~~F.R. Note No. 280/1956~~
Research Programme
Objective B2

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

This report has not been published and should be considered as confidential advance information. No reference should be made to it in any publication without the written consent of the Director, Fire Research Station, Boreham Wood, Herts. (Telephone: ELStree 1341 and 1797).

THE EFFECT OF MOISTURE CONTENT ON THE SPONTANEOUS IGNITION OF WOOD BY RADIATION

by

P. H. Thomas, D. L. Simms and Margaret Law

The time taken to ignite wood by a given intensity of irradiation increases with increasing moisture content. These times have been measured over a range of intensities and moisture contents for woods of different densities. An empirical relation has been developed using a theoretical model which predicts these increased times satisfactorily.

December, 1956.

File No. B2/1(P)

Fire Research Station,
Boreham Wood,
Herts.

THE EFFECT OF MOISTURE CONTENT ON THE SPONTANEOUS IGNITION OF WOOD BY RADIATION

by

P. H. Thomas, D. L. Simms and Margaret Law

1. Introduction

In previous work(1) on the ignition of wood, oven dried specimens were used, although normally wood contains water, partly bound, partly free, in amounts depending upon the relative humidity and temperature of the atmosphere. This paper describes experiments on the effect of different moisture contents on the spontaneous ignition of wood by radiation.

2. Experimental procedure and results

The woods examined are listed in Table I. They were used in thicknesses of $\frac{1}{2}$ in. or more and these behave in the conditions of these experiments as if they were infinitely thick. Specimens 2 in. square were cut so that the faces were parallel with the grain. The densities of the woods were obtained from the volume and the weight when oven-dry. The variation in density of the specimens for each type of wood was of the order of 15 per cent. The different levels of moisture content were obtained by storing the specimens over saturated solutions of various salts until equilibrium conditions had been reached.

TABLE I

Moisture content and densities of woods used

	Moisture content - per centage of oven dry weight					Mean density g/cm ^{3} (oven dry)
Fibre insulation board	5.0	7.5	11.5	15.0	28.0	0.24
Western red cedar (thuja plicata)	5.0	7.5	10.5	13.5	17.0	0.37
Columbian pine (pseudosuga taxifolia)	5.0	8.5	10.5	14.5	19.0	0.55
African mahogany (khaya ivorensis)	5.5	9.5	12.0	15.5	21.0	0.52
Oak (quercus sp.)	4.5	9.5	11.5	15.5	19.5	0.66

The experimental procedure was the same as that described in detail elsewhere(1). The source of radiation was a 1 foot square gas-fired radiant panel with a maximum radiant intensity of 3 cal $cm^{-2}sec^{-1}$ (12 w/cm^2). The specimen under test was moved rapidly into place in front of the radiant panel and the time to ignite was measured. The results are shown in Figures 1 - 5; the individual points are the mean of six readings, the variation between samples being of the same order as that for oven-dried samples(1). Certain results, in particular those for 14.5 per cent moisture content in Columbian Pine appear to be anomalous (see Figure 3). Although not measured, the height and thickness of the flames were observed to decrease with increasing moisture content. When the specimens were removed from the radiation they did not continue to burn.

3. Effect of moisture in the ignition process

There are two main stages in the heating of moist wood to the ignition point. In the first stage, the surface is heated to about 100°C, the thermal constants are those relating to moist wood. In the second stage, the surface is heated to the ignition point whilst behind the surface region the water is evaporated. In addition, migration of moisture and the presence of water vapour in the volatiles emitted and other physical and chemical changes may affect the time taken to ignite. A complete analysis of the effect of moisture on the ignition process would, therefore, be exceedingly complex.

3.1 Increase in time taken to ignite

An approximate expression for the increase in time taken to ignite may be derived by considering two effects only; the increase in the value of the thermal constants and the latent heat. These are assumed to act independently. It is also assumed that the thermal constants are unchanged throughout the heating period. As wood dries, these values decrease and after 100°C reduce to about those of dry wood. No information is available on the variation after chemical changes occur, but the approximations made will overestimate the effect on the time taken to ignite. Thus if t_m is the time taken to ignite moist wood as measured experimentally and t_m' is the hypothetical time necessary to raise wood to the ignition temperature discounting the latent heat effect then it is assumed that

$$I\,t_m = I\,t_m' + Q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where I is the intensity of irradiation

and Q is the latent heat required.

The temperature rise θ of an irradiated semi-infinite solid, neglecting heat losses, is given by (2)

$$\theta = \frac{2I}{K\sqrt{\pi}} \sqrt{kt}\ \mathrm{ierfc}\ \frac{x}{2\sqrt{kt}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where t is the time of heating

$k \equiv \frac{K}{\rho c}$, the thermal diffusivity

and K is the thermal conductivity

ρ the density

c the specific heat of the wood

and $\mathrm{ierfc}\ u = \frac{2}{\sqrt{\pi}} \int_u^\infty d\alpha \int_\alpha^\infty e^{-x^2} dx$

At the surface, x = 0, equation (2) reduces to

$$\theta = \frac{2I}{\sqrt{\pi}} \sqrt{\frac{t}{K\rho c}}$$

Neglecting heat losses will underestimate the heat required for ignition and thus compensate for the effect of the thermal constants.

If it is assumed that for a given intensity the surface temperature at ignition is independent of moisture content then, in the absence of latent heat, the time to ignite depends on $K\rho c$ and

$$\theta = \frac{2I}{\sqrt{\pi}} \sqrt{\frac{t_o}{K_o\rho_o c_o}} = \frac{2I}{\sqrt{\pi}} \sqrt{\frac{t_m'}{K_m\rho_m c_m}}$$

where the suffix o refers to oven dry conditions.

