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THE RATE OF BURNING OF WOOD

by

P. H. THOMAS, D. L. SIMMS AND MARGARET LAW

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ABSTRACT

Vertical pieces of wood about 2.5 cm thick and 12-15 cm square have been exposed in normal ambient surroundings to the radiation from a hot source and weighed while charring. The rates of weight loss for various degrees of charring have been measured for woods of different density and permeability. The effective permeability has been altered by various devices such as sealing the edges of the wood specimens and inserting an impermeable layer between two pieces of half thickness.

The rate of weight loss increases with the intensity of radiation, the density and the actual or effective permeability. Provided the charring is not too shallow the results can be interpreted in terms of a mass transfer theory in which 'Q', the amount of heat required to produce 1 gm loss of weight, is independent of the heating rate. In the absence of measurements of surface temperatures the calculations are perforce somewhat crude but the order of magnitude of Q (assuming the specific heat of the volatiles is 0.5 cal g^{-1} $^{o}C^{-1}$) is about 1300 cal/g for woods of low permeability and about 550 for some woods of high permeability when the weight loss is about 10 per cent (about 4 mm char). The rate of weight loss decreases and Q increases as charring proceeds.

The variation of weight loss with time and least squares formulae relating the rate of weight loss at particular times to density, incident radiation and permeability are given for various experimental conditions.

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

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1. INTRODUCTION

The rate at which wood burns is presumed to depend on the rate at which heat is received and at which it is transferred within the wood. Transfer within the wood by conduction depends on the thermal conductivity, density and specific heat, transfer by convection depends on the movement of volatile gases; self-heating has been shown to be small[1] compared with the rate of heating in fires. The rate of burning of different woods should therefore vary with density, which largely determines thermal conductivity, and with its permeability, which is not correlated with density.

Experiments have been performed in which the rate of burning was measured as the rate of weight loss of a specimen of wood (15 cm square) receiving radiation and flaming on one surface only. The permeability along the grain, which was parallel to the heated surface, is much greater than across it so volatiles tend to move parallel to the surface heated in these experiments.

2. EXPERIMENTAL ARRANGEMENT

The source of radiation was a 30 cm square gas fired radiant panel[2] at various distances from the heated wood. The maximum value of intensity attainable was limited by the minimum distance at which the specimen was uniformly irradiated, (see Fig.1). The intensity of radiation was measured by a water cooled thermopile and the loss in weight of the wood was recorded in units of not less than 1 gm.

In some of the experiments all the wood surfaces other than that facing the radiant panel were coated with an intumescent type fire retardant paint, to prevent the emission of volatiles. No burning took place on the painted surfaces. In some other experiments an impermeable layer was placed within the heated specimen parallel to the heated surface. Before any experiment, all specimens were dried in an oven at 95°C and allowed to cool in a sealed container.

2.1. Woods with varying density and permeability

In the first series of experiments specimens of eight species of wood approximately 2.5 cm thick were exposed to radiation over an area approximately 15 cm x 12.5 cm. Details of the woods are given in Table 1.

The grain was vertical and perpendicular to the direction of heat flow, see Fig.1. One specimen of each species was exposed to each of three levels of radiation, I, 0.5, 0.7 and 1.0 cal $cm^{-2}s^{-1}$. Intensities above these values were not used since spontaneous ignition would have occurred and painting the surfaces with fire retardant paint to restrict burning to the heated surface would have affected the permeability. The experiments were carried out in random order.

2.1.1. The effect of sealing sides and edges parallel to the direction of heat flow

Since a statistical analysis of these experiments indicated that permeability accounted for a significant variation in the rate of burning of different woods a second series of experiments was then carried out on specimens which were sealed at the edges to reduce their effective permeability; all surfaces therefore, except the heated one, were sealed with fire retardant paint. Specimens of the most permeable wood used in the first series, Abura, and the most impermeable, Makoré, were exposed to intensities of 0.5 and 1.0 cal $cm^{-2}s^{-1}$. Specimens both sealed and unsealed were exposed in random order with grain both vertical and horizontal, perpendicular to the direction of heat flow. Details of the specimens are given in Table 2.

The fire retardant paint had been found by experience to be the most effective material for sealing edges of wood but with the highly permeable wood, Abura, volatiles were emitted in jets with such force, see Fig.2, that the sealing tended to break down near the charring surface.

2.2. Woods with an impermeable layer perpendicular to heat flow

Fibre insulating board and two types of deal were burnt with and without impermeable layers parallel to the heated surface. Details are given in Table 3.

The rate of burning of a 2.5 cm thick piece of fibre insulating board was compared with the rate for two 1.3 cm boards stuck together with a layer of impermeable paint thin enough to have negligible effect on the conduction of heat. All surfaces except the heated one were also painted and the heated surface was ignited as soon as it was exposed to radiation.

For the deal it was found more satisfactory to use aluminium foil as the impermeable layer. The foil had a weight per unit area of 5 mg/cm^2 and its thermal capacity was therefore small compared with that of the wood. Experiments for each wood were carried out with specimens in random order on one batch to reduce variability within the species. Pieces of 2.5 cm wood were split in two, the foil was inserted, the pieces were screwed together and all surfaces except the heated one were painted with fire retardant paint. The specimens were not ignited as it was found this did not affect the rate of burning but spontaneous ignition of most of the specimens occurred.

3. RESULTS

The experimental results for all the measurements of weight loss are shown in Figs 3, 4, 5, 6, 7 and 8. As would be expected the rate of weight loss depends on the intensity of radiation and the species of wood. It also varies with exposure time, i.e. as the wood chars the rate of weight loss falls. In order to compare the effect of the impermeable layer and the variation in permeability for the different species of wood it was decided to compare the rate of weight loss for the same fraction of weight lost (M denotes the percentage loss in weight). For equal initial thicknesses of wood, char depths are approximately the same when equal proportions of the uncharred weight have been lost; there would be an exact correspondence if the density of the charred residue were always the same fraction of the density of the uncharred wood. However, since the density of the residue is small, even if it is not the same fraction, the error will be small.

3.1. The effects of density and permeability

The curves of weight loss against time in Figs 3, 4 and 5 are approximately linear from about 20 per cent to 50 per cent loss in weight of exposed wood. The rate of weight loss has been derived and is given in Table 4 at the times when each specimen has lost 5 per cent, 10 per cent, 20 per cent and 30 per cent weight.

If we take the volatiles as nominally 0.6 of the total weight a 10 per cent weight loss corresponds to a depth of char of $\frac{0.1 \times 2.5}{0.6}$ cm i.e. about 4 mm.

The rate of weight loss per unit surface area, $\dot{m}''$, increases with intensity of irradiation, the permeability and the density. The effects

are at the 0.1 per cent significance level except at 5 per cent weight loss where permeability has 1 per cent and density 5 per cent significance. Dividing the rate by density gives a variable $\dot{m}''/\rho$ with the dimensions of velocity and, except early in the heating, viz: for 5 per cent weight loss, this variable can be correlated with intensity and permeability only, density not being significant.

A regression analysis gives equations for rate of burning shown in Table 5.

A regression equation for the range of weight loss 10 per cent - 30 per cent, and corresponding to M = 10 - 30 can be obtained:

$$\frac{\dot{m}''}{\rho} \times 10^4 = 12.0\ I + 1.3 \log_{10}\mu + 5.6 - 0.090\ M$$

3.1.1. The effects of sealing the edges

The curves of weight loss against time are shown in Figs 7 and 8. The rate of weight loss has been derived at 5 per cent, 10 per cent, 20 per cent and 30 per cent weight loss, see Table 6, and a factorial analysis of this rate divided by density, $\frac{\dot{m}''}{\rho}$ cm/s, has been carried out. The effects of species and sealing, as well as weight loss and intensity, have been found significant at the 0.1 per cent level. The interaction of intensity with species and sealing with species is significant at the 1.0 per cent level; grain direction and the interaction of grain direction with species are significant only at the 5 per cent level. Taking effects of 1.0 per cent significance and better the equations obtained are:

$$\frac{\dot{m}''}{\rho} \times 10^4 = 0.09M + 17.3I - 0.34MI + 4.0 \begin{cases} +(0.9 + 2.5I) \text{ sealed} & \text{(for Abura} \\ +(2.9 + 2.5I) \text{ unsealed} & \text{high permeability)} \\ -(2.9 + 2.5I) \text{ sealed} & \text{(for Makoré} \\ -(2.1 + 2.5I) \text{ unsealed} & \text{low permeability)} \end{cases}$$

$$\sigma = 1.5 \times 10^{-4}$$

Sealing produces a greater reduction in the rate for Abura, the more permeable wood. The effect of a change in the heating rate is greater for the wood of higher permeability.

3.2. Woods with an impermeable layer perpendicular to the direction of heat flow

The rates of weight loss are given in Table 7. The equations for rate of weight loss are given in Table 8. For all three materials the effect of the layer, and its interaction with weight loss are significant. The rates of weight loss are, initially, lower when the layer is present but the difference lessens.

4. DISCUSSION AND CONCLUSIONS

A "magic number" often quoted for the burning of wood is $^1/40$ in/min but for these experimental conditions and choice of woods, the rates of weight loss $\dot{m}''$ vary between 0.3 and 1.5 mg $cm^{-2}s^{-1}$ or, in units of $\dot{m}''/\rho$, from about $^1/40$ in/min to $^1/10$ in/min. The "magic number" quoted above is based on many furnace tests conducted in a standard manner where the effect of the increasing thickness of char is offset by the increase in temperature of the furnace. In these experiments the gross rate of heating is constant and the rate of burning decreases with time. Wood is much more permeable along the grain than across it but data are not available for the lower permeability across the grain which the effects of inserting an impermeable layer show to have some importance. The relation between the permeability of the char to that of unburnt wood is not known.

