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

THE PREDICTION OF THE DISTANCE OF IGNITION OF WOOD FROM AN ATOMIC EXPLOSION

by

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1. Introduction

Previous attempts[1.2.] to predict the distance from an atomic explosion at which wood would be ignited have been based on the assumption that the radiation is constant for a period of 3 secs. after which it falls rapidly to zero. This is very far from the truth as will be seen on reference to Figure I which shows the probably variation of intensity with time at a distance of 1 km from the explosion. Although the average intensity used in the previous calculations was derived from the time integral of this curve it was felt that the non uniformity of the radiation with time would affect the results significantly and that the probable discrepancy should be determined.

In the past the distance of ignition has been found by determining experimentally the intensity required to ignite various species of wood in three seconds and then computing the distance from an atomic explosion at which this intensity would occur under various atmospheric conditions. This direct approach is not suitable when account has to be taken of an incident intensity which is varying with time and an alternative method has to be devised.

It is well known that the diffusion of heat in materials may be represented by the current flowing inside suitably designed electrical networks and this analogy has been exploited in the solution of the problem. The problem divides itself into two parts; first to determine the intensity of radiation required to bring the surface of the wood temperature for spontaneous ignition and second to determine the distance from the explosion at which these intensities will be encountered.

2. Intensity required for the spontaneous ignition of wood.

This part of the problem may be subdivided into two sections one in which the temperature at which spontaneous ignition takes place is calculated and the other in which the temperature of the irradiated material is determined.

2.1. The use of electrical networks for the determination of the ignition temperature of wood

It is well-known that the flow of charge in a repeated resistance capacity network of the type shown in Fig. 2 will represent the one-dimensional flow of heat inside a slab provided certain relationships are maintained between the resistances and the thermal resistance and between the capacity and the product of the density and specific heat. This being so, the potential difference across the network at any point will represent the temperature rise at a corresponding point in the slab on the heat problem and the current will represent the heat flux at the same point. The application of a constant current to the network would represent the irradiation of a slab at a constant intensity Fig. 3. As irradiation proceeds the temperature of the front face of the slab will rise and it will begin to reradiate heat. A suitable electrical circuit which will represent this loss of heat due to Stefan radiation and convection has been developed by Lawson and McGuire[3.] and this is shown connected to the line network in Fig. 4.

Lawson and Simms[4] have determined the minimum intensities of radiation which will cause wood to ignite spontaneously after the irradiation has been continued for a very long time. They call this the critical intensity and find that this is constant for nearly all the woods tested and equal to 0.6 cal./sq.cm./sec. Under these conditions the wood will have reached a uniform temperature since it has been irradiated for a long time and no heat will flow from the surface to the interior. This means that the surface temperature will be governed only by the heat lost from the surface. The surface temperature may be found by adjusting the constant current to a value representing the critical radiation of 0.6 cals./sq.cm./sec. and applying this to the reradiation network only, with the rest of the transmission network representing the wood disconnected Fig. 5. In this way the temperature at which timber ignites spontaneously is found to be about 480°C.

2.2. The use of electrical networks to determine the surface temperature of wood irradiated by an atomic explosion.

An atomic explosion will radiate energy which will vary with time as shown in Fig. 1 and it is necessary to develop a current waveform of this type. Since at any instant the incident radiation is independent of the temperature of the irradiated surface, it is essential that this current waveform shall be delivered to the network from a source of high impedance. The time variation of the radiation may be closely represented by the flow of current in an overdamped series inductance resistance and capacity network. This current is applied to the network representing the wood through valve circuits which maintain it constant irrespective of the potential rise. The input current representing the radiation may be adjusted until the surface temperature rise is 480°C at which point ignition takes place. In this way, the peak value of radiation required for ignition is found. The curves in Figs. 6 and 7 show the rise in temperature with time for mahogany and American whitewood. In each case the intensity of radiation has been adjusted to raise the surface temperature by 480°C the requirement for spontaneous ignition. The temperature of the surface rises to its maximum value after 0.6 secs. so that ignition will not occur after this time. It will be seen that the peak intensity required for the ignition of mahogany (5.92 cals/sq.cm./sec.) is greater than that required to ignite American whitewood (5.25 cals./sq.cm./sec.) This is because mahogany, being a dense wood, has a greater thermal conductivity than American whitewood, a wood of medium density. Unfortunately it was not possible to compute accurately the radiation intensity required to bring fibre insulation board (a low density wooden board) to the point of ignition since this intensity was greater than that of the lowest range of the equipment and less than that of the highest range. By interpolation on a curve of a maximum surface temperature against peak intensity of radiation (Fig. 5) however, it has been found that a temperature rise of 480°C is produced by a peak intensity of 2.5 cal./sq.cm./sec. Time-temperature curves for a peak intensity of 2.1 cals./sq.cm./sec. are shown in Fig. 9.

Experiments which have been carried out to measure the radiation necessary to ignite wood in the presence of a pilot flame show that the critical intensity is about 0.25 cals./sq.cm./sec. Employing the methods used for spontaneous ignition it can be shown that all species of wood ignite at 250°C in the presence of a pilot flame. Reference to Figs. 5, 6, and 7 will show that as this temperature is achieved at a depth of about $\frac{1}{4}$mm below the surface. The burning layer would have a depth of about $\frac{1}{100}$ in.

Of course, if the applied intensity is greater, a higher maximum surface temperature will be reched. Figures 10 and 11 show that the surface temperatures attained by mahogany and American whitewood for intensities of 12 cals./sq.cm./sec. reach values of about 900°C. The surface temperature for fibre insulation board for an intensity of only 5.25 cals./sq.cm./sec. is 750°C Fig. 12. It will be seen that for all these conditions the spontaneous ignition temperature on the surface is attained after about 0.2 seconds. The pilot ignition temperature is reached at a depth of about $\frac{3}{4}$ mm. or about $\frac{3}{100}$in.

Knowing the intensity required for ignition and the energy released by the bomb it is possible to construct a table showing the distance at which ignition will take place under various atmospheric conditions.

/TABLE I

TABLE I

Distances in feet from ground zero at which ignition will take place

(Ignition in 0.6 secs. Depth of burning $^{1}/_{100}$in.)

Atmospheric Absorption coefficient km^{-1}	Mahogany	American Whitewood	Fibre Insulation Board
0 = Abs. clear	10,200	10,800	15,700
0.08 = Vis. 30 m.	9,100	9,600	13,000
0.2 = Vis. 12 m.	8,000	8,400	10,900
0.4 = Vis. 6 m.	6,700	7,000	8,800
0.8 = Vis. 3 m.	5,400	5,500	6,700
1.6 = Vis. 1½m.	3,900	4,000	4,700

3. Comparison of results with previous work

It is now possible to compare with previous work the distances at which ignition takes place when radiation is applied to a wooden surface such that the intensity varies with time as in an atomic explosion. In previous computation the incident intensity was assumed to be constant with time and had a value such that the total quantity of radiation at any given distance from ground zero was equal to the total radiation flux at that point from the bomb.

Figures 13, 14 and 15 show the distances from ground zero at which ignition takes place for mahogany, American whitewood and fibre insulation board, both for radiation following the bomb flash curve, and for radiation which is maintained constant with time.

It will be seen that in all cases the radiation following the bomb flash curve gives rise to ignition at a greater distance from ground zero than for constant intensity radiation. This is due to the fact that if a given quantity of radiation is applied rapidly there is little time for an appreciable quantity of heat to be conducted away from the surface layers and the surface temperature is higher, or conversely less heat is required to bring the surface of wood to a given value the more rapidly the heat is applied. For low density materials under perfectly clear conditions the increase in distance at which ignition takes place may be as much as 40% greater than previous estimates. For medium or high density wood the increase is only just over 10%. The lower the visibility the less the percentage discrepancy between the present estimates and previous work.