Thus $$t_m' = A\,t_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where $A = \frac{K_m\rho_m c_m}{K_o\rho_o c_o}$

If the depth of wood heated above 100°C is Δ, then the heat required to evaporate the moisture in this depth is given by $\Delta m \rho_o L$, where L is the latent heat of steam,

$$Q = \Delta m \rho_o L \text{ - - - - - - - - - - - - - - } (4)$$

The temperature at the surface when ignition occurs is approximately 500°C[3] and as a first order approximation Δ is assumed to be given by the equation for dry wood, by solving equation (2) for the following conditions,

$$\text{when } t = t_m', \quad \theta = 500, \quad x = 0$$
$$\theta = 100, \quad x = \Delta$$

This leads to

$$\Delta \doteqdot 1.9 \sqrt{k_m t_m'}$$

$\therefore$ from equation (3)

$$\Delta \doteqdot 1.9 \sqrt{k_m A t_o}$$

Substituting for Δ in equation (4)

$$Q = 1.9 L m \rho_o \sqrt{k_m A t_o}$$

and hence $I t_m = I t_m' + 1.9 L m \rho_o \sqrt{k_m A t_o}$

and substituting for t_m' from equation (3)

$$t_m = A t_o + B \frac{\sqrt{t_o}}{I} \text{ ....} (5)$$

where $B = 1.9 L m \rho_o \sqrt{k_m A}$

From the experimental values of t_o it is therefore possible to estimate t_m and these are compared with the observed values in Figure 6; there is reasonable agreement between them. Although the scatter is quite large, the calculated values are in the middle of the range of measured values and in the range of these experiments the measured values do not appear to differ from the calculated ones in any systematic way.

3.2 The effect of moisture on the critical and minimum intensities for ignition

If it is assumed that ignition occurs at a given surface temperature - at least at long times of irradiation - the intensity corresponding to this surface temperature, $\therefore$ the critical intensity, is given by[1]

$$I_o = I\left(1 - \left(\frac{t_r}{t}\right)^{\frac{1}{2}}\right)$$

where t is the time to ignite at an intensity I greater than I_o. This equation is only true to the extent that the surface temperature for ignition tends to a constant value at long times. I_o is obtained graphically from the intercept of a graph of I against $I/\sqrt{t}$. In these experiments there is no evidence that I_o obtained in this way is dependent on moisture content, a result which is consistent with the view that after a long time of heating the wood is dry.

In practice, however, if ignition does not occur within a certain time it does not occur at all, presumably as a result of certain changes occurring in the wood leading to a reduction in the quantity of volatiles. There is thus a minimum intensity for ignition to occur which is greater than the theoretical critical intensity. This minimum intensity is seen from Figure 7 to increase with moisture content, the increase being approximately proportional to the moisture content. The presence of different amounts of water vapour in the combustible vapour no doubt affects the flammable limits.

4. The effect on the fire hazard

Most fires burn for much longer than the times necessary to ignite wet or dry wood, so the possibility of a fire spreading by radiated heat is not lessened appreciably by the moisture present in the wood. However, in the early stages of a fire, the extra heat required to evaporate the moisture may not be available and the chance of a continuing fire being started is reduced.

5. Conclusions

(1) The extra time taken to ignite due to moisture content for a given intensity of radiation has been related to the ignition time for dry wood by an empirical formula based on theoretical considerations.

$$t_m = A\,t_o + \frac{B\sqrt{t_o}}{I}$$

where $A = \dfrac{K_m \rho_m c_m}{K_o \rho_o c_o}$

and $B = 1.9\, L \rho_o m \sqrt{A\, k_m}$

(2) There is no marked change in the critical intensity with moisture content but the minimum intensity at which ignition actually occurs increases linearly with moisture content.

6. References

1. LAWSON, D. I. and SIMMS, D. L. The ignition of wood by radiation. Brit. J. App. Phys. 3, pp. 288-92, 1952.

2. CARSLAW, H. and JAEGER, J. C. Heat Conduction in Solids. O.U.P. London, 1950. Chap. II. p. 56. equation (6).

3. Fire Research 1955. H.M.S.O. London, 1956.

4. MACLEAN, J. D. Trans. Amer. Soc. Heat. Vent. Engrs., 47, p. 1184 (1941).

5. HEARMON, R. F. S. and BURCHAN, J. N. Specific heat and heat of wetting of wood. Nature, 176, Nov., 26, (55) 978.

APPENDIX I

Variation in thermal constants with moisture content

The variation of thermal conductivity is taken from a paper(4); the variation of thermal capacity is obtained by the method of mixtures.

$$K_m = 10^{-4}\left(\frac{\rho_o\,(4.78 + 10.2m) + 0.57}{1 + m\rho_o}\right)$$

$$\rho_m = \frac{(1 + m)\rho_o}{1 + m\rho_o}$$

$$c_m = \frac{c_o + m}{1 + m} = \frac{0.34 + m}{1 + m}$$

This expression for c_m may underestimate the true value by up to 6 per cent. m is based on oven dry weight.