Woods with lower permeability along the grain, specimens with an impermeable layer parallel to the heated face or with their edges sealed, all lose weight more slowly than when permeability is high and the volatiles can escape more easily. The results for the specimens sealed at the edges will probably be more representative of large specimens.

Increasing the incident radiation raises the rate of weight loss, particularly at the beginning of heating before there is a thick insulating layer of charcoal between the hot surface and the zone of primary decomposition. The reciprocal regression coefficient between $\dot{m}''$ and I has the important units of joule/gm measuring the amount of <u>extra</u> incident energy required to produce an <u>extra</u> unit mass of decomposition. This quantity varies in these experimental conditions over a substantial range between about 380 and 2000 cal/gm, dependent on the thickness of char and species, White Deal having a particularly low value.

At the beginning of heating the decomposition appears to be as readily accountable for on a mass basis as on a volume basis but later ($M \gtrsim 10$), a volume basis appears to be preferable, i.e. charring can be described as a velocity rather than a rate of weight loss. It is not without significance that the "magic number" referred to above is in such units.

A second difference between the early and the later stages of decomposition is that the "impermeable" layer produces its major effect in reducing the rate of weight loss in the early stage. This is unlikely to be a conduction effect, since the time for heat to be conducted 1.3 cm into the wood considerably exceeds the times of order of 1 minute which are involved.

A reduction in the effective permeability, whether by sealing or changing the wood species, should tend to raise the temperature at which the volatiles are emitted since escape through the cold unburnt wood is more difficult; that is, more heat is extracted from the solid phase which thereby tends to become cooler. This, or an endothermic reaction, may perhaps be associated with the lower rate of decomposition. Much more detailed work would be required, however, to explore these effects further.

4.1. Analysis of data

In the absence of data for the surface temperatures the following approximate analysis only may be offered. Wright and Hayward[3] dropped small 0.3 - 1.9 cm cubes of wood into a retort containing nitrogen at 500°C, 700°C and 900°C. Their data have been recorrelated (see Appendix) showing that the results can be interpreted in terms of mass rates of weight loss

$$\dot{m}'' = \left[0.0053 \left(\frac{T}{1000}\right) - 0.0033\right] (1 - 0.75\, \rho\, l) \text{ g cm}^{-2}\text{s}^{-1}$$

where $\dot{m}''$ is the mean rate of weight loss across the grain

T is the absolute temperature of the nitrogen

ρ is the wood density and l is the size of the cubes

For Wright and Hayward's experiments with small cubes we shall have to assume that though the surface temperature of the cubes is less than T they are effectively equal. In these experiments the surface temperature will similarly be less than that given by inserting experimental data into the above expression. We shall neglect the effect of the factor ρl,

partly because of uncertainties in the way it should be interpreted in these experiments with non-cubical specimens and partly because the effect of so doing tends to lower the estimate of T thereby partly compensating for the use of this expression. Clearly this procedure is rather dubious but it is the only one available in the absence of data.

We have performed calculations which assume quasi-steady conditions and shallow depths of char. There is less difference between the rates of weight loss at 10 per cent weight loss and those occurring later than between those at 10 per cent loss and the earlier values at 5 per cent loss, where stronger transient effects prevail. For the later values the depth of char would be too large to neglect. Thus the use of data at 10 per cent loss is arbitrary but is thought to be a better choice for calculations which assume quasi-steady conditions and shallow depth of char. Accordingly, values of θ have been calculated from the above expression and used as surface temperature for the data in Table 4. We shall proceed to compare the relation between $\dot{m}''$ and I with one derived from conventional mass transfer theory.

A mass transfer equation appropriate for a vertical surface of size 'd' in laminar free convection[4], and therefore appropriate for these experiments, is

$$\frac{\dot{m}''}{\rho_g D} = 0.65 \left(\frac{g\, d^3}{\nu^2}\right)^{\frac{1}{4}} \operatorname{Log}_e (1 + B)$$

where B is a transfer number defined by

$$B = \frac{\Delta H . m_o/r + C_g(T_g - T_s)}{Q^{\ell}}$$

$\dot{m}''$ is the rate of mass transfer per unit area which here we identify with the rate of burning

ρ_g is the gas density

D is the diffusion coefficient

g is the acceleration due to gravity

ν is the kinematic viscosity

d is the height of the transferring surface

ΔH is the heat release per gm of fuel

m_o is the oxygen concentration

r is the stoichiometric oxygen/fuel ratio

C_g is the specific heat of gas

T_g is the environment temperature

T_s is the surface temperature

and Q' is the heat required from the convective processes to produce 1 gm of the transferred substance.

The left hand side of the expression is similar to the Nusselt number for heat transfer and the first term on the right hand side is approximately the Grashof number for large values of T.

When both convection and radiation are producing mass transfer

$$Q' = Q - \frac{I - I'}{\dot{m}''}$$

where Q is the heat required thermodynamically (i.e. enthalpy change) to produce 1 gm of the transferred substance

I is the incident radiation flux

and I' is the radiation flux emitted by the hot surface.

For intense radiation Q' is negligible and $\dot{m}''$ would be obtained directly as

$$\dot{m}'' = \frac{I - I'}{Q}$$

From the calculated values of $Ts(=T)$, I' was calculated and from this and the values of I used experimentally Q was obtained.

For these calculations d was taken as 15 cm, ν as 0.45 cm^2/s, $\Delta H\, m_o/r$ as 700 cal/g, T_g as 293°K. To obtain a value for ρD it was assumed that the Prandtl number for the gases could be taken as approximately unity giving

$$\rho D = K/C_g$$

where K is thermal conductivity taken as 1.9×10^{-4} cal $cm^{-1}s^{-1}$ $degC^{-1}$. C_g was taken both as 0.5 and 0.75 cal $degC^{-1}g^{-1}$. The results are shown in Table 9 and 10 where one can see that the values of Q are independent

of I. This is to be expected according to the theory but it was not so for the few calculations made for $\dot{m}''$ at 5 per cent loss.

The results fall into two groups; woods with a high Q and with a low Q. There is no significant difference within each group but the groups are quite different. One cannot associate this with density differences but the distinction might well be one of permeability. Thus the two woods of highest permeability, Podo and Abura, have low values of Q. Of the two woods with the next highest permeability one is in each group. Thus the correlations previously given for $\dot{m}''$ in terms of Log μ as a continuous variation of $\dot{m}''$ might be better expressed as separate ones for high and low permeabilities.

The precise value of C_g for wood volatiles is uncertain and depends much on the amounts of water vapour and acetic acid vapour, especially the latter which has a specific heat of 1.5 cal $degC^{-1}g^{-1}$. Taking $Cg = 0.75$ cal $degC^{-1}g^{-1}$ gives mean values of 860 and 270 cal/g for the two groups at 10 per cent weight loss, taking C_g as 0.5 cal $degC^{-1}g^{-1}$ gives respectively 1270 and 540 cal/g at 10 per cent weight loss, and 1520 and 680 cal/g at 30 per cent weight loss.

Q must comprise all changes in sensible heat in the volatiles, latent heats and endothermic effects. If wood volatiles are assumed to be emitted at a temperature of 400°C, 200-300 cal/g, say, of the value Q is associated with sensible heat while the remainder represents endothermic reactions, latent heats, etc. This is greater for the low permeability woods and its total effective value is of order 600-1000 cal/g. For the woods of high permeability the corresponding value is less than 300 cal/g, and may well be zero or even slightly negative (exothermic).

For hardwoods, though not for softwoods, the lower the permeability[5] the greater the durability and consequently the more durable hardwoods, chosen for use in buildings, have a comparatively low burning rate. This may account in part for the general belief that hardwoods are safer than softwoods.

Acknowledgment.

The specimens of woods of different permeabilities were selected and supplied by the Forest Products Research Laboratory.

Table 1

Specimens tested unsealed

(Area exposed = 14.8 x 12.7 cm^2)

Wood	ρ Density (oven dry) g/cm^3	μ Permeability $cm^3/sec\ cm^2\ atm/cm$	Thickness cm
Western Hemlock	0.34	10	2.45
Western Red Cedar	0.36	2	2.45
Podo	0.46	100	2.45
Douglas Fir	0.45	2	2.45
Larch	0.51	2	2.45
Abura	0.59	$2 \times 10^{+3}$	2.1
Makoré	0.64	10^{-3}	2.1
Ash	0.65	10	2.45

Table 2

Specimens tested sealed and unsealed

(Area exposed = 15.2 x 12.7 cm^2)

Wood	Density (oven dry) g/cm^3	Permeability $cm^3/sec\ cm^2\ atm/cm$	Thickness cm
Abura	0.49	$2 \times 10^{+3}$	2.45
Makoré	0.58	10^{-3}	2.5

Table 3

Specimens tested with and without impermeable layer

Wood	Density (oven-dry) g/cm^3	Area exposed to radiation cm^2	Intensity of radiation cal $cm^{-2}s^{-1}$	Thickness cm	Area irradiated cm^2
Fibre insulating board	0.24	15.2 x 15.2	0.7, 0.9, 1.1, 1.3	2.5	230
Yellow Deal	0.69	14.3 x 15.5	0.7, 0.9, 1.1	2.2.	220
White Deal	0.57	14.3 x 15.5	0.7, 0.9, 1.1	2.2	220

Table 4

Rate of burning of unsealed woods

Figures in brackets denote time in min.

