

F.R. Note No.446.

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

ON THE RATE OF BURNING OF WOOD

by

P. H. Thomas

SUMMARY

If it is assumed that the primary decomposition of wood is exothermic and depends only on the temperature and the concentration of decomposing material in the solid phase, the heat balance and reaction kinetic equations show that it is possible to find a steady state where the rate of decomposition in one direction and hence the loss in weight becomes constant in time. This may be expected to represent a limiting value after burning has been in progress for a long time.

The numerical results obtained are very sensitive to the value of the heat of reaction and since this is not known within narrow enough limits, it is not possible yet to make a proper comparison between experiments and theory, but the calculated results are of the same order of magnitude as those measured. If the primary reaction is endothermic or if oxygen is required, the rate of propagation must eventually tend to that given by a diffusion law and cannot be constant in time. Experiments are in progress to study the rate of charring at long times.

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, Boreham Wood, Herts. (Telephone Elstree 1341 and 1797.)

September, 1960.

Fire Research Station,
Boreham Wood,
Herts.

ON THE RATE OF BURNING OF WOOD

by

P. H. Thomas

Introduction

In designing structures to withstand a fire, it is necessary to know how long the fire lasts and one of the important quantities that must be determined is the rate of burning of the combustible material, which is usually wood.

There are a number of experimental data which may be used to derive instantaneous or mean rates of burning under various conditions and we shall first enumerate these before developing a hypothetical theoretical model of the burning.

Experimental data

Folk⁽¹⁾ gives values for the rate of loss in weight of cribs of wood sticks and these are given in Table 1. This rate increases from zero to a maximum value at which it may stay constant for some time before decreasing as the whole of the material is consumed. For two of the cribs Folk also gives the loss in weight at various times for each layer of sticks. Where these data give higher values of rate of loss in weight per unit area of wood than does the average figure for the whole crib, it is because some of the lower layers have passed their peak burning rate before the upper layers have become fully involved.

The values in Table 1 are based on the average of the maximum rate of burning for each layer. Folk gives results for another crib having seven 1 cm sticks in a layer of 10 cm width. With such a close packing, it is perhaps not surprising that the average rate of burning for the whole crib was much lower than for the other cribs and probably lower than for any one layer in the crib. Bryan's⁽²⁾ cribs, for which some results are also given in Table 1, were better aerated and the average values for each layer - will be more likely to be representative of any one element of surface.

Fig.1 reproduces a graph drawn by C. F. Fischl⁽³⁾ from data given by Lawson, Webster and Ashton⁽⁴⁾ for the depth of char on timber beams subjected to a fire resistance test, i.e. heating in a furnace according to B.S. 476 : Pt.1. The line corresponds to a rate of growth of char of $1/40$ in/min. This rate is proportional to the rate of weight loss. Webster and Ashton⁽⁵⁾ have also given results for the fire resistance of wood of different species and thickness ($1/2$ in. to 2 in.) which under the test conditions gave effective charring rates of $1/40$ in/min.* (See Fig.2). Webster and others have recently obtained mean rates of loss of weight in cribs of wood⁽⁶⁾. For 1 in. sticks they obtained $0.57 \text{ mg.cm}^{-2}\text{sec}^{-1}$ which, for the density of wood used, corresponded to $1/30$ in/min approximately. For larger strips they obtained somewhat lower values.

Discussion of results

In all the data referred to above the heat transfer to the surface or the surface temperature itself increased with time throughout the burning and this must tend to increase the charring rate with time, but the increasing depth of charcoal tends to reduce it. The combination of the two effects may tend to make the charring rate more constant than if either effect were acting alone. In the following theory we shall not consider the early variations in time, due to the initial heating of the surface, but only the theoretical limiting value at long times. Any endothermic reaction or any reaction requiring the presence of oxygen must rely on the diffusion of heat or oxygen or both from the surface and the rate of propagation of the reaction zone, i.e. the rate of charring must tend to that given by a controlling diffusion law, i.e. the rate must eventually tend to vary

*It is reasonable to assume that the arrival of the char layer at the unexposed face and the time of flame penetration are the same in these tests.

