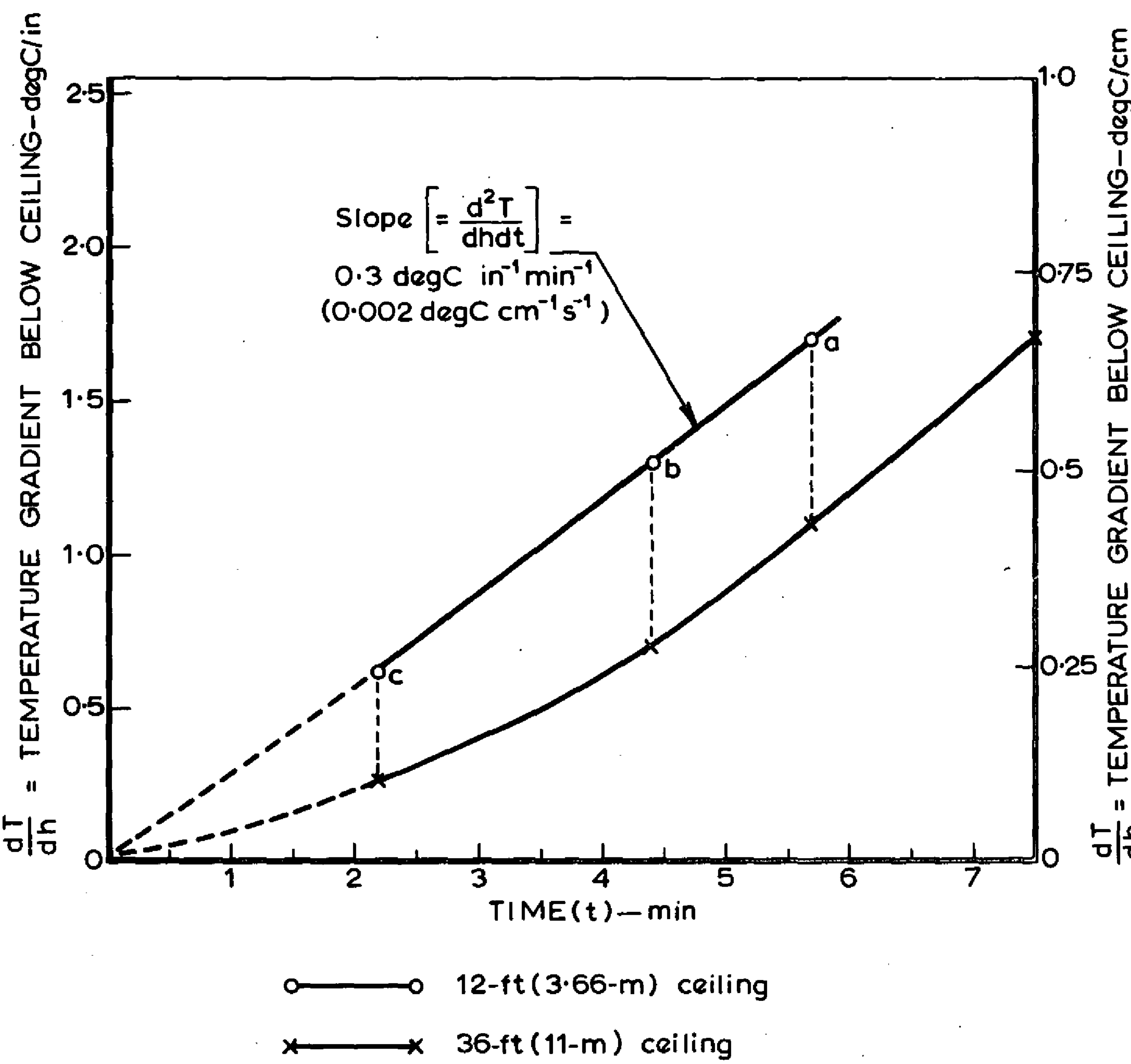
FIG. 3. AIR TEMPERATURES AT VARIOUS DISTANCES BELOW A CEILING 12 FT (3·66 M) ABOVE A FIRE



Symbol	Heat output of fire Btu/s	kcal/s	Time min
×	2000	505	7·5
o	1000	252	5·7
●	500	126	4·4
+	100	25	2·2

Air temperature measured 10 ft (3·05m) from axis of fire

FIG. 4. AIR TEMPERATURES AT VARIOUS DISTANCES BELOW A CEILING 36 FT (11 M) ABOVE A FIRE



	Rate of burning Btu/s	kcal/s
a	1000	252
b	500	126
c	100	25

FIG. 5. TEMPERATURE GRADIENTS NEAR CEILINGS AS A FUNCTION OF TIME

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