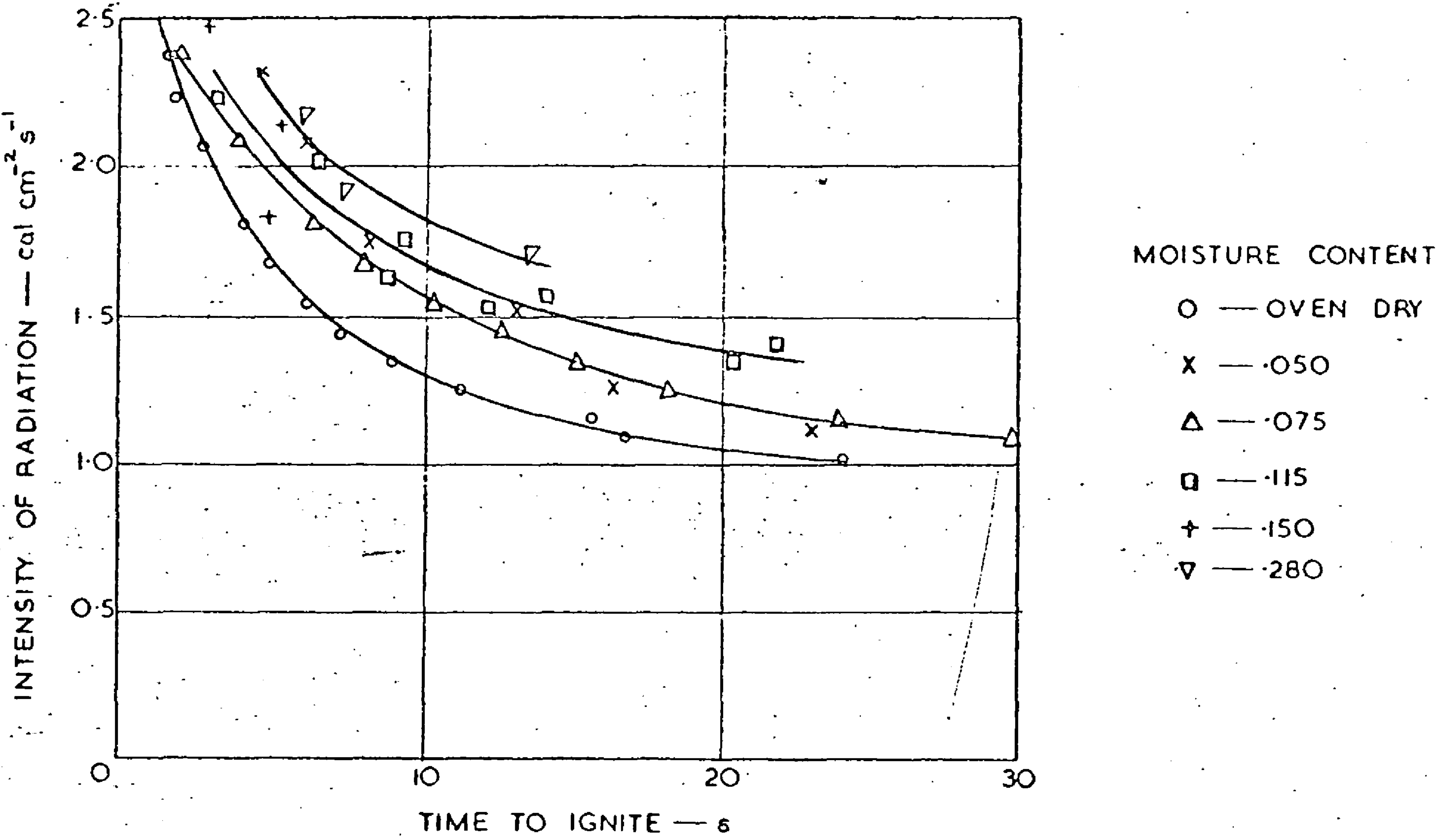


FIG. I. EFFECT OF MOISTURE CONTENT ON THE SPONTANEOUS IGNITION OF FIBRE INSULATION BOARD

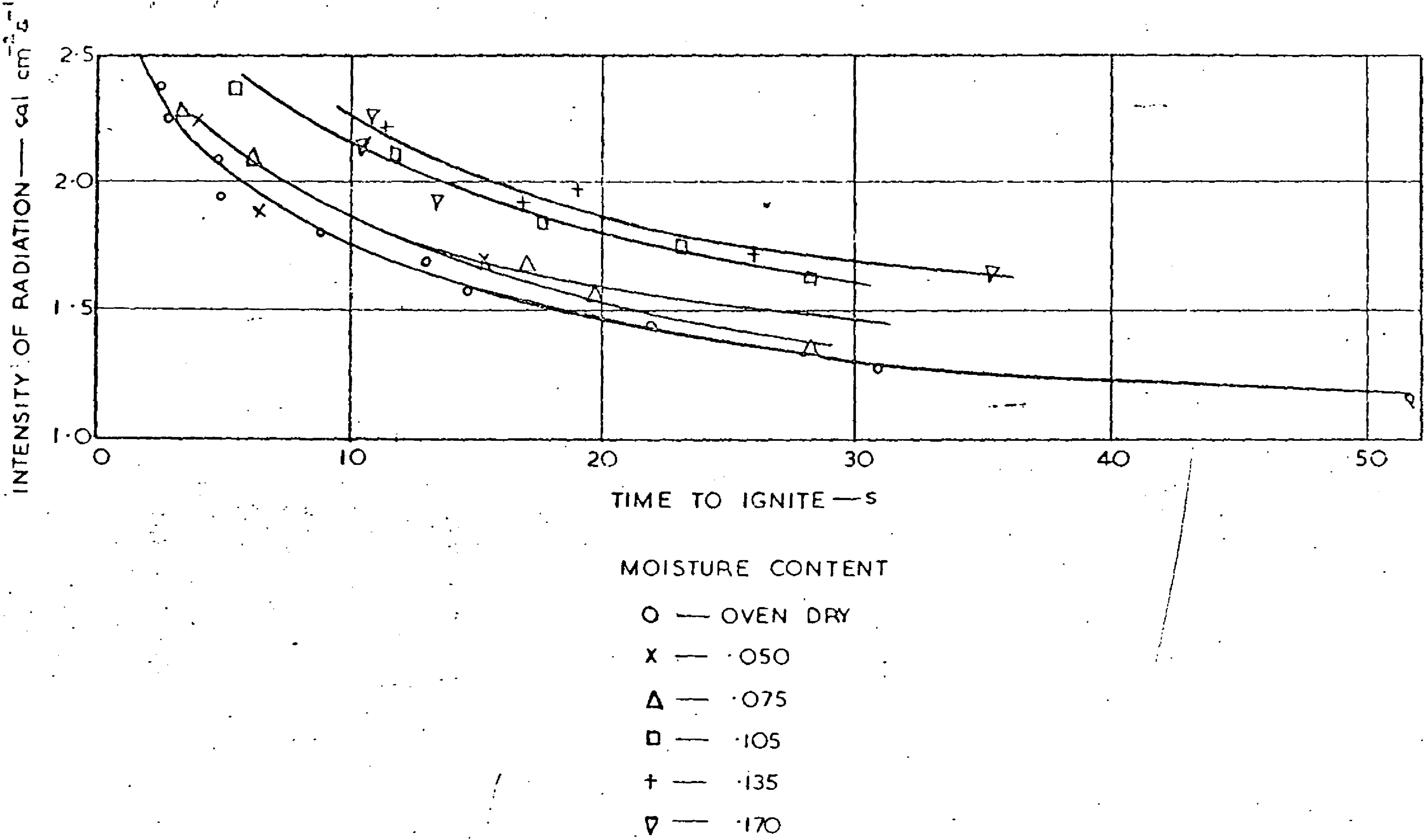