TABLE 1

Details of cribs and rates of burning

Number of layers	No. of sticks in each layer	Size of stick cm	Height of crib cm	Total exposed wood surface $\text{cm}^2 A_w$	Area of vertical air passages $A_v \text{ cm}^2$	Area of side inlets $A_s \text{ cm}^2$	A_v/A_w	Rate of burning $\text{mg cm}^{-2} \text{ sec}^{-1}$		
								Maximum value of total rate averaged over whole exposed surface	Average of maximum rates for each single layer in crib	
Folk	(10	4	10 x 1 x 1	10	1,350	36	108	0.026	0.62	1.0
	(10	5	10 x 1 x 1	10	1,600	25	90	0.0156	0.50	1.4
	(10	7	10 x 1 x 1	10	1,990	9	54	0.0045	0.21	-
	(6	3	15 x 2.5 x 2.5	15	2,240	42	176	0.019	0.49	0.49
Bryan	(20	3	61 x 5.1 x 5.1	102	73,470	2,500	18,000	0.036	0.94	-
	(20	3	53 x 4.4 x 4.4	89	55,420	1,940	13,800	0.036	0.85	-
	(20	3	38 x 3.1 x 3.1	63	27,860	1,070	7,000	0.036	0.82	-

as $1/(\text{time})^{1/2}$. There is evidence that the rate of exothermic heating may depend on the oxygen concentration and clearly if this is so, oxygen diffusion must eventually become the rate controlling factor here also. However, it is difficult to estimate how deep the charcoal layer must become before this happens because cracks develop in the char and these are not of equal size. Volatiles, tend to flow out of the larger cracks so that it is easier for oxygen to diffuse in through the smaller ones than would be the case where oxygen had to diffuse against the volatile stream through a mass of uniform porosity. Although the experimental evidence is not conclusive because in some of the tests the severity of the exposure at the surface increased with time, the evidence available to date does suggest the rate of charring is more constant than would arise from a diffusion law. In view, however, of the lack of data for long burning times the existence of a steady charring rate for the conditions of no heat loss that are assumed is the following theory must be regarded as somewhat tentative.

Theory

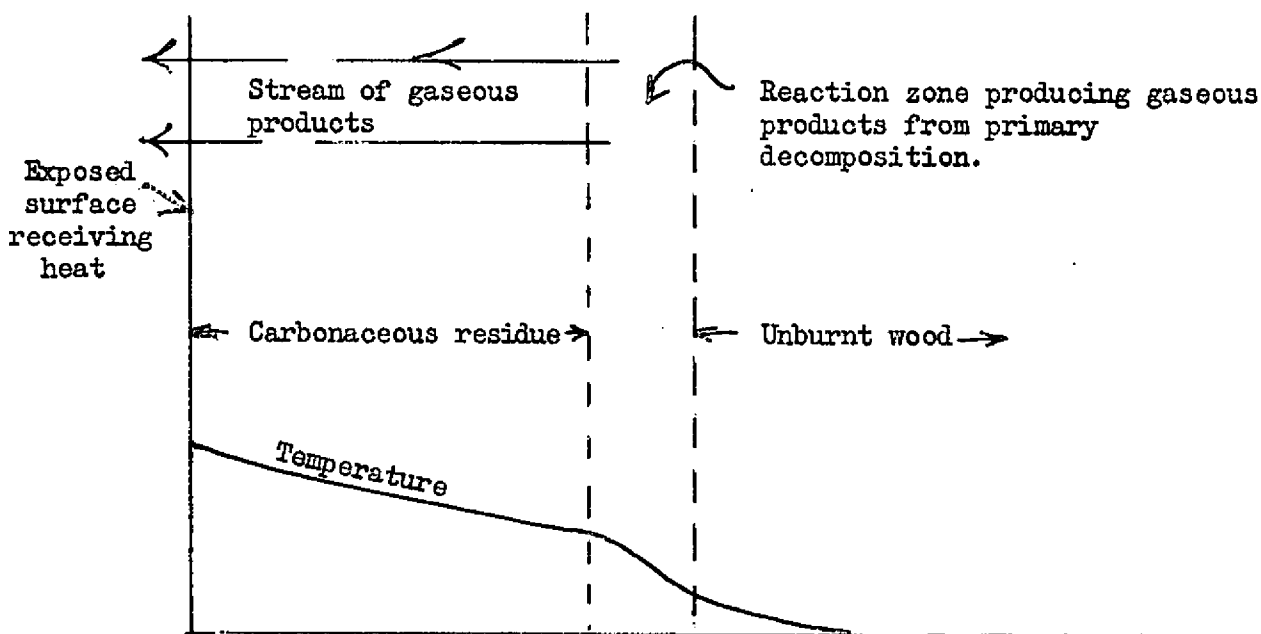


Fig.(3). Diagrammatic representation of temperature distribution and reaction zone in semi infinite wood solid

The decomposition of wood by heating is assumed to be exothermic and is assumed here to be first order with respect to reactant concentration. Stamm(7) found such a kinetic law for the loss in weight of wood when heated for various times. The volatile material produced by this decomposition is flammable and will burn in a suitable atmosphere, transferring heat back to the wood surface. The volatiles produced in the reaction zone pass back through the carbonaceous residue where further heat transfer and reaction may take place. In this model the reaction, is represented by the overall kinetic law given below for the decomposition (equation 2)