Wood	Total Wt gm	Intensity of radiation cal $cm^{-2}s^{-1}$	Rate of burning g $cm^{-2}s^{-1}$ x 10^4			
			5% loss	10% loss	20% loss	30% loss
Western Hemlock	155	0.5	2.7 (4.8)	4.3 (6.8)	4.1 (10.0)	3.6 (13.9)
	167	0.7	6.8 (1.8)	6.3 (3.1)	5.0 (5.7)	4.6 (8.8)
	165	1.0	10.9 (1.0)	6.6 (1.9)	6.3 (4.1)	6.7 (6.5)
Western Red Cedar	168	0.5	2.9 (5.2	4.2 (7.2)	4.1 (10.5)	3.6 (14.3)
	167	0.7	4.8 (2.8)	5.3 (4.2)	4.6 (7.1)	4.1 (10.7)
	170	1.0	8.5 (1.4)	6.4 (2.4)	6.1 (4.9)	5.6 (7.5)
Podo	211	0.5	4.4 (5.1)	6.9 (6.7)	6.7 (9.3)	5.8 (12.4)
	202	0.7	9.2 (2.0)	9.1 (3.0)	7.7 (5.0)	7.4 (7.4)
	204	1.0	9.2 (1.2)	9.2 (2.0)	8.4 (4.0)	8.7 (6.1)

(cont'd) ....

Table 4 (cont'd)

Wood	Total Wt gm	Intensity of radiation cal $cm^{-2}s^{-1}$	Rate of burning β $gm^{-2}s^{-1} \times 10^4$			
			5% loss	10% loss	20% loss	30% loss
Douglas Fir	220	0.5	2.2 (7.7)	3.5 (11.4)	4.0 (16.4)	3.7 (24.7)
	202	0.7	4.3 (3.3)	5.6 (4.9)	5.4 (8.1)	5.0 (11.6)
	199	1.0	7.7 (1.8)	6.8 (3.1)	5.8 (5.9)	5.7 (9.1)
Larch*	236	0.5	2.4 (8.1)	4.1 (11.6)	4.5 (16.3)	4.1 (21.4)
	230	0.7	4.6 (3.6)	5.8 (5.5)	5.5 (9.1)	5.6 (13.0)
Abura**	235	0.5	5.0 (6.9)	7.5 (8.8)	7.4 (11.8)	6.9 (15.2)
	225	0.7	7.8 (2.7)	9.9 (3.9)	9.6 (6.2)	7.8 (9.1)
	242	1.0	10.7 (1.6)	13.0 (2.6)	10.9 (4.8)	10.2 (7.4)
Makoré**	252	0.5	2.5 (9.8)	3.9 (14.3)	4.3 (20.1)	3.5 (27.1)
	254	0.7	5.6 (2.9)	6.1 (6.0)	5.4 (10.3)	5.1 (15.3)
	252	1.0	8.8 (1.8)	8.5 (3.4)	6.2 (6.8)	6.3 (10.9)
Ash	296	0.5	3.5 (7.0)	6.4 (9.9)	7.3 (13.4)	6.8 (17.2)
	295	0.7	9.0 (2.5)	9.8 (3.9)	9.2 (6.7)	8.3 (9.9)
	295	1.0	12.5 (1.5)	11.4 (2.6)	10.0 (5.1)	9.9 (7.9)

*The specimen exposed to 1.0 cal $cm^{-2}s^{-1}$ ignited and no readings are given.

**These specimens were thinner than the others and the rates were therefore measured at 6%, 12%, 23% and 35% loss in weight.

Table 5

Rate of burning - unsealed woods

Weight loss %	Rate - gm $cm^{-2}s^{-1}$	$\frac{\text{Rate}}{\text{Density}}$ cm/s
5	$\dot{m}'' \times 10^4 = 12.91I^{***} + 0.53 \log_{10}\mu^{**} + 5.3\rho^{*} - 5.94$ $\sigma = 1.28 \times 10^{-4}$	$\frac{\dot{m}''}{\rho} \times 10^4 = 27.6I - 13.7\rho + 0.93 \log_{10}\mu - 0.33$ $\sigma = 3.67 \times 10^{-4}$
10	$\dot{m}'' \times 10^4 = 7.29I^{***} + 0.75 \log_{10}\mu^{***} + 11.3\rho^{***} - 4.45$ $\sigma = 0.97 \times 10^{-4}$	$\frac{\dot{m}''}{\rho} \times 10^4 = 14.7I^{***} + 1.45 \log_{10}\mu^{***} + 2.73$ $\sigma = 1.90 \times 10^{-4}$
20	$\dot{m}'' \times 10^4 = 4.55I^{***} + 0.75 \log_{10}\mu^{***} + 10.6\rho^{***} - 2.71$ $\sigma = 0.59 \times 10^{-4}$	$\frac{\dot{m}''}{\rho} \times 10^4 = 9.7I^{***} + 1.37 \log_{10}\mu^{***} + 5.24$ $\sigma = 1.42 \times 10^{-4}$
30	$\dot{m}'' \times 10^4 = 5.50I^{***} + 0.65 \log_{10}\mu^{***} + 9.53\rho^{***} - 3.13$ $\sigma = 0.47 \times 10^{-4}$	$\frac{\dot{m}''}{\rho} \times 10^4 = 11.6I^{***} + 1.20 \log_{10}\mu^{***} + 3.34$ $\sigma = 1.45 \times 10^{-4}$

*5% significance
**10% "
***0.1% "

Table 6

Rate of burning sealed and unsealed wood

Figures in brackets denote time in min.

Wood	Average Wt gm	Intensity of radiation cal $cm^{-2}s^{-1}$	Sealing	Grain	Rate of burning gm $cm^{-2}s^{-1} \times 10^4$			
					5% loss	10% loss	20% loss	30% loss
Abura	230	0.5	S	V	4.1 (4.6)	7.1 (6.3)	6.6 (9.2)	5.8 (12.5)
			"	H	4.8 (4.8)	7.5 (6.4)	8.4 (8.8)	6.0 (11.7)
			US	V	4.6 (5.2)	7.6 (6.6)	7.6 (9.1)	7.1 (11.9)
			"	H	5.0 (4.8)	8.7 (6.2)	8.7 (8.5)	7.1 (11.1)
		1.0	S	V	12.8 (1.3)	10.4 (2.2)	8.7 (4.3)	8.1 (6.7)
			"	H	13.2 (1.3)	11.5 (2.1)	9.8 (4.0)	8.7 (6.2)
			US	V	12.4 (1.3)	12.1 (2.1)	11.1 (3.9)	10.5 (5.7)
			"(1)	H	16.5 (1.1)	14.8 (1.8)	11.6 (3.4)	10.3 (5.3)
Makoré	280	0.5	S	V	2.9 (7.5)	3.9 (11.1)	4.2 (17.0)	3.5 (23.3)
			"	H	2.6 (8.1)	3.7 (11.8)	4.0 (18.1)	3.4 (24.9)
			US	V	3.8 (5.6)	5.0 (8.5)	5.1 (13.3)	4.6 (18.4)
			"	H	3.4 (6.6)	4.9 (9.6)	5.5 (14.1)	4.8 (18.9)
		1.0	S(2)*	V	12.3 (2.1)	8.4 (2.9)	6.1 (7.0)	5.2 (11.4)
			"(3)*	V	11.8 (2.0)	8.5 (3.2)	6.5 (6.7)	5.5 (10.8)
			US	H	8.7 (1.9)	8.7 (3.2)	7.3 (6.3)	6.3 (9.8)
			"(4)*	H	12.8 (1.8)	8.8 (2.9)	6.3 (6.2)	5.5 (10.3)
			US	V	8.7 (2.0)	7.8 (3.5)	6.8 (6.8)	6.0 (10.7)
			"	H	7.9 (2.4)	7.4 (3.9)	6.1 (7.6)	5.3 (11.9)

(1) Ignition after 6 min exposure
(2) " " 2 " "
(3) " " 1 min 43 s exposure
(4) " " 1 min 30 s "

*Since the edges were coated with fire retardant paint burning took place on the exposed face only and the experiment was continued.

Table 7

Rate of weight loss gm/min, of wood with and without impermeable layer

(Area exposed to radiation $\simeq$ 220 cm^2)

Figures in brackets denote time in min.