4. Conclusions

It has been shown that if allowance is made for the time variation of radiant intensity during the bomb flash that the distances at which ignition takes place may be up to 40% greater than previous estimates. The discrepancy is greatest for low density woods under clear conditions.

At the instant of ignition, at maximum ignition distance, the wood which will burn is a layer up to a depth of about $^{1}/_{100}$in. for all cases considered. The depth of burning will increase to a layer $^{3}/_{100}$ in thick when the peak radiation intensity is 12 cals./sq.cm./sec. for mahogany and for American whitewood. The same depth of burning will be given for a radiation intensity of 5.25 cals./sq.cm./sec. in the case of fibre insulation board.

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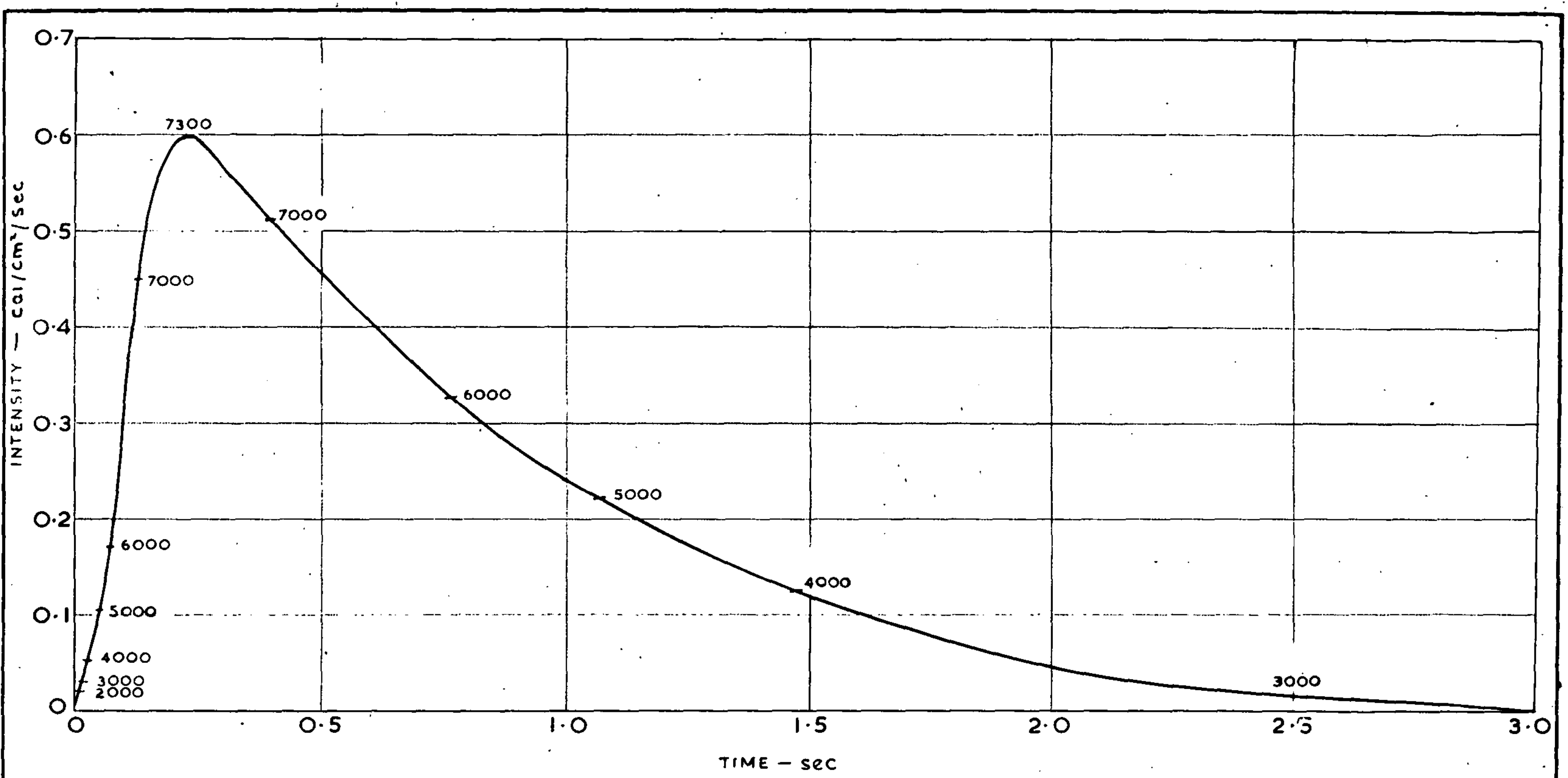

FIG. 1. VARIATION OF RADIATION INTENSITY WITH TIME. (FIGURES ON CURVE REFER TO TEMPERATURE OF FIRE BALL IN °C

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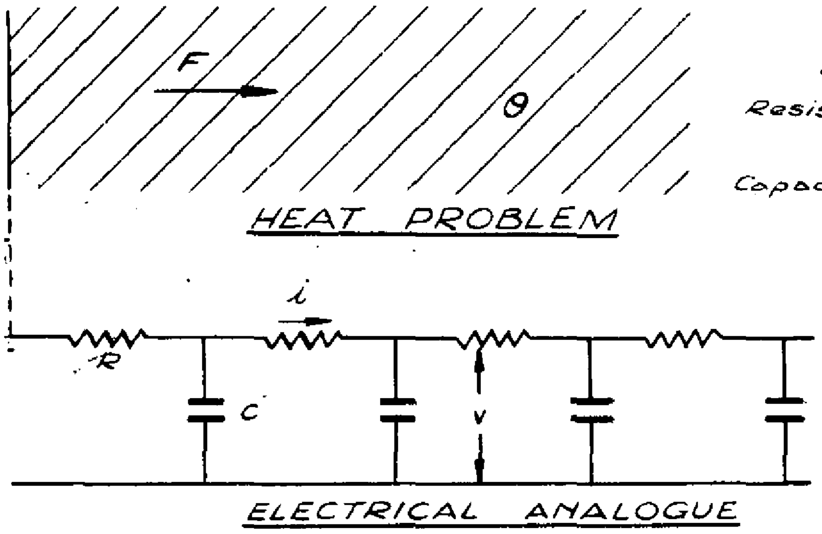


Electrical Current i analogous to heat flux F
Potential difference v analogous to temp. rise θ

Resistance $R \propto \frac{1}{\text{Thermal Conductivity}}$

Capacity $C \propto$ Specific Ht. × density

FIG. 2.
ELECTRICAL ANALOGUE OF HEAT PROBLEM.