We represent the heat balance of unit volume in the wood at a depth, x , in an infinitely wide and thick slab by

$$M C_p \frac{\partial T}{\partial t} + \kappa \frac{\partial^2 T}{\partial x^2} = \rho c \frac{\partial T}{\partial t} + \frac{\rho Q}{\omega} \frac{\partial \omega}{\partial t} \quad (1)$$

where T is the absolute temperature
 K is the thermal conductivity
 ρ is the density
 c is the specific heat of the solid
 c_g is the specific heat of the gases
 M is the local mass flow of gaseous products
 w is the mass concentration of reactant per unit volume
 Q is the heat of reaction per unit gm. of total substance
 t is time

We assume that the thermal and physical properties of the wood and residue are the same. This is not strictly so and represents an error in the model but the resulting expression for the rate of propagation of the reaction zone depends on the diffusivity and this varies less between the different materials than does K or ρc

The equation for the reaction is taken as

$$-\frac{dw}{dt} = wf e^{-E/RT} \quad (2)$$

where f is the frequency factor
 E is the activation energy
 R is the universal gas constant

Apart from the inclusion of the convection term $M c_g \frac{dT}{dx}$ which, as we shall see later, is not of major importance, these are the equations studied by Bamford Crank and Malan(8).

We now assume that the rate of propagation of the reaction zone in the x direction reaches a constant velocity ' v ' so that we replace $\frac{dw}{dt}$ by $-v \frac{dw}{dx}$. In front and behind the reaction zone the temperature and concentration gradients tend to zero. This implies that no heat is lost or gained from the exposed surface and the boundary conditions are given by

$$T = T_m \quad \text{and} \quad w = 0 \quad \text{at} \quad x = -\infty$$

$$T = T_0 \quad \text{and} \quad w = w_0 \quad \text{at} \quad x = +\infty$$

where T_m is the temperature in the layer of carbonaceous residue and w_0 is the initial concentration of reactant in the unburnt material. The possibility of a constant velocity ' v ' depends on the conditions of the problem. Thus, in the heating of a slab of finite thickness, it is not theoretically possible to attain a constant rate and Bamford, Crank & Malan(8) integrated the transient equations numerically.

We note that there are two terms in $\frac{dT}{dx}$ and the ratio of these is $\frac{M c_g}{v \rho c}$. The maximum value of M is $w_0 v$ so the ratio is less than $w_0 c_g / c \rho$. Taking c_g as 0.24, c as 0.3 and ρ as 0.4 this ratio is about 1.0 and this represents the maximum possible effect of the convection term. In fact, wood cracks when burning and the relatively large cracks may be large enough for the heat transfer between the gases and the char to be low enough for there to be little rise in temperature of the volatiles once formed. M varies with x from 0 to $w_0 v$ within the reaction zone and so its mean value is $\frac{w_0 v}{2}$ - giving a 50 per cent effect for the convection term. This may be taken as a reasonable first approximation.

Integrating equation (1) over the entire range of x, we obtain

$$T_m - T_0 = \frac{Q}{c \left(1 + \frac{\omega_0 c_g}{2pc}\right)} \quad (3)$$

Following Spalding⁽⁹⁾ we now define a number of dimensionless parameters:

$$\tau = \frac{T - T_0}{T_m - T_0} \quad (4)$$

$$\alpha = \omega / \omega_0$$

$$dy = - \frac{\rho c v}{K} \left(1 + \frac{\omega_0 c_g}{2pc}\right) d\tau \quad (5)$$

$$\lambda = \frac{K \omega_0 \bar{R}}{(T_m - T_0) \rho^2 c^2 v^2 \left(1 + \frac{\omega_0 c_g}{2pc}\right)^2} \quad (6)$$

$$\phi = \frac{Q \alpha f \rho e^{-E/RT}}{\omega_0 \bar{R}} \quad (7)$$

$$\bar{R} = \int_0^1 \frac{Q}{\omega_0} (1 - \tau) f \rho e^{-E/RT} d\tau \quad (8)$$

from which we obtain, with equation (3), equation (1) and (2) respectively in the form.

$$\frac{d^2 \tau}{dy^2} - \frac{d\tau}{dy} = -\lambda \phi \quad (9)$$

$$\frac{dk}{dy} = -\lambda \phi \quad (10)$$

and

$$\begin{aligned} x=0, \tau=1 \text{ at } y = \infty \\ x=1 \tau=0 \text{ at } y = -\infty \end{aligned}$$