Wood	Intensity of radiation cal $cm^{-2}s^{-1}$	With layer			Without layer		
		Weight loss %			Weight loss %		
		5	10	15	5	10	15
Fibre insulating board	1.3	15.7 (0.6)	13.0 (1.1)	9.9 (1.8)	20.0 (0.4)	14.4 (0.8)	10.8 (1.4)
	1.1	13.3 (0.4)	11.3 (0.9)	8.7 (1.6)	16.3 (0.5)	10.4 (1.1)	7.9 (1.8)
	0.9	13.1 (0.4)	8.0 (1.1)	8.0 (1.8)	13.0 (0.6)	10.2 (1.2)	7.2 (2.1)
	0.7	10.2 (0.7)	8.4 (1.5)	6.6 (2.4)	12.7 (0.6)	9.3 (1.3)	6.8 (2.2)
White Deal	1.1	16.4 (1.5)	13.0 (2.1)	12.5 (4.2)	20.5 (1.1)	15.0 (1.6)	11.6 (3.5)
	0.9	11.0 (2.5)	11.8 (3.6)	11.0 (6.5)	13.3 (2.1)	11.3 (2.9)	10.3 (5.4)
	0.7	6.0 (3.7)	8.6 (5.0)	8.3 (8.3)	6.8 (3.3)	8.6 (4.4)	8.2 (7.2)
Yellow Deal	1.1	12.1 (1.6)	8.9 (3.6)	8.6 (6.0)	15.7 (1.4)	11.1 (2.9)	9.4 (5.0)
	0.9	10.8 (1.8)	8.1 (4.0)	7.6 (6.6)	12.7 (1.6)	9.1 (3.5)	7.8 (5.8)
	0.7	8.5 (2.3)	6.5 (5.0)	6.0 (8.1)	11.6 (1.8)	8.5 (3.8)	7.2 (6.4)

Table 8

Equation for rate of weight loss, gm $cm^{-2}s^{-1}$, of woods without and with impermeable layer

Wood	Equation	
Fibre insulating board	$\dot{m}'' \times 10^4 = 5.9I^{***} - 0.44M^{***} + 6.5 + (1.3 - 0.93M)^{*}$	without
	$\sigma = 0.76 \times 10^{-4} \quad - (1.3 - 0.93M)^{*}$	with
Yellow Deal	$\dot{m}'' \times 10^4 = 5.5I^{***} + 0.04M^{2***} - 1.0M^{***} + 8.2 + (1.4^{***} - .08M^{**})$	without
	$\sigma = 0.37 \times 10^{-4} \quad - (1.4 - .08M)$	with
White Deal	$\dot{m}'' \times 10^4 = 26.6I^{***} - 1.37MI^{***} + 1.05M^{***} - 18.0 + (1.8^{*} - 0.14M^{**})$	without
	$\sigma = 0.59 \times 10^{-4} \quad - (1.8 - 0.14M)$	with

*** 0.1% significance

** 1.0% "

* 5.0% "

Table 9

Values of Q calculated for results in Table 4 for 10% weight loss

Wood	Density g/cm^3	I cal $cm^{-2}s^{-1}$	Q based on C_g = 0.75 cal/g	Mean	Q based on C_g = 0.5 cal/g	Mean
Western Hemlock	0.34	0.5 0.7 1.0	800 650 1030	830	1300 1000 1350	1220
Western Red Cedar	0.36	0.5 0.7 1.0	820 900 1060	930	1380 1300 1350	1340
Podo	0.46	0.5 0.7 1.0	200 280 600	360	700 500 800	670
Douglas Fir	0.45	0.5 0.7 1.0	1100 800 1000	970	1750 1200 1300	1420
Larch	0.51	0.5 0.7 -	880 750 -	810	1400 1100 -	1250
Abura	0.59	0.5 0.7 1.0	200 220 180	200	550 450 300	430
Makore	0.64	0.5 0.7 1.0	900 700 700	770	1450 1050 900	1130
Ash	0.65	0.5 0.7 1.0	250 200 320	260	700 450 450	530

Table 10

Values of Q calculated for results in Table 4 for 30% weight loss

Wood	Density g/cm^3	I cal $cm^{-2}s^{-1}$	Q based on C_g = 0.75 cal/g		Q based on C_g = 0.5 cal/g	
				Mean		Mean
Western Hemlock	0.34	0.5	1090	1080	1700	1500
		0.7	1090		1600	
		1.0	1050		1300	
Western Red Cedar	0.36	0.5	1090	1250	1700	1700
		0.7	1320		1900	
		1.0	1350		1700	
Podo	0.46	0.5	400	510	850	820
		0.7	460		750	
		1.0	670		870	
Douglas Fir	0.45	0.5	1050	1120	1620	1600
		0.7	990		1400	
		1.0	1320		1700	
Larch	0.51	0.5	860	840	1400	1300
		0.7	810		1200	
		1.0	–		–	
Abura	0.59	0.5	280	390	600	620
		0.7	400		650	
		1.0	480		620	
Makoré	0.64	0.5	1100	1060	1700	1500
		0.7	970		1400	
		1.0	1100		1500	
Ash	0.65	0.5	250	340	600	600
		0.7	360		550	
		1.0	500		650	

APPENDIX

Wright and Hayward[3] measured the rates of decomposition of cubes of wood between 3 and 19 mm in size when they were suddenly immersed into vessels containing nitrogen maintained at temperatures of 500°C, 700°C and 900°C. Two kinds of wood (oven dried) were used, Hemlock, density 0.43 and Western Red Cedar, density 0.34 g/cc. The results were expressed as

$$100 \frac{d(P/P_\infty)}{dt} = k\sqrt{100(1 - P/P_\infty)} \qquad (1)$$

where

$$k = \left(\frac{1}{\rho \ell} - 0.75\right)(0.00065T - 0.4) \qquad (1A)$$

P = pressure in vessel at time 't'
P_∞ = pressure at end of heating
k = "rate constant" sec^{-1} (sic)
T = absolute temperature of vessel
ρ = density of wood
ℓ = size of cube
t = time in seconds

We now show how equation (1) can be related to the rate of decomposition of the cubes.

In some subsidiary experiments Wright and Hayward showed that the rate of decomposition along the grain was twice that across the grain. One may presume this to be associated with the greater conductivity along the grain.

For a cube cut normally and along the grain decomposition across the grain occurs on four faces and along the grain on two. We denote the slower of the two mass rates of decomposition, i.e. the mean rate across the grain by $\bar{m}''$ ($gcm^{-2}s^{-1}$) and assume that this is constant in time. We can then write the volume of the undecomposed wood at time t as

$$V_t = \ell^3 \left(1 - \frac{2\bar{m}''t}{w\rho\ell}\right)^2 \left(1 - \frac{4\bar{m}''t}{w\rho\ell}\right) \qquad (2)$$

where w is the fraction of the total mass of wood that volatalizes and is here taken as 0.6. Since the excess pressure in the vessel is proportional to the amount of volatiles:

$$P \propto V_o - V_t \tag{3}$$

and

$$P_\infty \propto V_o$$

From these equations we obtain

$$\frac{d}{dt}\left(P/P_\infty\right) = \frac{8\,\bar{m}''}{w\rho l}\left(1 - \frac{2\,\bar{m}''t}{w\rho l}\right)\left(1 - \frac{3\,\bar{m}''t}{\rho w l}\right) \tag{4}$$

and

$$1 - P/P_\infty = \left(1 - \frac{2\,\bar{m}''t}{w\rho l}\right)^2 \left(1 - \frac{4\,\bar{m}''t}{w\rho l}\right) \tag{5}$$

From equations (4) and (5) we can write

$$\frac{d}{dt}\left(P/P_\infty\right) = \frac{8\,\bar{m}''}{w\rho l}\, f\left(1 - P/P_\infty\right) \tag{5i}$$

Figure 1 shows $f(1 - P/P_\infty)$ as a function of $(1 - P/P_\infty)$. Also on the same graph are shown $(1 - P/P_\infty)^{\frac{1}{2}}$ and $(1 - P/P_\infty)^{\frac{2}{3}}$ and it is seen that the calculated relation is intermediate between them. A better agreement with Wright and Hayward's equation would be obtained by adopting some factor other than 2 for the ratio of the decomposition rates in the two directions. However, the average difference between $(1 - P/P_\infty)^{\frac{1}{2}}$ and the curve calculated on the assumption of a constant value of $\bar{m}''$ is only about 10 per cent, and accordingly we write as an approximation

$$\frac{d}{dt}\left(P/P_\infty\right) \simeq \frac{8\,\bar{m}''}{1.1\,w\rho l}\left(1 - P/P_\infty\right)^{\frac{1}{2}} \tag{6}$$

Comparing equations (1) and (6), we obtain the value of the slower of the two rates of decomposition as

$$\bar{m}'' \simeq \frac{1.1\,w}{80}\left(1 - 0.75\rho l\right)\left(0.00065T - 0.4\right)$$

$$\simeq \left(\frac{0.0053T}{1000} - 0.0033\right)\left(1 - 0.75\rho l\right)$$

Clearly the slight quantitative discrepancy between this formulation of the decomposition of the cubes and that of Wright and Hayward is not, in practice, a significant one. For example, no attention has been paid to the "rounding" of the corners or edges of the cubes. Nevertheless, it is preferable to regard the decomposition as the result of a linear or almost linear charring rate than in terms of a theory which is formulated in kinetic terms.