FIG. 2 EFFECT OF MOISTURE CONTENT ON SPONTANEOUS IGNITION OF CEDA

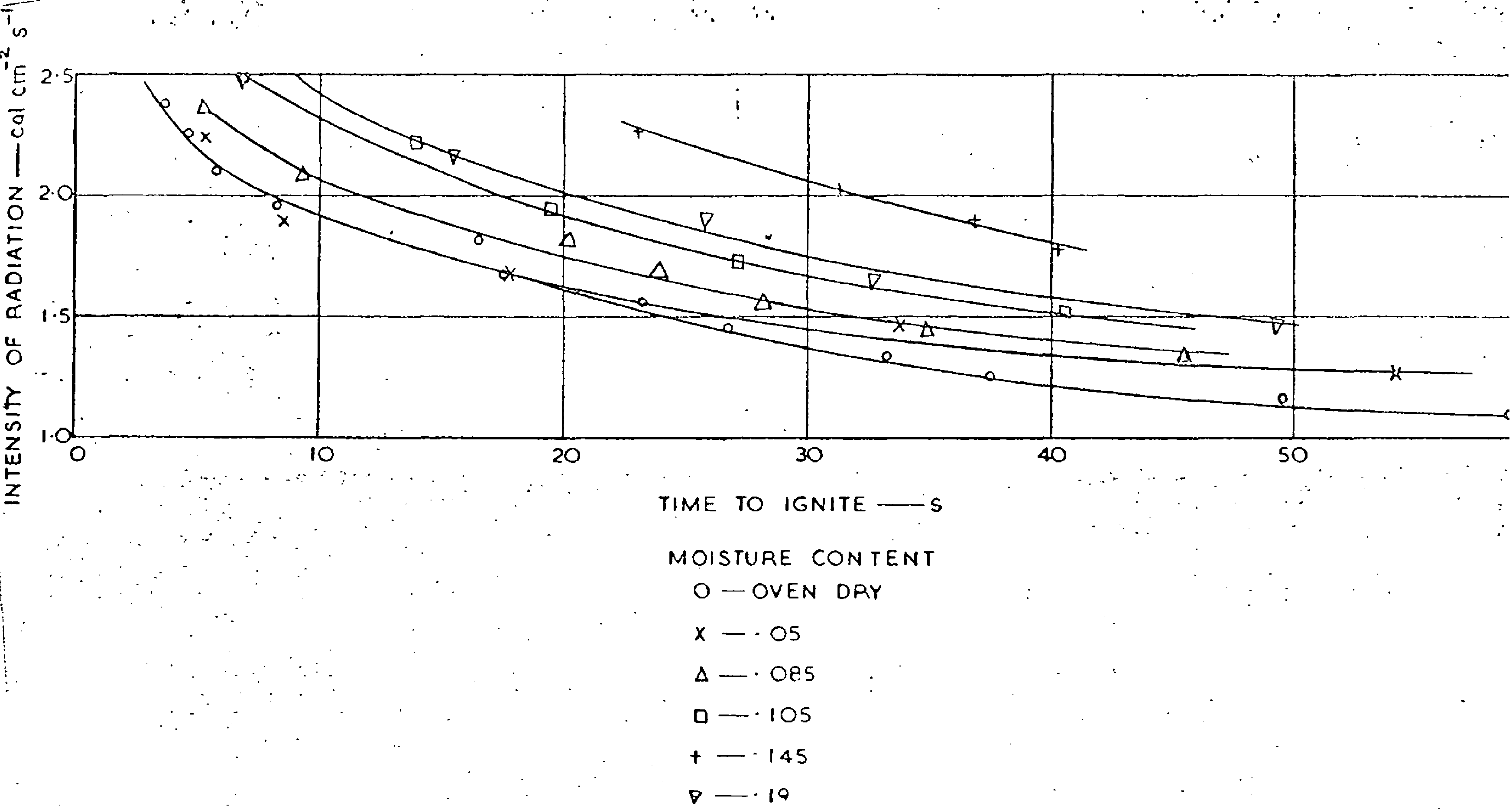


FIG.3. THE EFFECT OF MOISTURE