DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

AND

FIRE OFFICES' COMMITTEE

JOINT FIRE RESEARCH ORGANIZATION

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## THE DURATION OF FLAMING OF WOODEN STICKS IN A SPREADING FIRE

by

P. H. THOMAS, D. L. SIMMS, and H. G. H. WRAIGHT



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Fire Research Station.
Boreham Wood.
Herts.
('phone ELStree 1341)

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## SUMMARY

The times for which sticks in a wooden crib continue to flame have been measured in experiments on spreading fires. No direct measurements of either the intensity of radiation or the surface temperature of the fuel are available, but for these experiments, the velocity of burning, i.e. the original thickness of a stick divided by the time of flaming, is inversely proportional to the density of the original wood and decreases with stick thickness and nominal moisture content of the fuel bed. The velocity of burning also appears to increase with increasing permeability of the wood along the grain. Because the effect of this permeability is a function of the length of the stick along the grain, the width of the crib itself might affect the rate of spread in wood of high permeability, but further experiments are required to test this.

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## INTRODUCTION

The rate of burning of wood has an important effect on almost all aspects of the growth and spread of fire in cellulosic materials. The rate at which the wood is heated is clearly important, but at any given rate of heating many properties of the wood itself may also be relevant, e.g. density, thermal conductivity, permeability to volatiles and specific heat, as well as the condition of the wood, i.e. its thickness and moisture content.

One of the ways in which this property is important in the study of fire spread is in the relation

$$t = \frac{D}{V} \tag{1}$$

where $t$ is the time for which any single element of fuel liberates gases which support a flame*

$V$ is the velocity of spread

and $D$ is the depth of the flaming zone in the direction of spread

Fons et al[1] have carried out experiments on the spread of fire in cribs made of wood of different stick thicknesses (0.7 to 3.2 cm but mostly 1.1 cm), moisture contents (2.5 to 17 per cent) and densities (0.3 to 0.77 g/cm$^3$). Most of the cribs were constructed from white fir (Abies concolor), density 0.30 to 0.55 g/cm$^3$ but a few experiments were carried out on magnolia (Magnolia grandiflora), density 0.45 to 0.55 g/cm$^3$, basswood (Tilia americana), density 0.36 to 0.50 g/cm$^3$, sugar maple (Acer saccharum), density 0.69 to 0.77 g/cm$^3$, longleaf pine (Pinus palustris), density 0.51 to 0.75 g/cm$^3$, with, however, only one thickness (1.2 cm) and nearly all woods were burnt at a nominal moisture content of 11 per cent.

The experimental arrangement kept the flaming zone of the burning crib in a fixed position by manual operation of a chain belt upon which the crib rested, and $V$ and $D$ were measured. The value of $t$ was calculated from equation (1). No measurements were made of the intensity of radiation or the surface temperature of the woods within the burning zone, but an empirical relation appropriate to these experimental conditions can be obtained between $t$ and the physical properties of wood.

For all the experiments using white fir the values of $t$ obtained from equation (1) have been subjected to a regression analysis with density $\rho$ ⁎, stick thickness $d_0$ and nominal moisture content $M$ as the independent variables.

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*Fons[1] defined this as the burning time of the fuel particle. In his notation $t = \theta_r$

⁎Over the range of values of $\rho$ in these experiments, thermal conductivity is directly proportional to the density.

The analysis was undertaken on the logarithm of all these quantities to obtain the best power law. The following equation was obtained

$$t = 340\, \rho_f^{0.91}\, d_o^{\ 1.3} \left(\frac{M}{10}\right)^{0.26} \qquad (2)$$

where $d_o$ is in cm.,

$\rho_f$ in $g/cm^3$

M in percentage moisture content by weight

and $t$ is in seconds

Equation (2) normalises the results to a moisture content of 10 per cent. The multiple correlation coefficient of this regression is about 0.90. The index on density, 0.91, is not significantly different from unity and a second regression, assuming a direct proportionality between $t$ and $\rho_f$ gives

$$t = 380\, \rho_f\, d_o^{\ 1.3} \left(\frac{M}{10}\right)^{0.26} \qquad (3)$$

An average rate of burning may be defined as half the original thickness of the fuel divided by the time of flaming. This, if multiplied by the original mass, is a convenient expression for the average mass rate of burning per unit of initial surface area per unit time, viz,

$$\dot{m}''_{gr} = \frac{\rho_f\, d_o}{2t} \qquad (4)$$

The suffix gr denotes the gross rate of burning; the actual rate of burning during flaming was not measured and could only be obtained if the weight of carbonaceous residue <u>prior</u> to glowing combustion were known.