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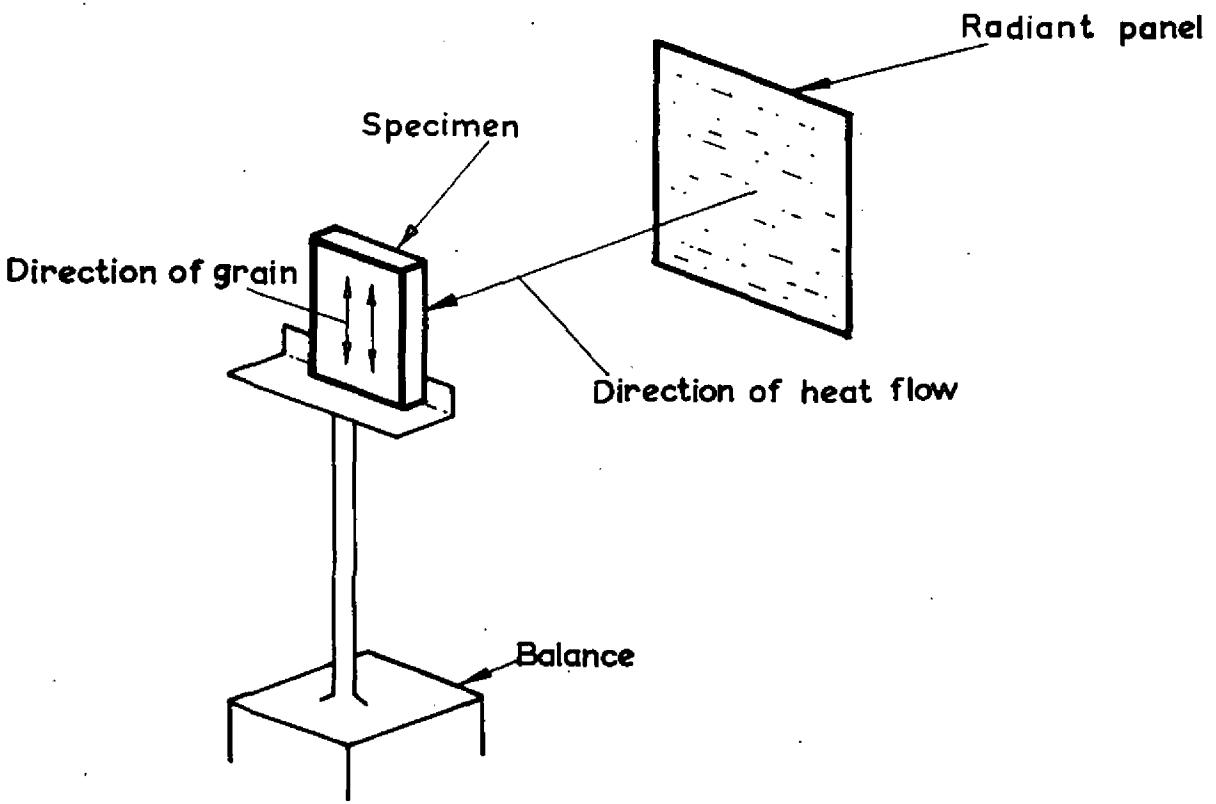