CONTENT ON THE SPONTANEOUS IGNITION OF COLUMBIAN PINE

F.R. 280 1/2526

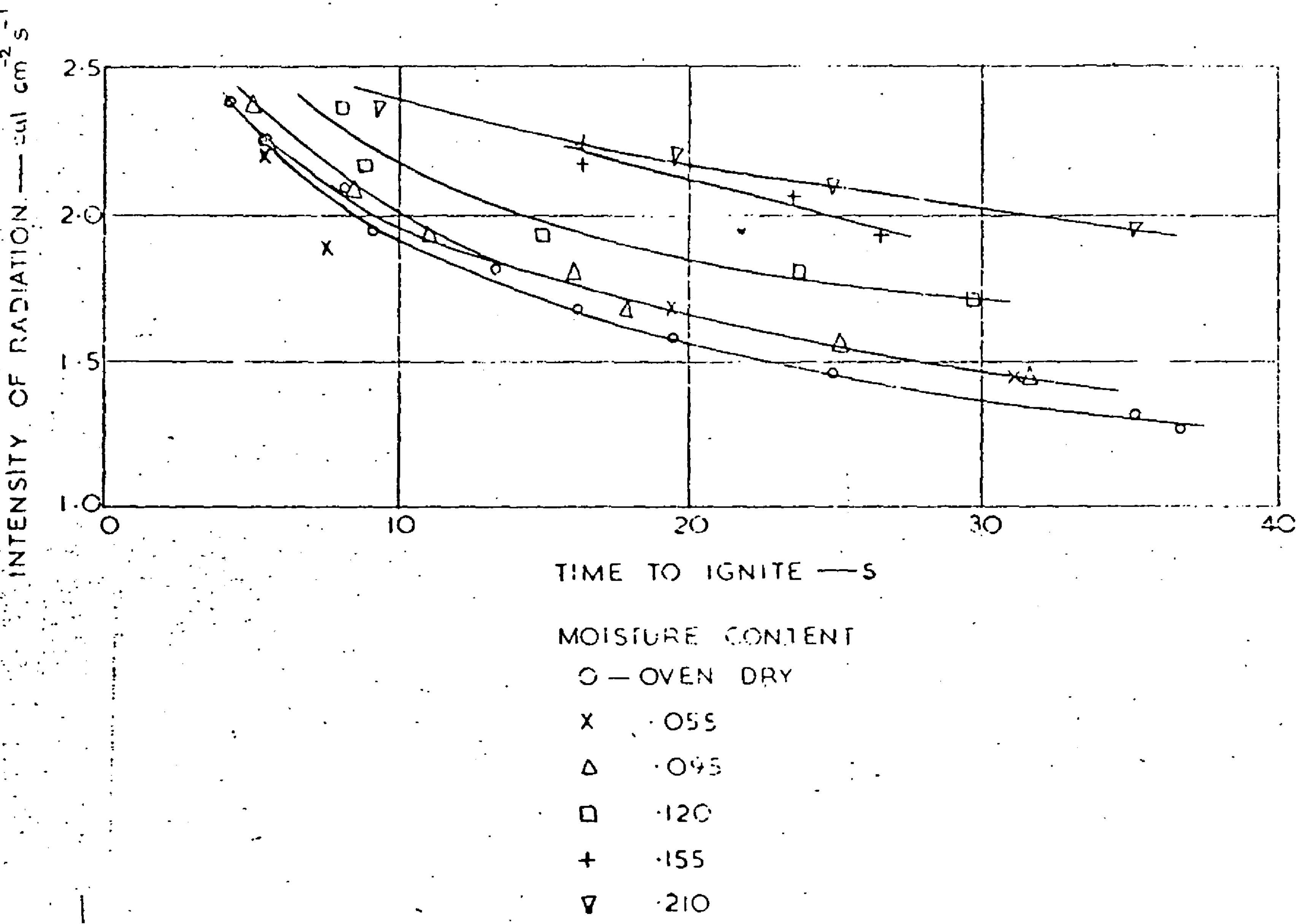
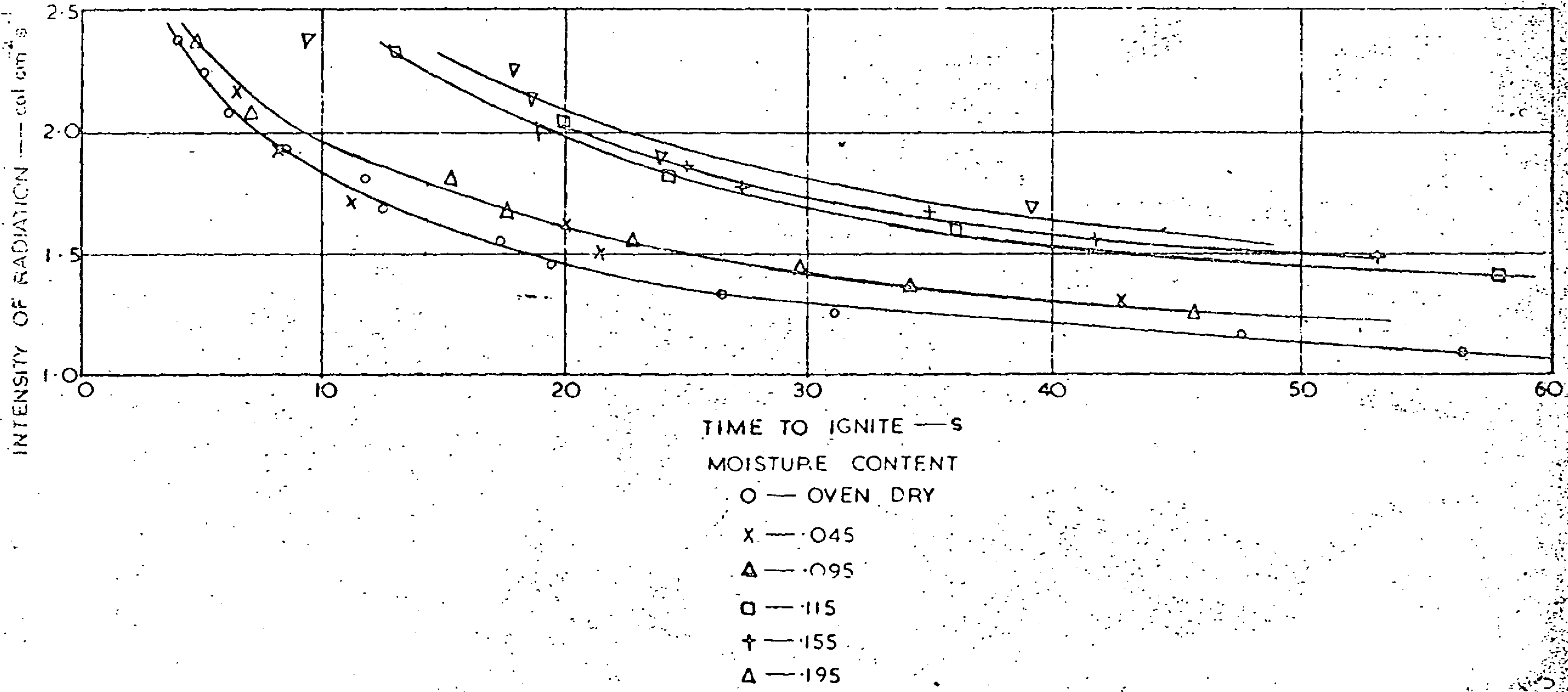