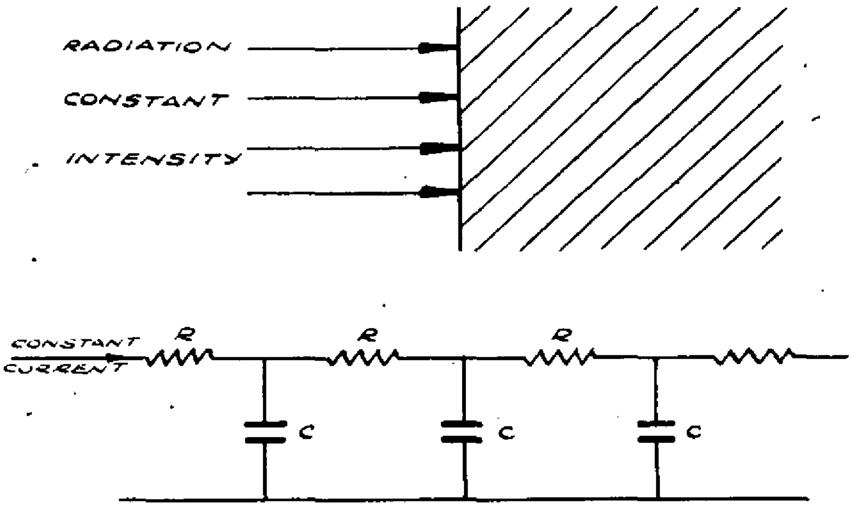


FIG. 3.
CONSTANT RADIATION REPRESENTED BY APPLICATION OF CONST. CURRENT TO NETWORK.

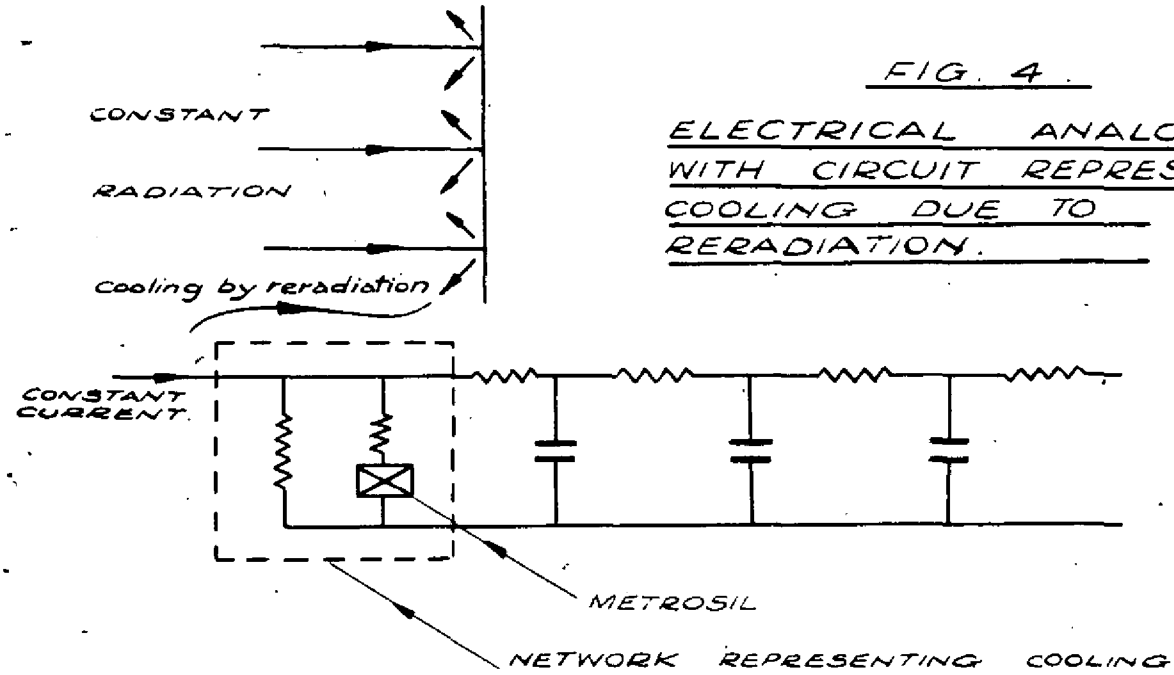


FIG. 4.
ELECTRICAL ANALOGUE WITH CIRCUIT REPRESENTING COOLING DUE TO RERADIATION.

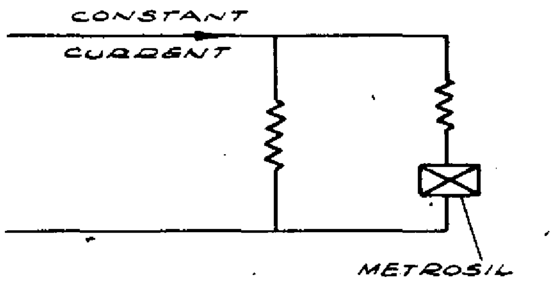


FIG. 5.
CIRCUIT REPRESENTING WOOD WHICH HAS BEEN IRRADIATED FOR A LONG TIME.

FIG. 6. TIME — TEMPERATURE CURVES FOR MAHOGANY WHEN IRRADIATED WITH A PEAK INTENSITY OF 5·9 CALS / SQ CM/SEC.

DISTANCES IN FEET FROM GROUND ZERO AT WHICH THE PEAK INTENSITY IS REACHED FOR VARIOUS ATMOSPHERIC CONDITIONS.

ATMOSPHERIC CONDITION	DISTANCE FT.
Perfectly Clear.	10,200
Vis. 30 ml.	9,100
" . 12 ml.	8,000
" . 6 ml.	6,700
" . 3 ml.	5,400
" . 1½ ml.	3,900