FIG.1. EXPERIMENTAL ARRANGEMENT

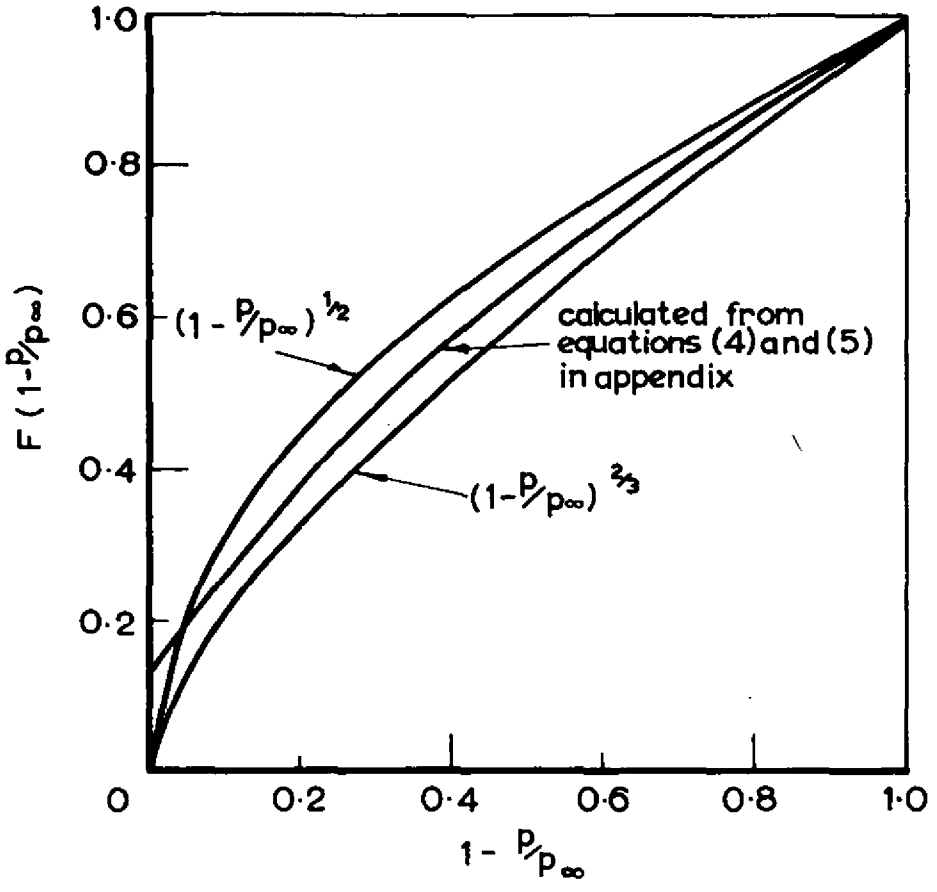

FIG.1.(APPENDIX) CURVE FITTING APPROXIMATIONS FOR WRIGHT AND HAYWARDS DATA

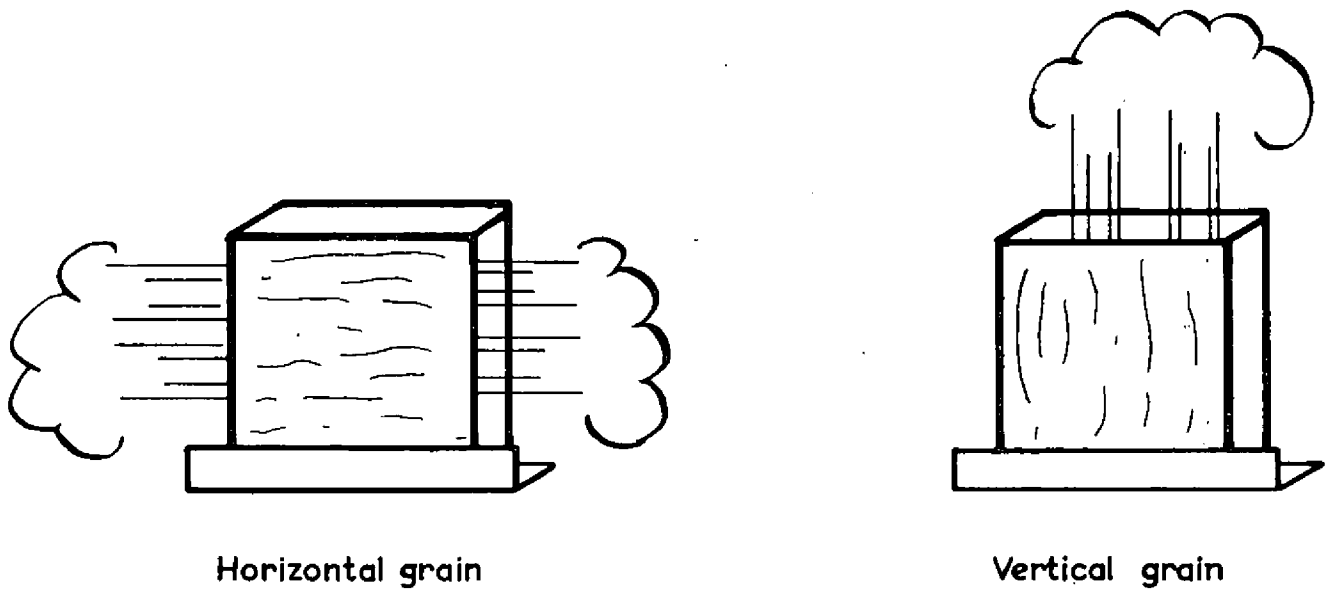

FIG.2. EMISSION OF VOLATILES FROM SEALED ABURA

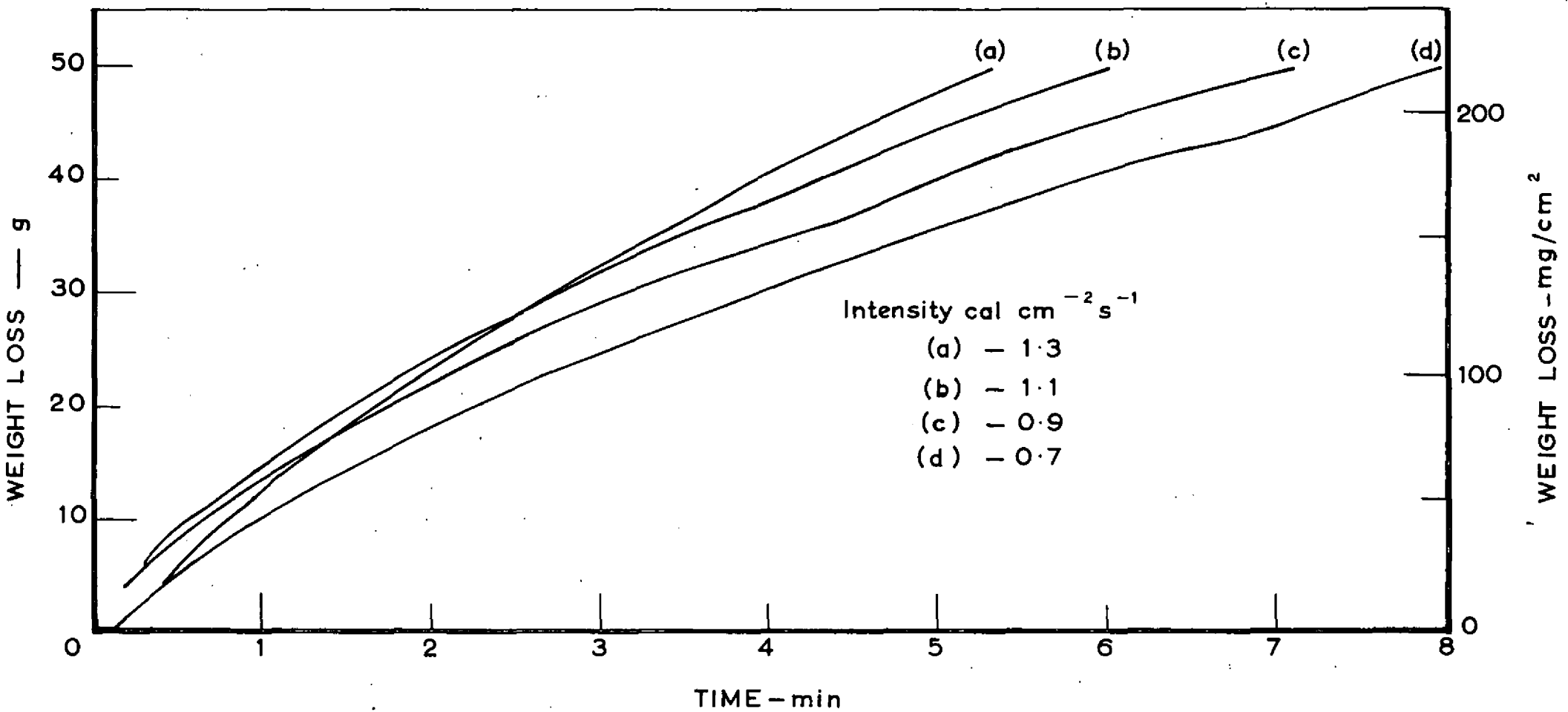

FIG.3a. WEIGHT LOSS OF FIBRE INSULATING BOARD WITH IMPERMEABLE LAYER

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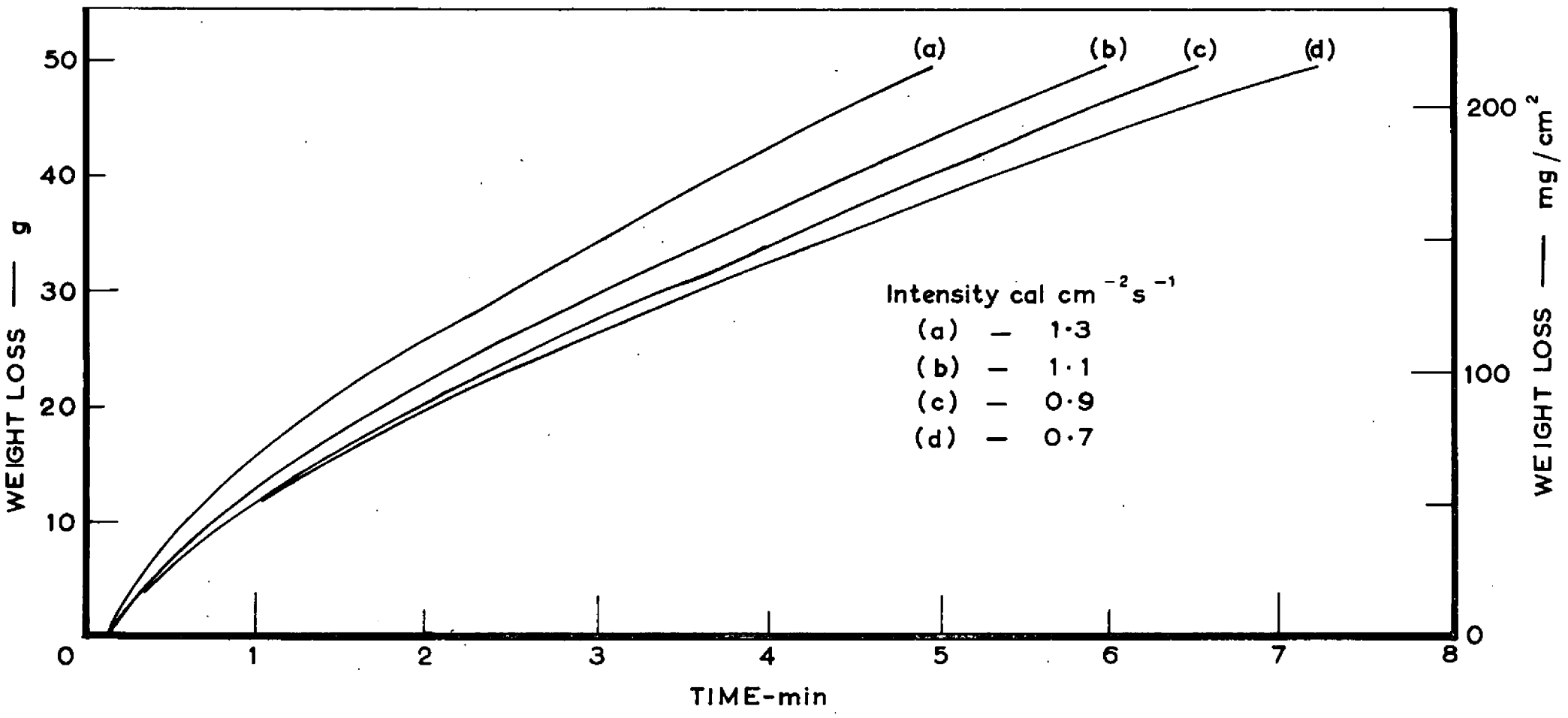