Substituting equation (4) in equation (3) gives

$$\dot{m}''_{gr} = 1.3 \times 10^{-3}\, d_o^{\,-0.3} \left(\frac{M}{10}\right)^{-0.26} \qquad (5)$$

Hence $\dot{m}''_{gr}$ is independent of the density and only weakly dependent on the thickness of the stick.

The results for white fir normalised to a moisture content of 10 per cent are shown in Fig 1 and compared with eqn. (3) because the major experimental variables are $t$ and $\rho_f$. The results for the other four species are also shown in Fig 1, on the assumption that the relationship between the variables is of the same form, even if the numerical constants differ. Most of the results for these species lie below those for white fir and all lie below eqn. (3) which suggests that a property other than those included in the regression analysis is responsible for the difference.

The effect of permeability[2]

Recently, measurements have been made of the permeability ($\mu$) of these woods to nitrogen[3] along the grain (Appendix 1) and it is possible to repeat the regression analysis including permeability as an additional variable. However, because the results for the species other than white fir are restricted to one thickness and practically one moisture content it is accurate enough and simpler to assume that eq'ns. (3) and (5) hold for these other species and to compare the best values of the numerical constant for the different woods.

The value of $\dot{m}''_{gr}\, d_o^{0.3} \left(\frac{M}{10}\right)^{0.26}$ for each wood is shown in Fig 2. Individual results are shown for the four species, other than white fir, for which only the mean value and the confidence limits at the 95 per cent level are given. There are two ways of expressing the results of this comparison. First, that white fir burns more slowly than do the other four woods, which do not differ significantly between themselves, or alternatively that there is a progressive increase in the rate of burning as the permeability increases, though the change in rate of burning falls off as the permeability becomes larger. The same values of the numerical constants are plotted on a log log scale in Fig 3: the line drawn corresponds to the best regression through the five species and is given by the equation (6)

$$\dot{m}''_{gr}\, d_o^{0.3} \left(\frac{M}{10}\right)^{0.26} = 1.13 \times 10^{-3} \mu^{0.074} \qquad (6)$$

The level of significance of this line is between 0.1 and 0.01 per cent, which is satisfactorily high allowing for the approximations made, although it is mainly due to the difference between white fir and other woods as a group. However, experiments(2) on the rate of loss in weight of woods of different density and permeability at various constant known levels of radiation also attribute an effect to permeability of a similar magnitude. It is reasonable therefore to conclude that the difference between white fir and the other four woods is associated with the difference in their permeability.

The value of the transverse permeability is very much smaller than the longitudinal permeability(3) and this suggests that its effect on the rate of burning is a function of the length of the stick and hence that the width of a crib will affect the rate of spread in a wood of high permeability. Experiments to test whether this is so are now being carried out.

## Discussion

The analysis has shown that the time for which a stick persists in flaming, i.e. remains in flaming zone of a spreading fire is proportional to the thickness. That is, a mass rate of burning can be defined which is independent of the density and which is proportional to $d_o^{-0.3}$ in the range of these thicknesses (0.7 - 3.2 cm). This mass rate of burning also decreases with the initial moisture content of the wood, but it is uncertain how much moisture is actually present in the wood by the time flames reach it.

The mass rate of burning also increases with the longitudinal permeability, but although magnolia and basswood have much higher permeabilities than the other three woods, their mass rates of burning are about the same as sugar maple and longleaf pine. However, the rates of spread along cribs of magnolia and basswood are significantly higher than the rates of spread in the other woods(4). The difference between the behaviour of the woods relative to each other in the burning zone and in the zone ahead of the fire front may be associated with the differences on the relative importance of the various physical properties and of the conditions in the two zones. Direct measurements of the heat transfer within the cribs are now being made. In addition, by comparing eqn. (5) with the results of direct experiments on the variation of rate of burning now being undertaken(2), it should be possible to obtain another estimate of the radiation level within the burning zone, and the way in which it varies with the physical properties of the wood.

It should then be possible to attempt to predict the rate of spread of fire in any given crib from its known rate of burning under such conditions.