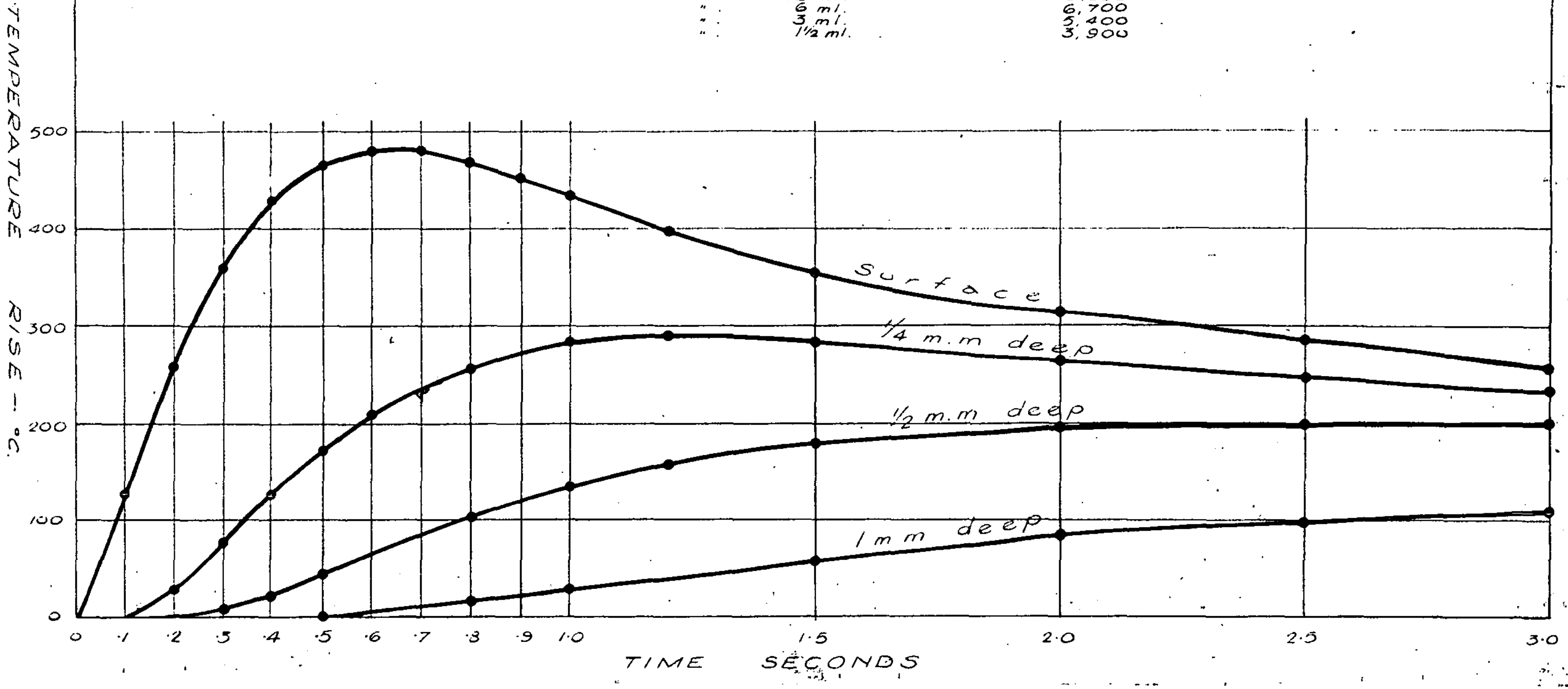


FIG. 7. TIME—TEMPERATURE CURVES FOR AMERICAN WHITEWOOD WHEN IRRADIATED WITH A PEAK INTENSITY OF 5·25 CALS/SQ.CM/SEC.

DISTANCE IN FEET FROM GROUND ZERO, AT WHICH THIS PEAK INTENSITY IS REACHED FOR VARIOUS ATMOSPHERIC CONDITIONS.

ATMOSPHERIC CONDITION.		DISTANCE
Perfectly Clear.		10,800 ft
Vis.	30 ml.	9,600 ft
"	12 ml.	8,400 ft.
"	6 ml.	7,000 ft
"	3 ml.	5,500 ft
"	1½ ml.	4,000 ft.

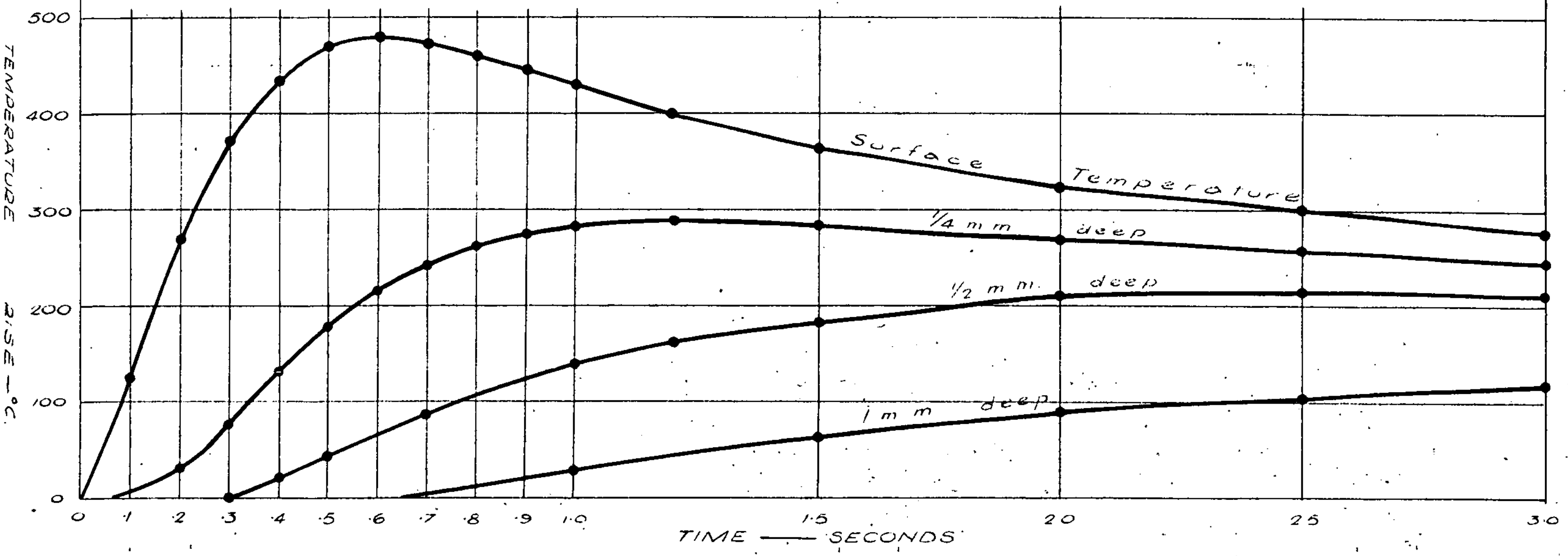


FIG. 8. MAXIMUM SURFACE TEMPERATURE ATTAINED BY FIBRE INSULATION BOARD PLOTTED AS A FUNCTION OF PEAK INTENSITY.

THE IGNITION TEMPERATURE OF 480°C IS ATTAINED WITH A PEAK INTENSITY OF 2·43 CALS/SQ.CM/SEC. THIS OCCURS AT THE FOLLOWING DISTANCES (IN FT) FROM GROUND ZERO.

ATMOSPHERIC CONDITION	DISTANCE FEET.
Perfectly Clean	15,700
Vis. 30 ml.	13,000
" 12 ml.	10,900
" 6 ml.	8,800
" 3 ml.	6,700
" 1½ ml.	4,700