FIG.3b. WEIGHT LOSS OF FIBRE INSULATING BOARD WITHOUT IMPERMEABLE LAYER

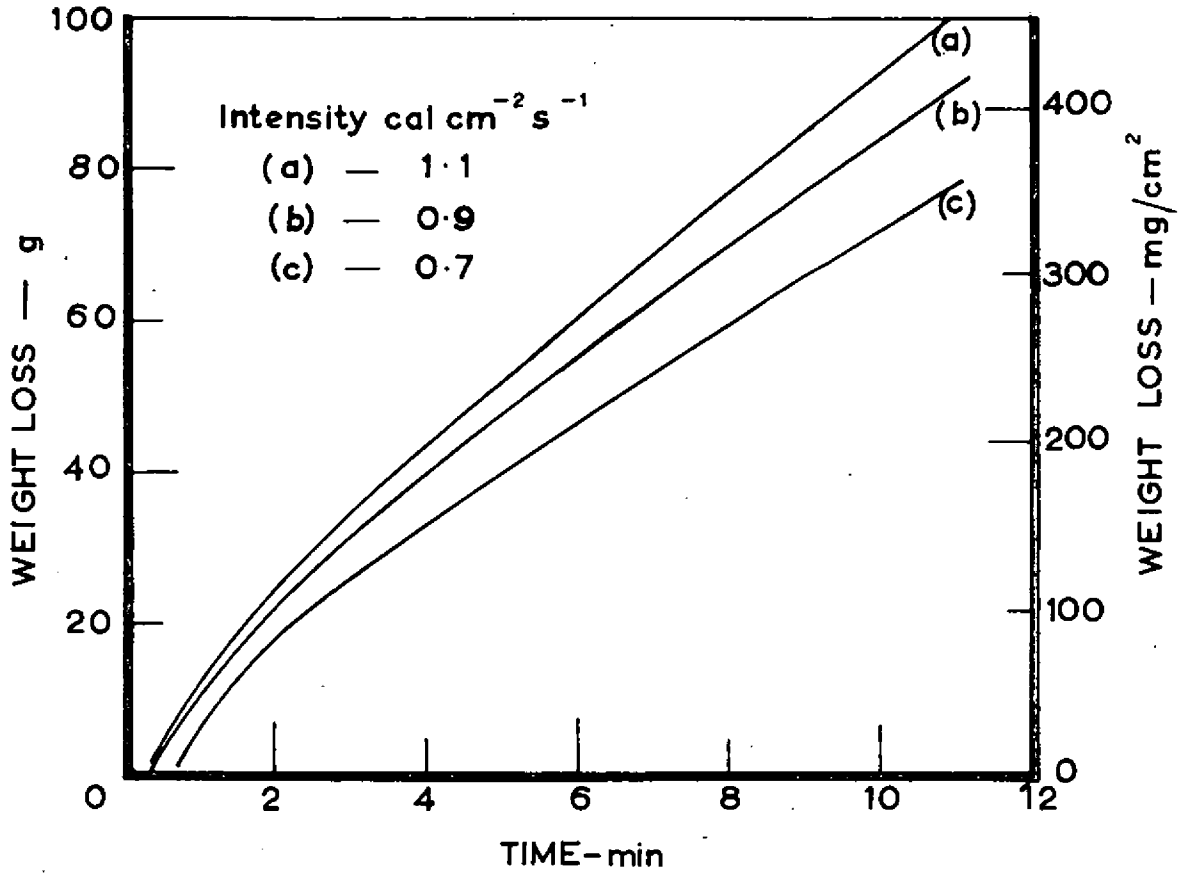

FIG.4a. YELLOW DEAL WITH IMPERMEABLE LAYER

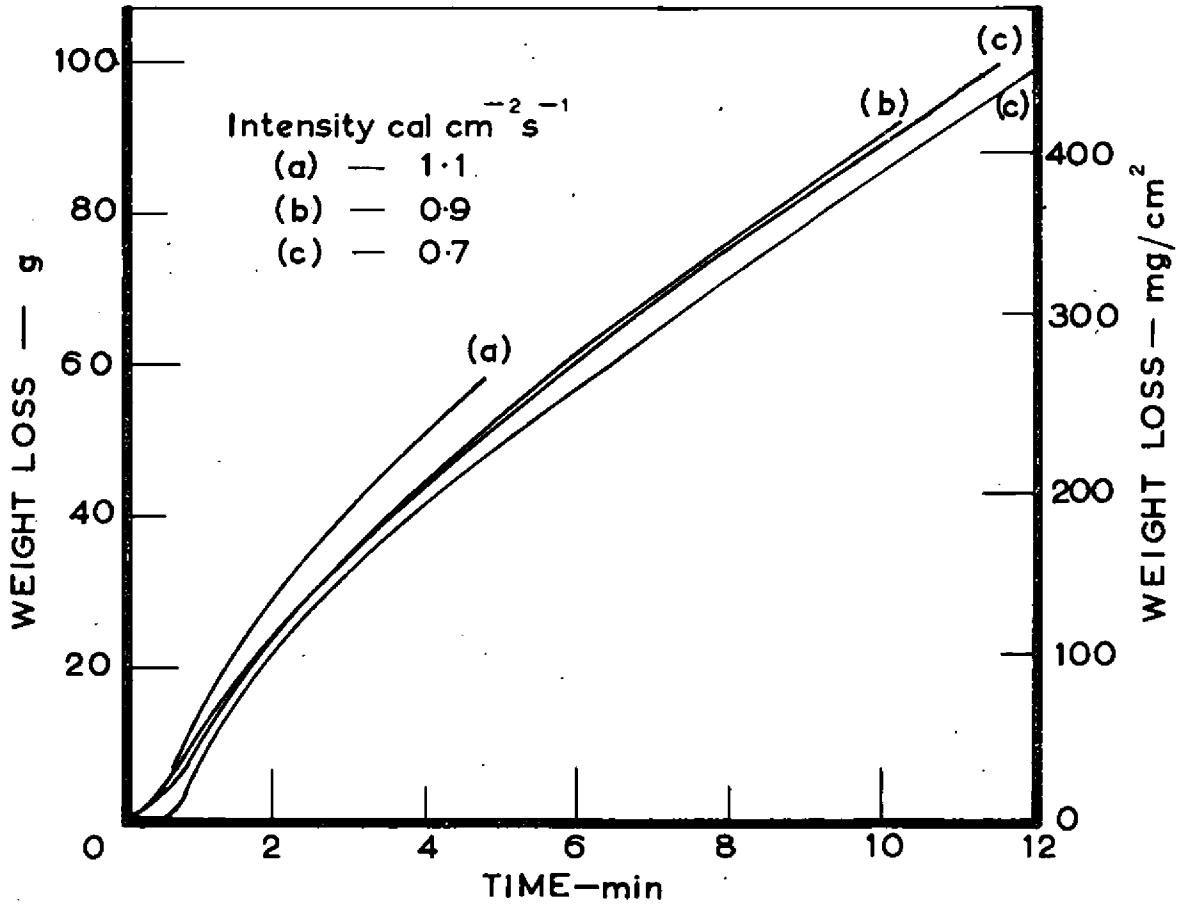

FIG.4 b. YELLOW DEAL WITHOUT IMPERMEABLE LAYER

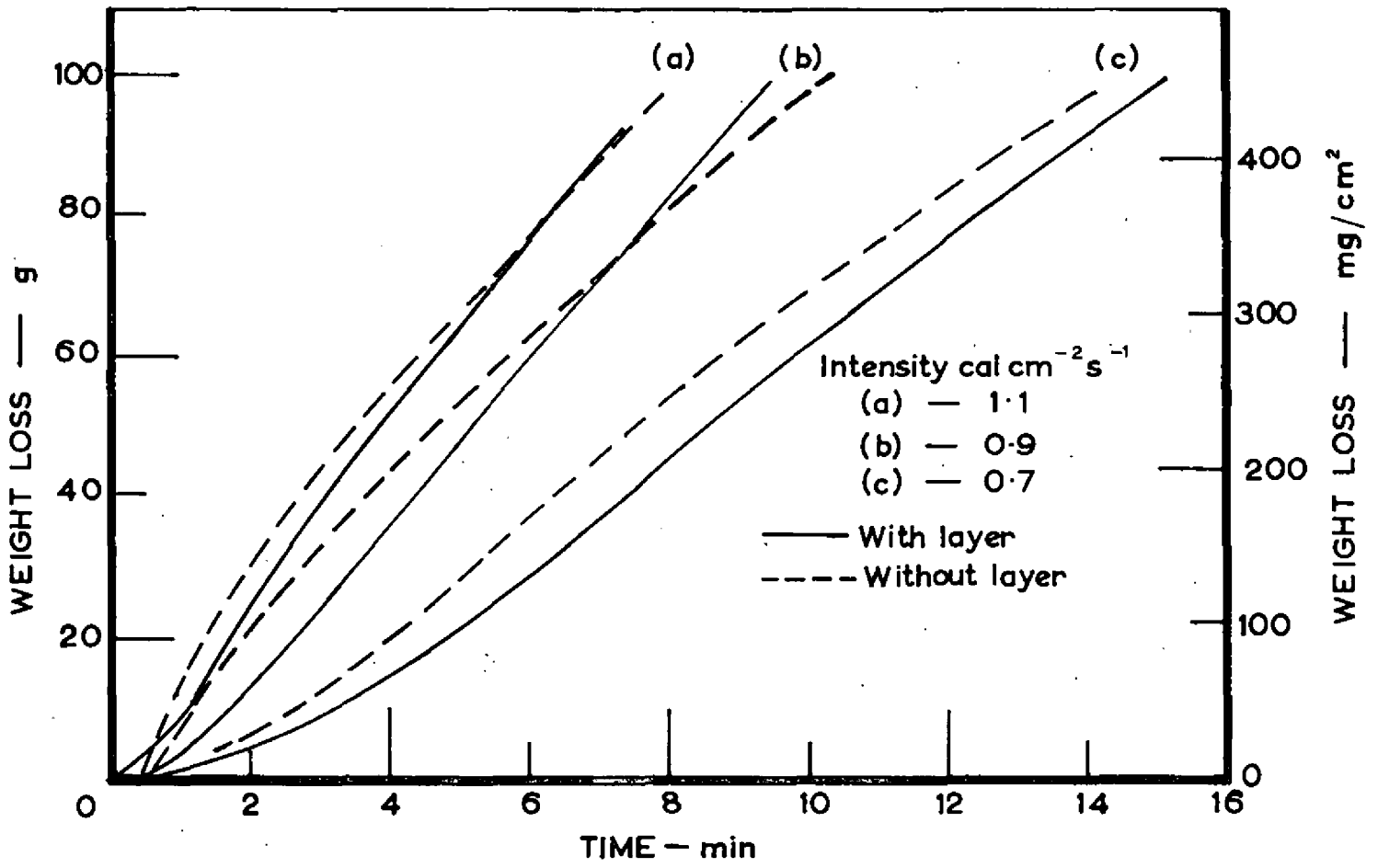