FIG. 4. EFFECT OF MOISTURE CONTENT ON THE SPONTANEOUS IGNITION OF MAHOGANY



IG. 5. EFFECT OF MOISTURE CONTENT ON THE SPONTANEOUS IGNITION OF C

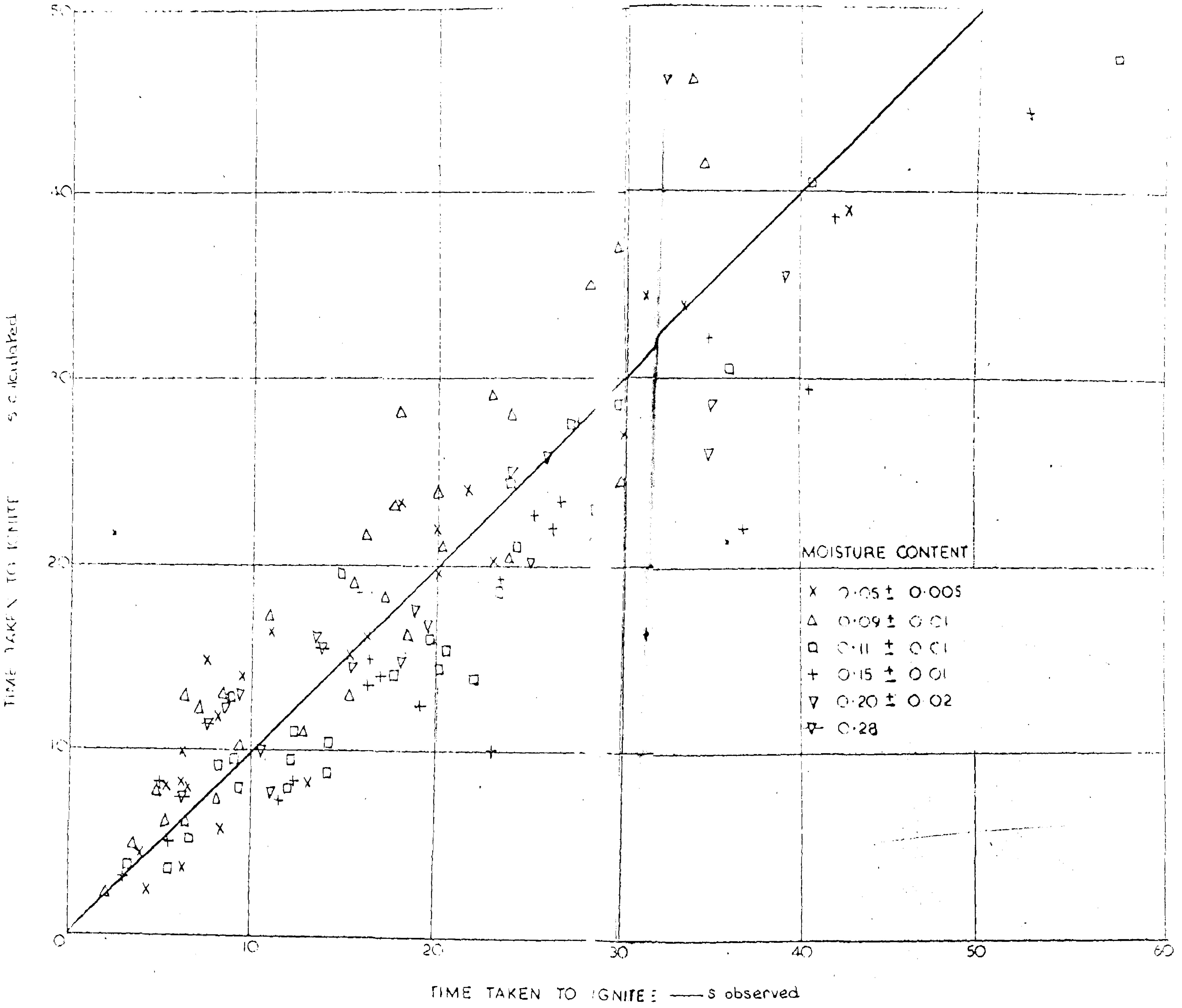


FIG. 6. COMPARISON OF OBSERVED AND CALCULATED TIMES TAKEN TO IGNITE FOR DIFFERENT MOISTURE CONTENTS, DIFFERENT WOODS AND DIFFERENT RADIANT INTENSITIES