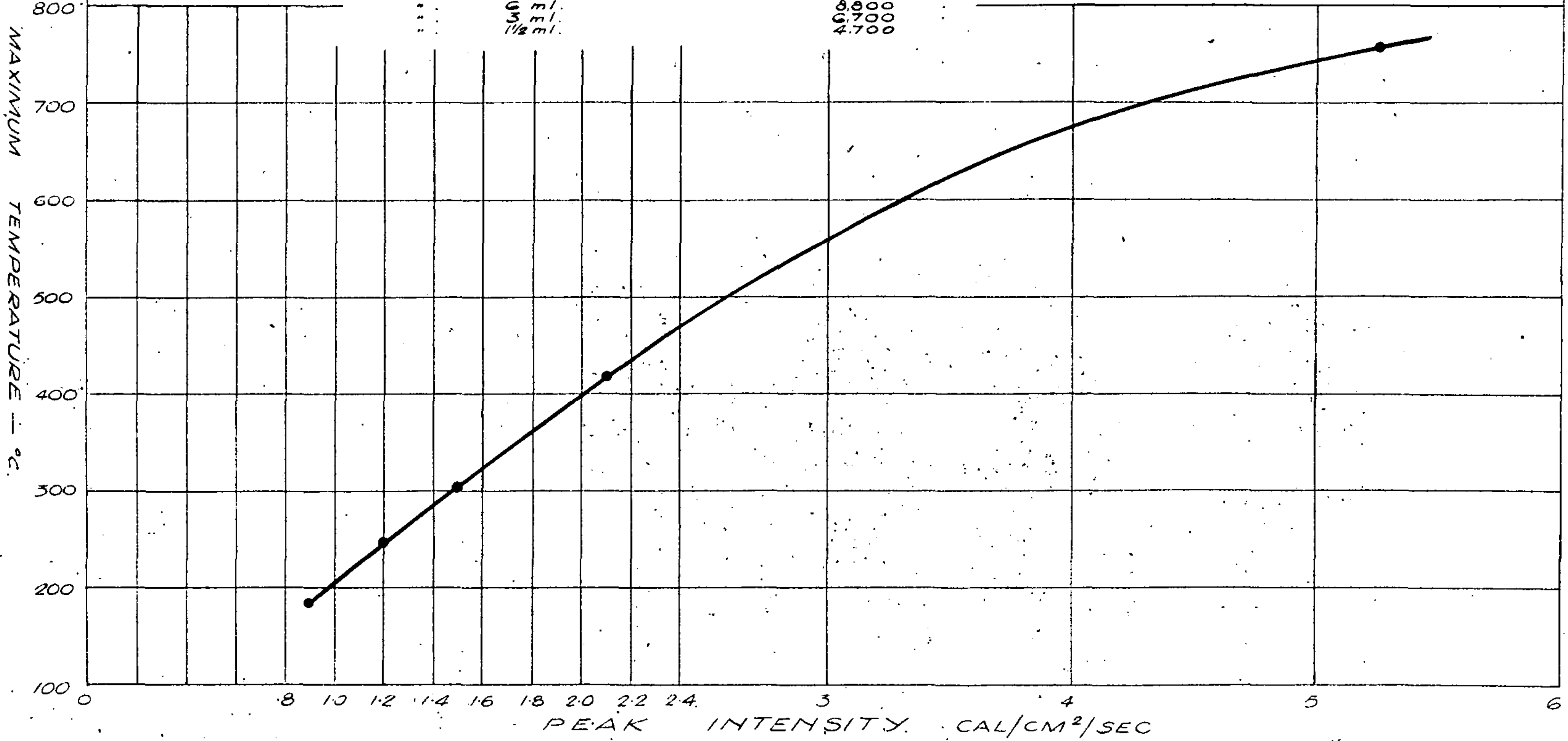
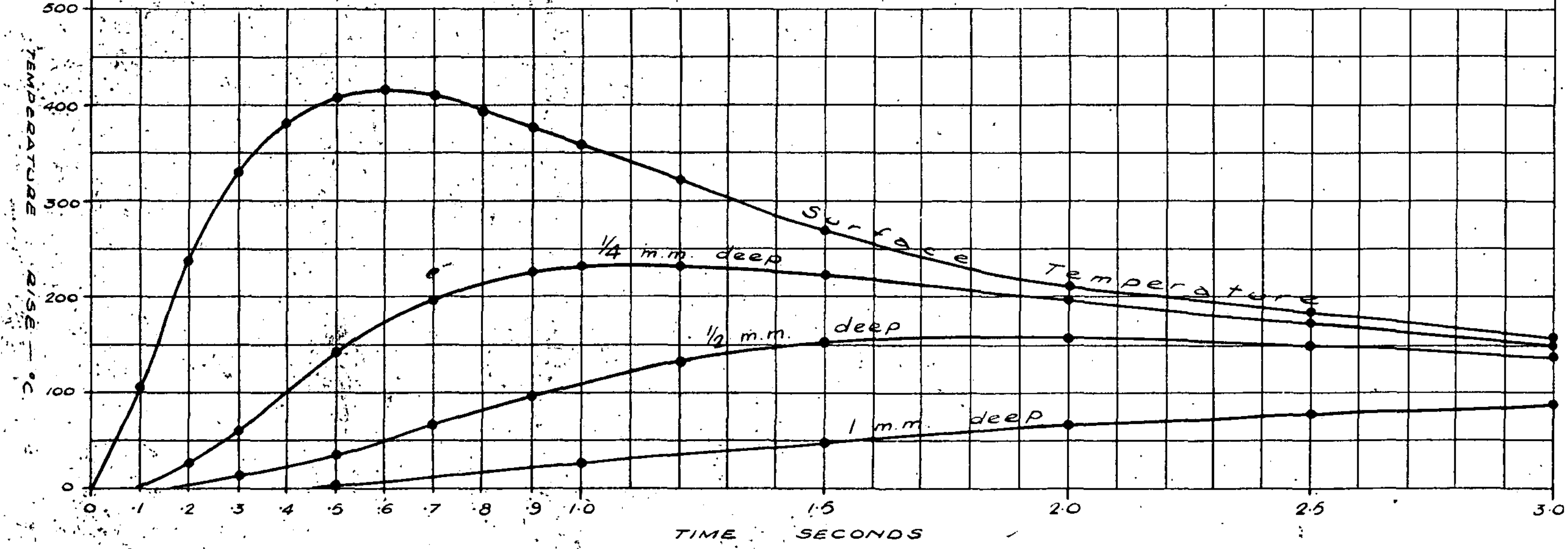


FIG. 9 TIME — TEMPERATURE CURVES FOR FIBRE INSULATION BOARD WHEN IRRADIATED WITH A PEAK INTENSITY OF 2·1 CALS/SQ CM/SEC.

DISTANCES IN FEET FROM GROUND ZERO AT WHICH THIS PEAK INTENSITY IS REACHED FOR VARIOUS ATMOSPHERIC CONDITIONS.

ATMOSPHERIC CONDITION	DISTANCE FEET
Perfectly Clear	17100 ft.
Vis. 30 ml.	13800 "
" 12 ml.	11600 "
" 6 ml.	9300 "
" 3 ml.	7000 "
" 1½ ml.	4900 "



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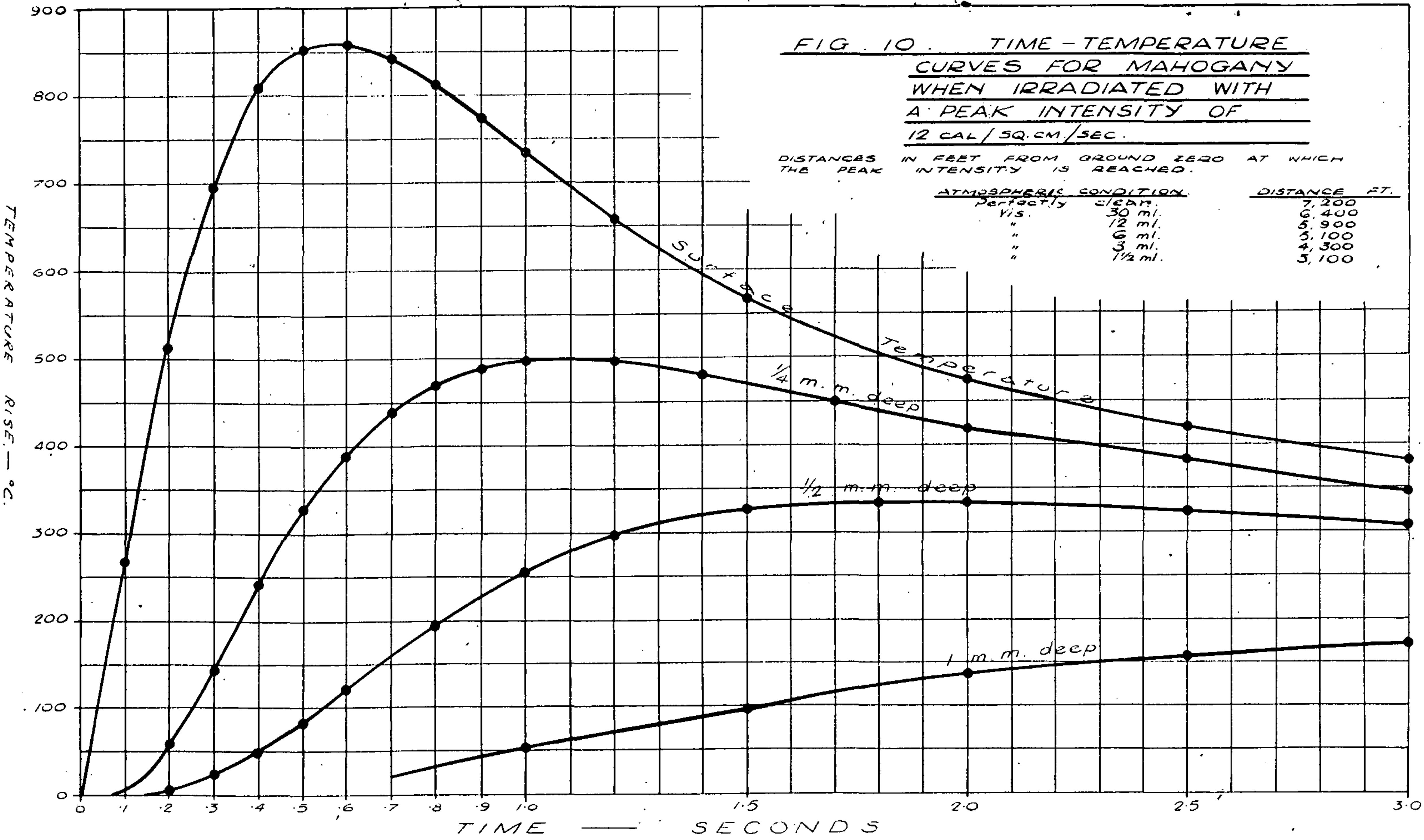