FIG.5. WHITE DEAL WITH AND WITHOUT IMPERMEABLE LAYER

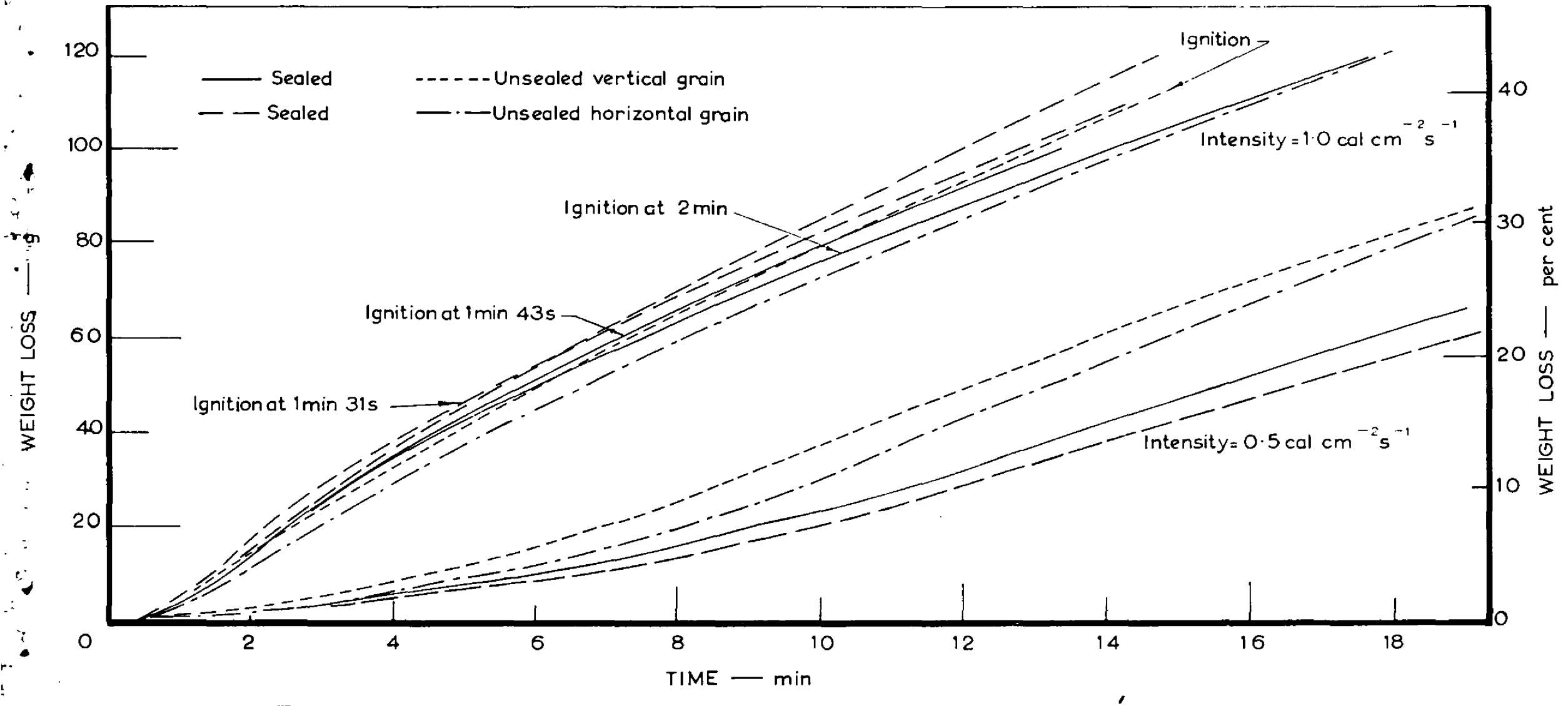

FIG.7. WEIGHT LOSS OF SEALED AND UNSEALED MAKORÉ

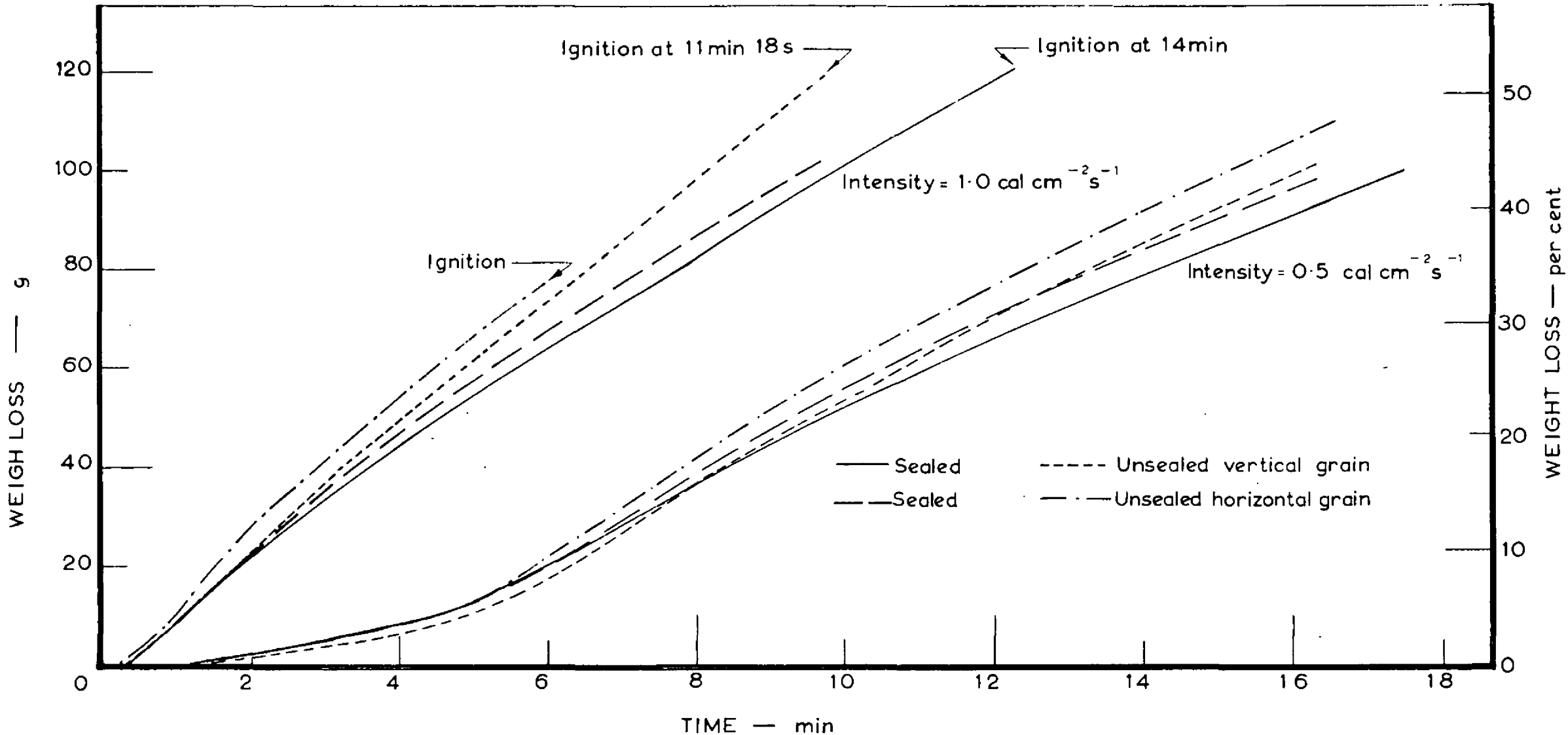

FIG.8. WEIGHT LOSS OF SEALED AND UNSEALED ABURA

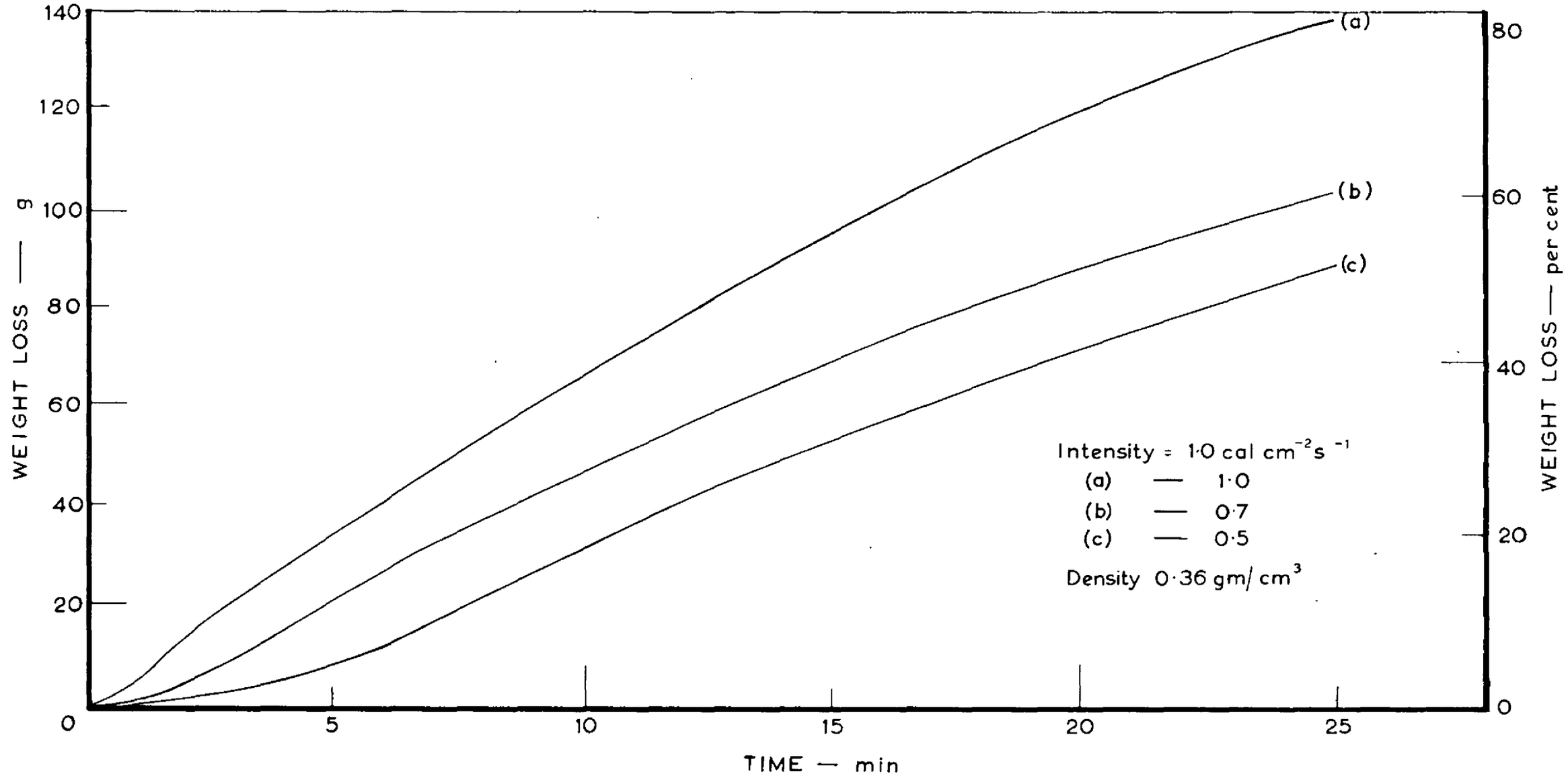

FIG.6. WEIGHT LOSS OF UNSEALED WESTERN RED CEDAR