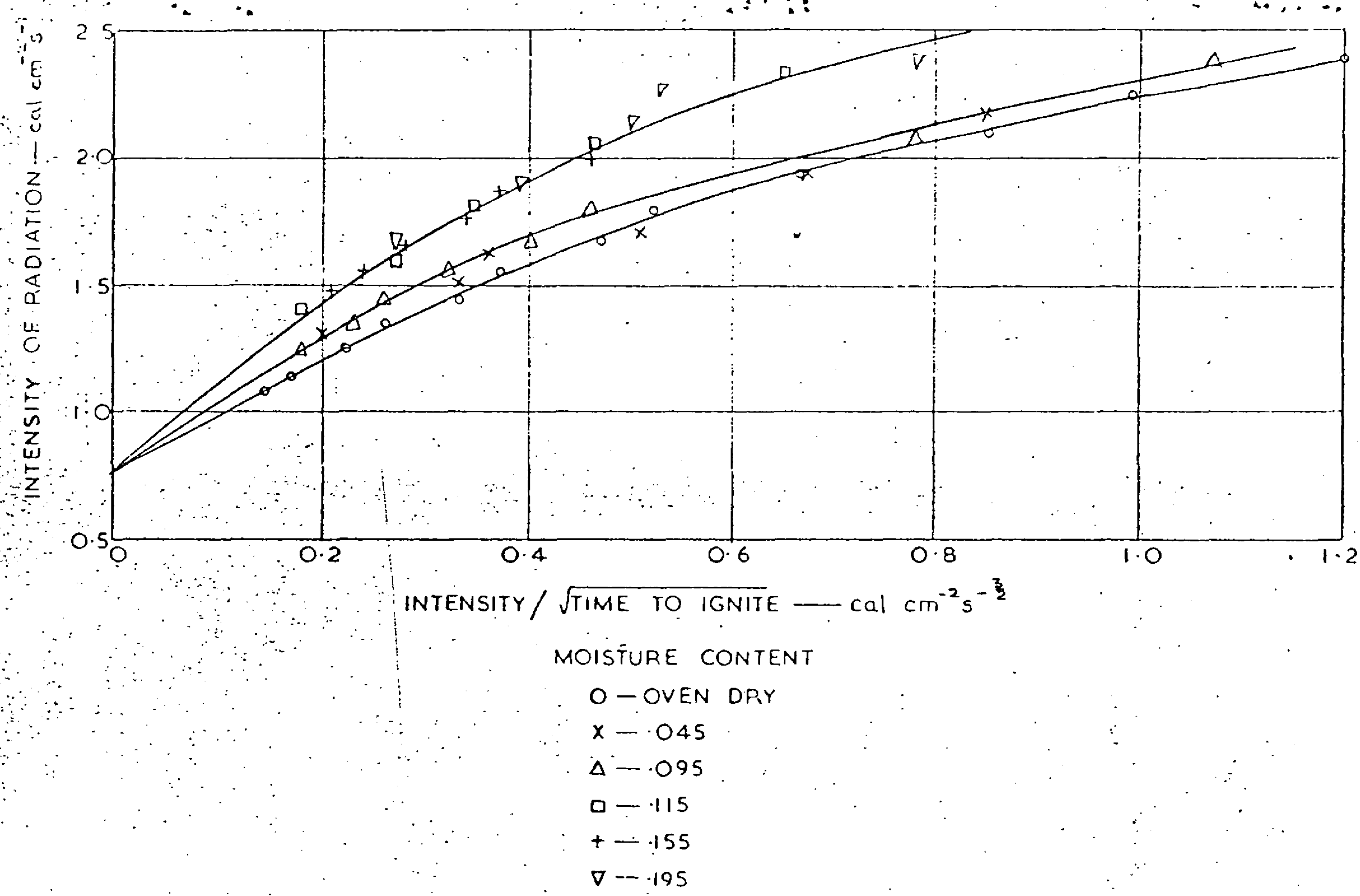


FIG. 8. EFFECT OF MOISTURE CONTENT ON THE CRITICAL INTENSITY FOR IGNITION OF OAK

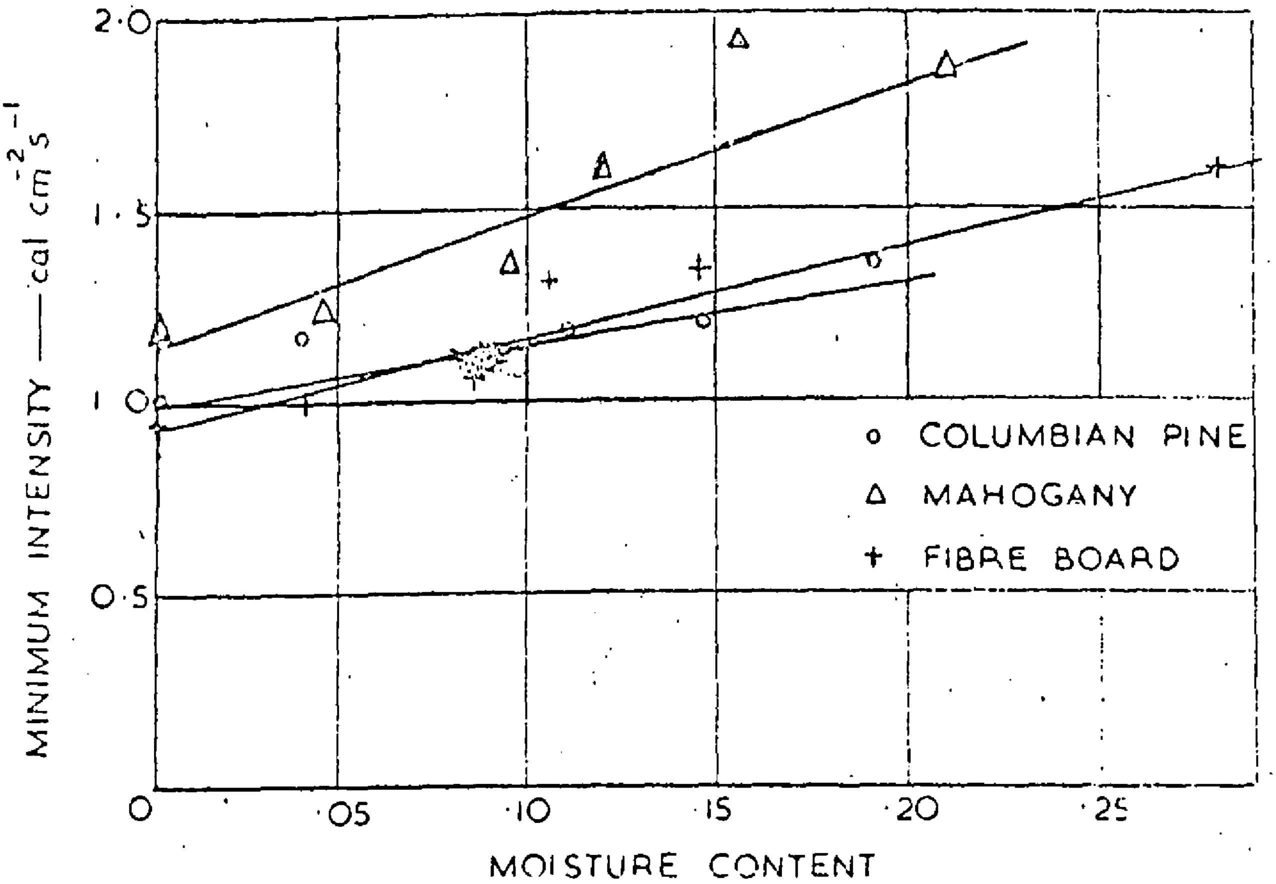