Equation (5) predicts that the rate of charring of white fir of density 0.4 $g/cm^3$, thickness 1.0 in (2.54 cm) and moisture content 10 per cent is $2.5 \times 10^{-3}$ cm/s. This is of the same order of magnitude, but higher than that found in experiments on the rate of burning of cribs in compartment fires[5], in which the comparable velocity for a wood of the same density and thickness and moisture content was $1.4 \times 10^{-3}$ cm/sec. Both values are somewhat higher than the well known figure of 1/40 in/min ($1 \times 10^{-3}$ cm/s) found in standard fire tests on timber floors and doors[6,7] where the rate of heating varies with time but is nominally standardised from one test to another. Wright and Hayward[8] have given decomposition rates for cubes of wood of various sizes but all less than 1.9 cm thick immersed in furnaces at various temperatures and Thomas[9] has expressed their results in the form

$$\dot{m}'' = \frac{1.1w}{40}\ (1-0.75\rho_f d)(0.00065\ T-0.4) \qquad (7)$$

where $\dot{m}''$ is the actual rate of loss of weight

$w$ is the proportion of the original weight lost

and $T$ is absolute temperature of heating ($900^\circ K < T < 1200^\circ K$)

Since $\dot{m}''_{gr}$ is the mass burning rate, equation (4), the charring rate is given by

$$\dot{m}''_{gr} = \frac{\dot{m}''}{w} \qquad (8)$$

Inserting $T = 1100^\circ K$, $\rho_f = 0.4\ g/cm^3$ and $d = 2.54$ cm

gives $\frac{\dot{m}''_g}{\rho_f} = 4.3 \times 10^{-3}$ cm/s. Equation (7) is an empirical one and the value of thickness inserted is outside the range of their experiments[8] but the result obtained is not unreasonable.

A more detailed review of both direct and indirect measurements of the rate of burning of wood is being prepared.

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The late Mr. W. L. Fons kindly supplied us with representative samples of the five species he used in his experiments from which values of their permeabilities were determined by the Forest Products Research Laboratory.

## Appendix I

### Longitudinal permeability of wood

One test specimen was taken from each stick with the exception of one of the white fire sticks from which it was not possible to obtain a suitable specimen. The test specimens were approximately 1.3 cm x 1.3 cm x 2.5 cm long, and they were conditioned to equilibrium moisture content (approx. 15 per cent) in air at 75 per cent relative humidity and 25°C before test.

The permeability of each specimen was measured in the longitudinal direction by gas flow with nitrogen. There is not a complete correspondence between the permeability to air and to toluene, but the value of $\mu$ is probably a fair guide to the permeability of wood to its own volatiles.[2]

| Species | Nitrogen Permeability-Longitudinal Direction cc/sec cm$^2$ atm/cm | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Average |
| Basswood | 480 | 435 | 1055 | 1035 | 875 | 1070 | 825 |
| Magnolia | 965 | 990 | 975 | 715 | 470 | 445 | 760 |
| Sugar maple | 158 | 130 | 119 | 61 | 123 | 39 | 105 |
| Longleaf pine | 75 | 43 | 65 | 65 | 9.0 | 63 | 55 |
| White fir | 5.9 | 3.3 | 3.6 | 16 | 2.7 | - | 6.3 |

The permeability of each specimen and an average figure for the species is given above.