FIG. 10. TIME-TEMPERATURE CURVES FOR MAHOGANY WHEN IRRADIATED WITH A PEAK INTENSITY OF 12 CAL/SQ.CM./SEC.

DISTANCES IN FEET FROM GROUND ZERO AT WHICH THE PEAK INTENSITY IS REACHED.

ATMOSPHERIC CONDITION	DISTANCE FT.
Perfectly clean.	7,200
Vis. 30 ml.	6,400
" 12 ml.	5,900
" 6 ml.	5,100
" 3 ml.	4,300
" 1½ ml.	5,100

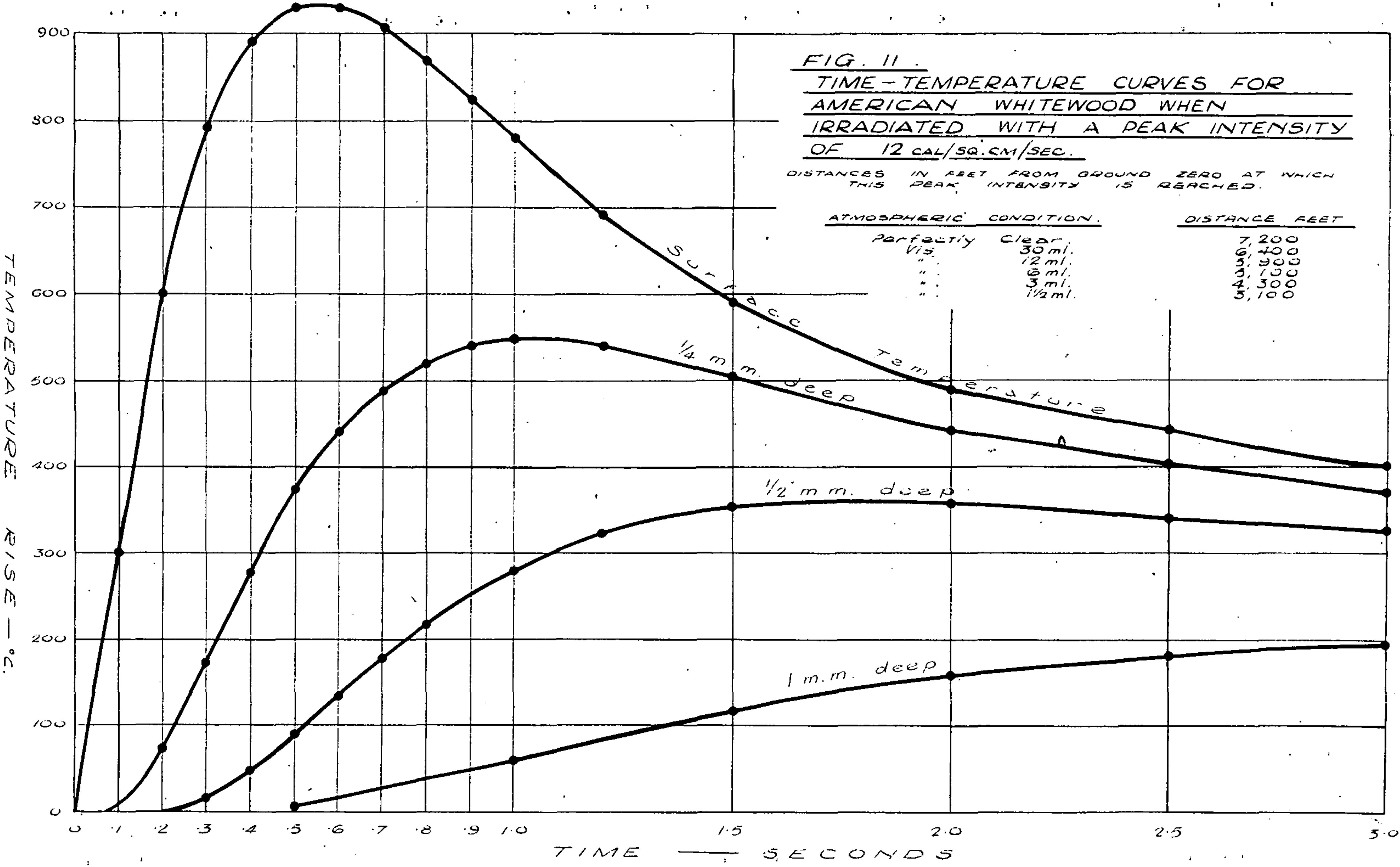

FIG. 11.
TIME–TEMPERATURE CURVES FOR AMERICAN WHITEWOOD WHEN IRRADIATED WITH A PEAK INTENSITY OF 12 CAL/SQ.CM/SEC.

DISTANCES IN FEET FROM GROUND ZERO AT WHICH THIS PEAK INTENSITY IS REACHED.

ATMOSPHERIC CONDITION.	DISTANCE FEET
Perfectly Clear.	7,200
Vis. 30 ml.	6,400
" . 12 ml.	5,900
" . 6 ml.	5,100
" . 3 ml.	4,300
" . 1½ ml.	3,100