FIG 7a EFFECT OF MOISTURE CONTENT ON MINIMUM INTENSITY FOR IGNITION

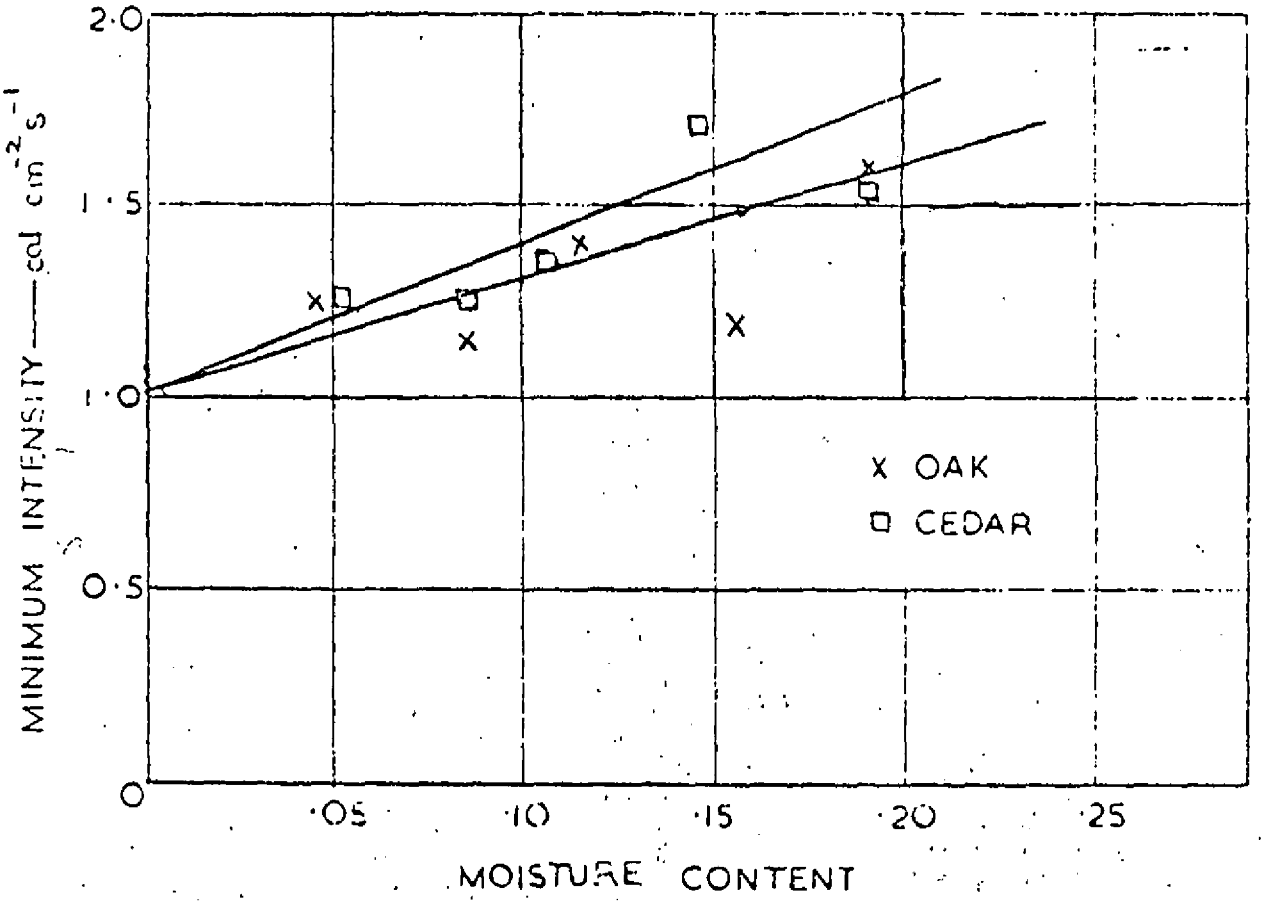


FIG. 7b. EFFECT OF MOISTURE CONTENT ON MINIMUM INTENSITY FOR IGNITION