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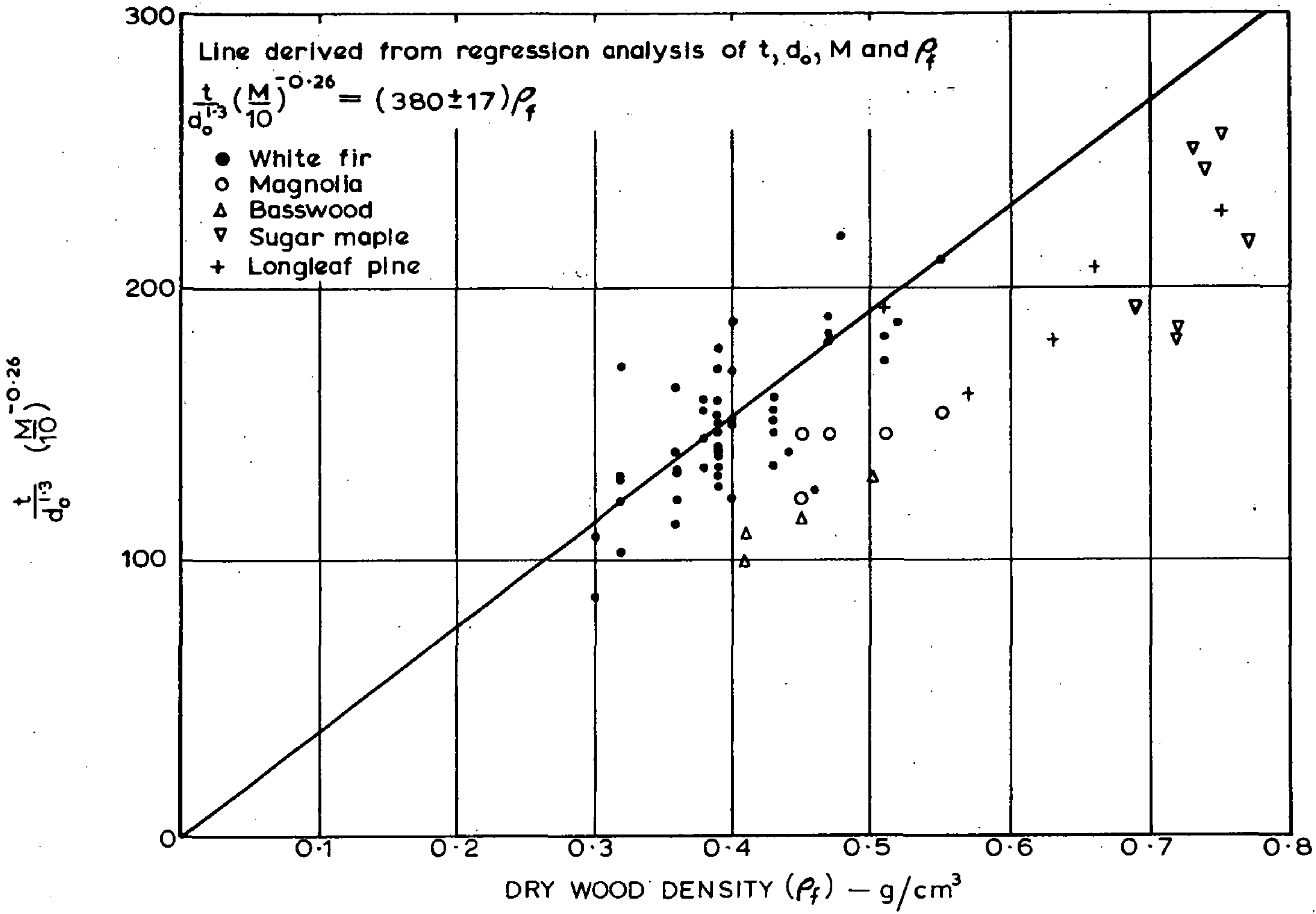