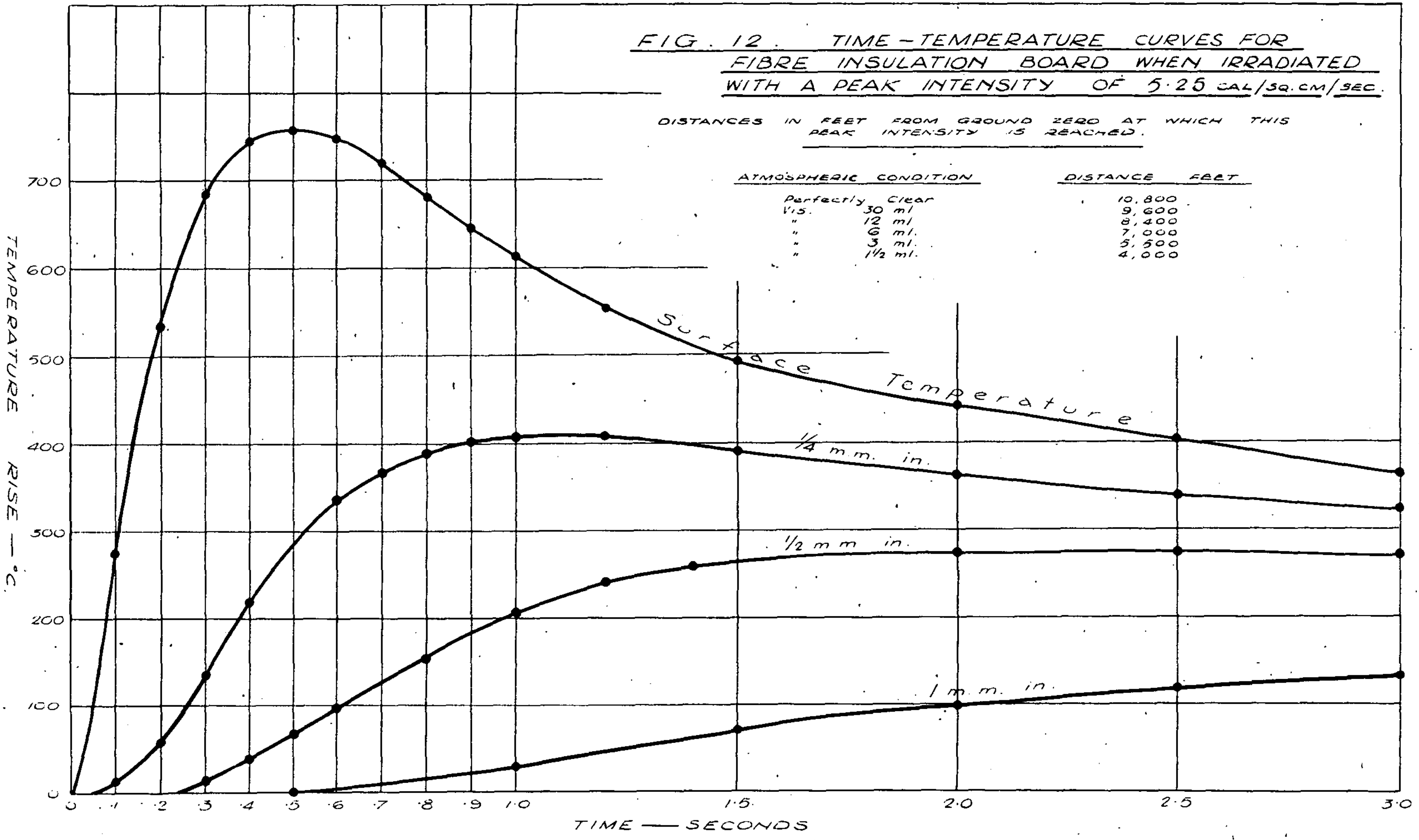

FIG. 12. TIME–TEMPERATURE CURVES FOR FIBRE INSULATION BOARD WHEN IRRADIATED WITH A PEAK INTENSITY OF 5·25 CAL/SQ.CM/SEC.

DISTANCES IN FEET FROM GROUND ZERO AT WHICH THIS PEAK INTENSITY IS REACHED.

ATMOSPHERIC CONDITION	DISTANCE FEET
Perfectly Clear	10,800
Vis. 30 ml	9,600
" 12 ml	8,400
" 6 ml.	7,000
" 3 ml.	5,500
" 1½ ml.	4,000

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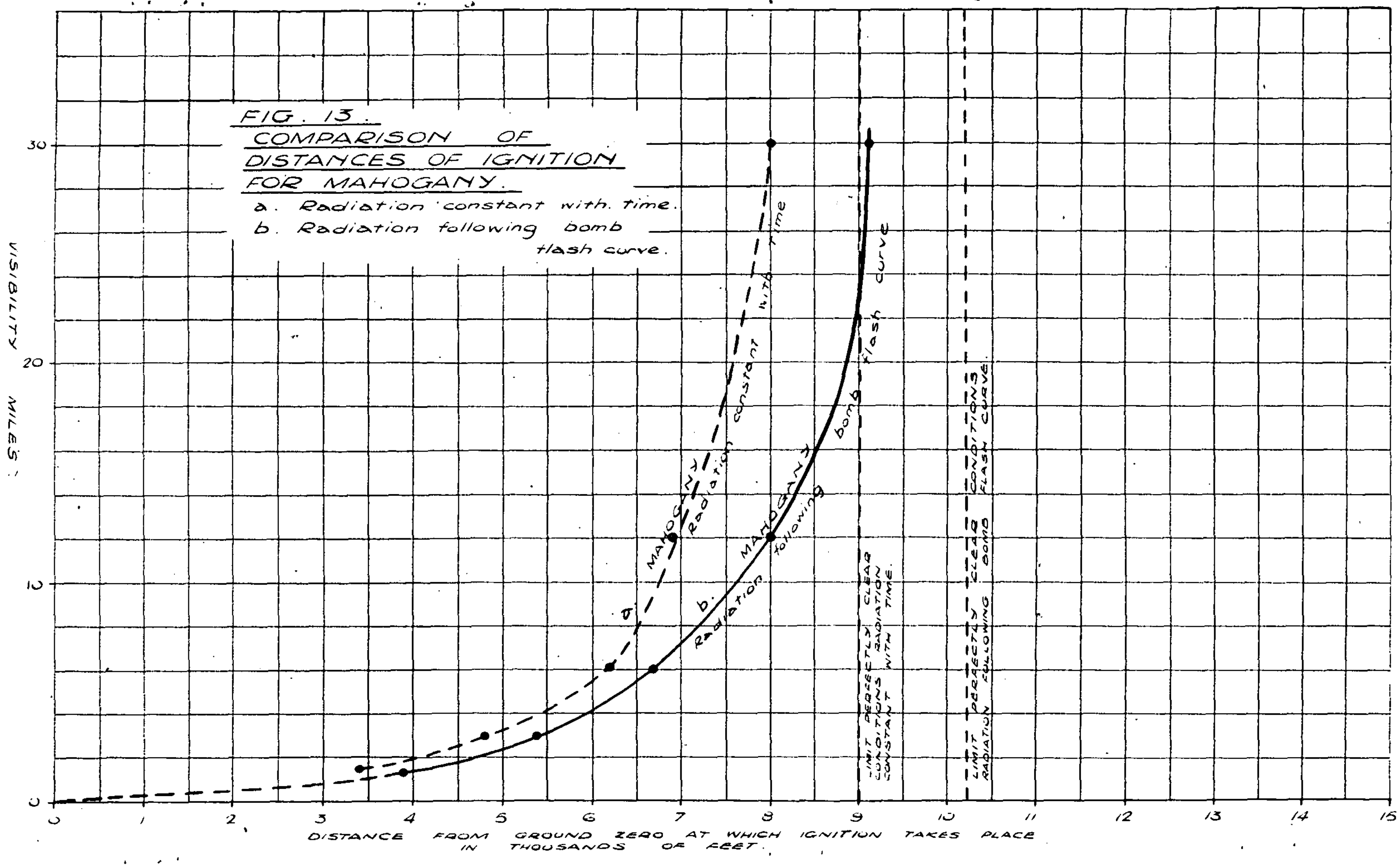

FIG. 13.
COMPARISON OF DISTANCES OF IGNITION FOR MAHOGANY.
a. Radiation constant with time.
b. Radiation following bomb flash curve.

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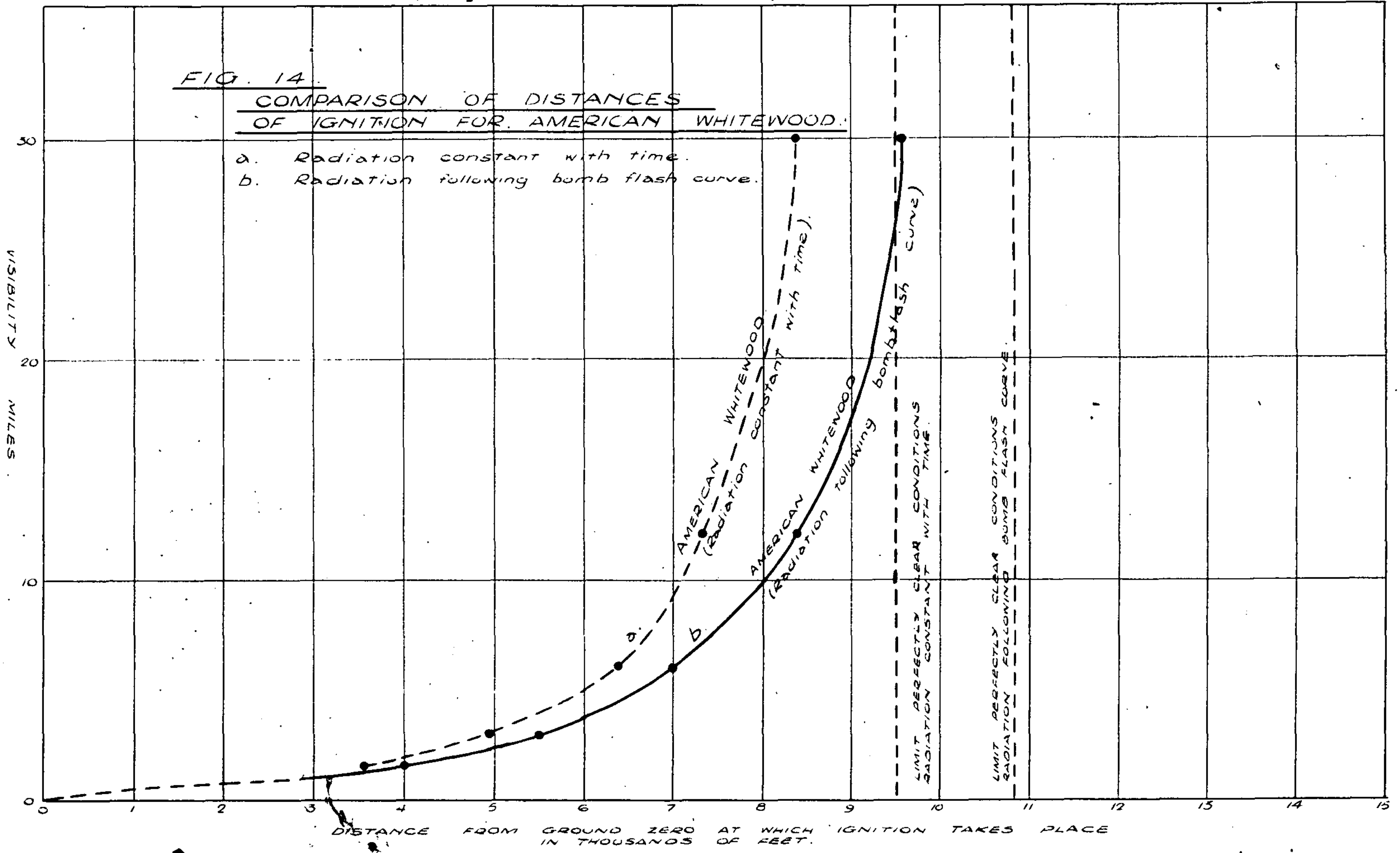
FIG. 14.
COMPARISON OF DISTANCES OF IGNITION FOR AMERICAN WHITEWOOD.

a. Radiation constant with time.
b. Radiation following bomb flash curve.



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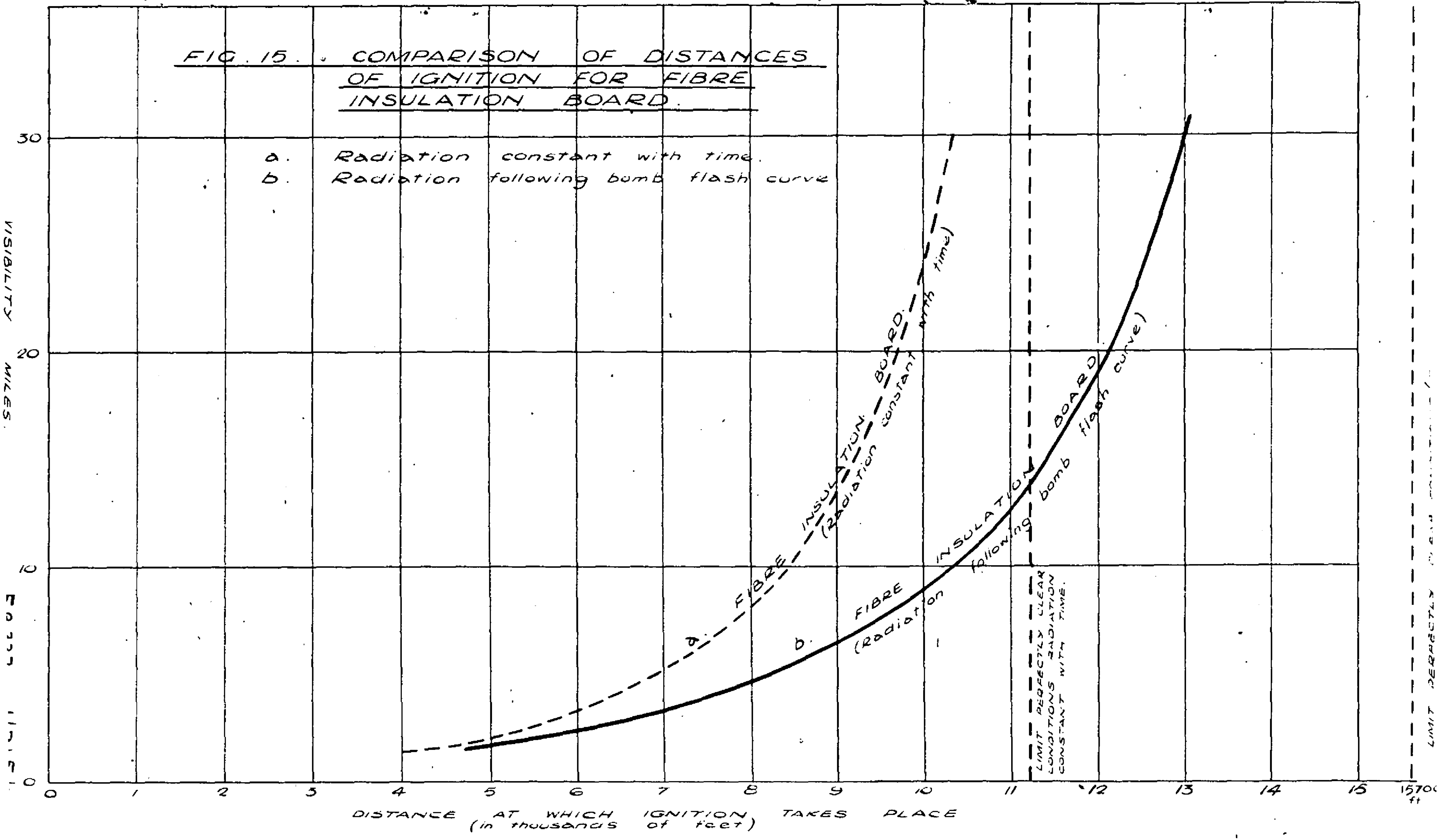

FIG. 15. COMPARISON OF DISTANCES OF IGNITION FOR FIBRE INSULATION BOARD.