FIG.1. RESIDENCE TIME — FUEL DENSITY

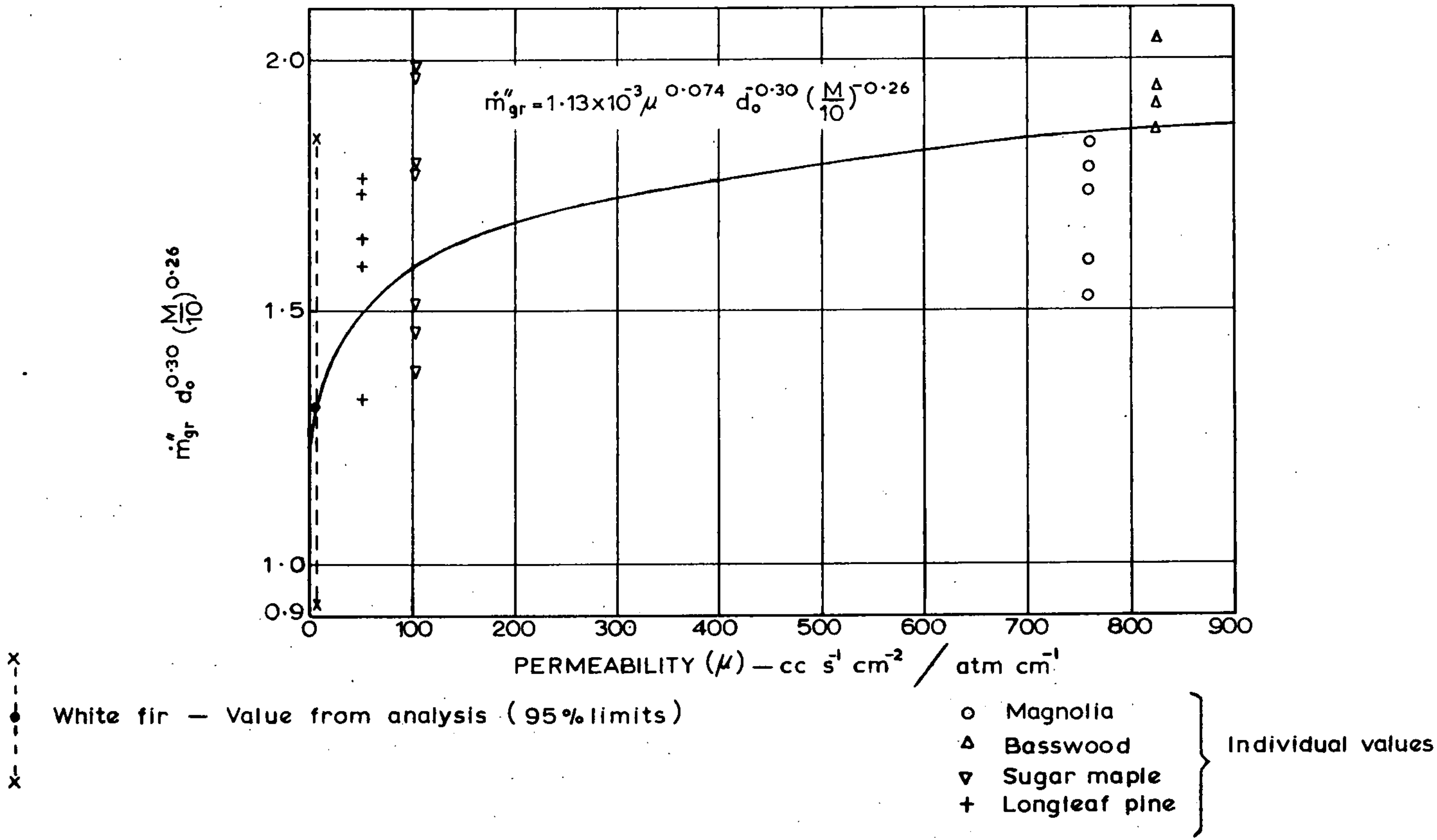


FIG.2. EFFECT OF PERMEABILITY

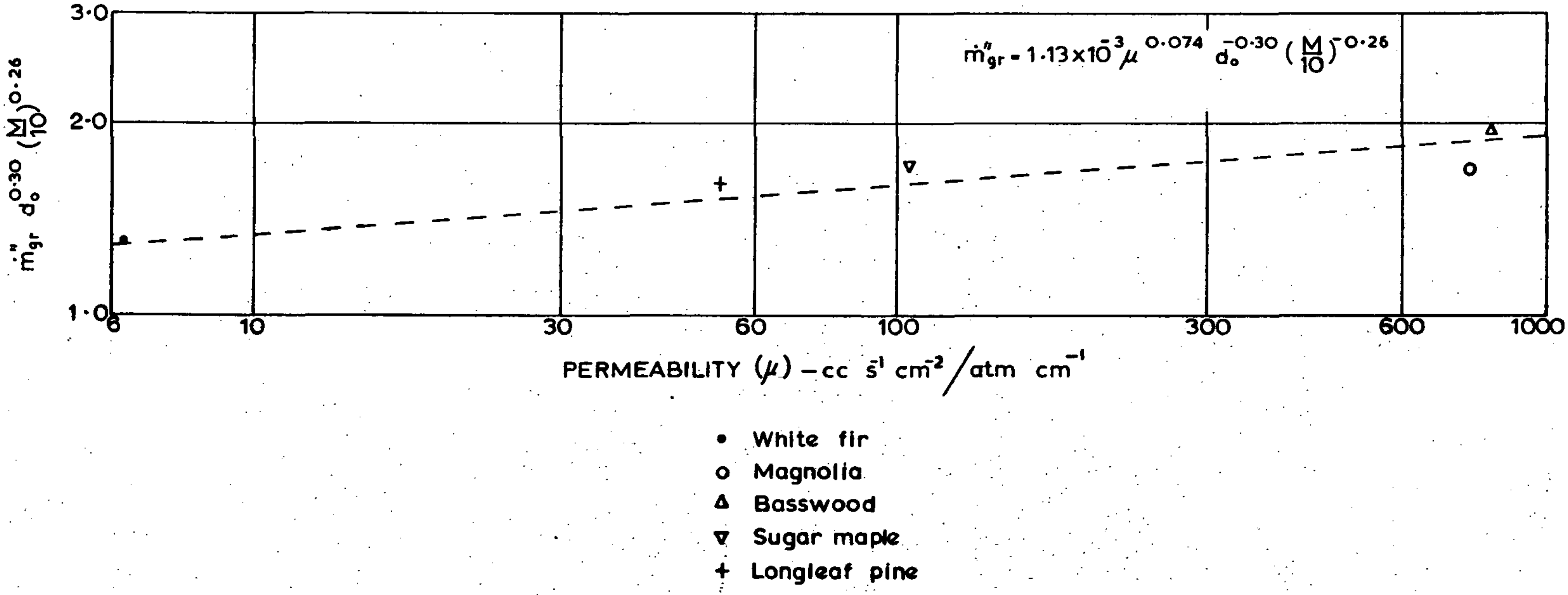


FIG.3. EFFECT OF PERMEABILITY