From the above definitions we have the required velocity given by

$$v = \sqrt{\frac{k \bar{R} \omega_0}{\lambda \left(1 + \frac{\omega_0 c_g}{2pc}\right) \rho \phi}} \quad (11)$$

where λ has an eigen value solution⁽⁹⁾

$$\text{and } k = K/pc$$

The solution to the above differential equations and boundary conditions has been obtained using Spalding's method(9) for 'non-normal' diffusion. Spalding defines a parameter

$$\tau^* = \frac{1}{\bar{R}} \int_0^1 \tau \underline{R} d\tau \quad (12)$$

where \underline{R} is given here by

$$\underline{R} = \frac{\phi f \rho (1-\tau) e^{-E/kT}}{\omega_0} \quad (13)$$

and for values of τ^* approaching unity, the value of λ is given(10) by

$$\lambda = 0.5 (1 - \tau^*) \quad (14)$$

for the case of zero reactant diffusion.

The integrations for \bar{R} and τ^* lead to

$$\lambda = \frac{T_m}{T_m - T_0} \frac{R T_m}{E} \quad (15)$$

$$\bar{R} = \frac{E}{R} e^{-E/R T_m} \frac{T_m}{(T_m - T_0)^2} \left(\frac{R T_m}{E} \right)^2 \frac{\phi f}{\omega_0} \quad (16)$$

from which we obtain

$$v = \sqrt{\frac{R f e^{-E/R T_m}}{\frac{E}{R T_m} \frac{\phi}{c T_m}}} \quad (17)$$

where T_m is given by equation (3)

The use of the analysis by Friedman and Burke(10) gives a solution which is the same, except that $T_m - T_0$ appears instead of T_m in the term $\frac{\phi}{c T_m}$, thus making 'v' smaller by the ratio $(T_m - T_0)/T_m$. This could be due to the

slightly different form of the temperature dependent component in the kinetic law that they used. Such a factor is of little consequence in flame propagation, where T_m is of the order of 2000°K but in this application T_m is of the order 800°K, so that the effect on 'v' is about 40 per cent. In a more detailed theory, where, for example, the convection flow is dealt with exactly, such a difference cannot be neglected. However, for the purpose of this paper, which is to show the main factors controlling 'v' and to obtain approximate results, we shall neglect the difference and use Spalding's formulation. There is some uncertainty as to the appropriate values of the constants to use in equation (17), particularly with regard to ϕ and f . The product of ϕf is relatively well established because it is obtainable directly from experimental data for the rate of heat evolution at various temperatures.

We shall use a value of $3.5 \text{ cal. gm}^{-1} \text{ min}^{-1}$ * at 250°C based on data reported by Bowes(11). Gross and Robertson(12) and Akita(13) give values differing only slightly from this. The effect of assuming a lower value is discussed below. The value of Q_f defines the value of $Q_f e^{-E/RT_m}$ for T_m equal to 523°K . Bamford, Crank and Malan(8) used 0.375 for ω , 0.6 for ρ , and 86 cal/gm for $\rho Q/\omega$, but this latter estimate was derived assuming $0.55 \text{ cal. g}^{-1} \text{ }^\circ\text{C}^{-1}$ for the specific heat of wood 'c' and with the correct value of 0.33 for c Bamford Crank and Malan's values become 52 cal/gm for $\rho Q/\omega$, i.e. 32 cal/gm for Q. Estimates for Q vary widely - from less than 30 cal/gm (13) to 400 cal/gm (14), but there are reasons for thinking Bamford, Crank and Malan and Akita's values for air are too small.** The value of E, the activation energy was given by Bamford, Crank and Malan as $30,000 \text{ cal/gm mole}$. While this is not unreasonable, the combination of their value of Q_f with it gives a value of the heat output at 250°C which is about 100 times lower than the value given above.

Calculations have been made for various values of Q and E and the results are shown in Fig.(3).

It is seen that the value of E is not of great importance, but the value of Q is critical. If the value of Q is larger than 80 cal/gm , the estimate of 'v' is the same order as that found experimentally. Recently Thomas and Bowes(15) have obtained a value of about 82 cal/gm for Q for a wood fibre insulating board in air.

If a lower value is taken for the rate of heat evolution at a particular temperature, Q being assumed the same but 'f' being lower then we may reduce the values of 'v' in Fig.(5) by the square root of the ratio of the actual rate to $3.5 \text{ cal. gm}^{-1} \text{ min}^{-1}$. Again, it is clear that small differences in f are not important compared with the effect of small differences in Q.

Conclusions

An exothermic decomposition which does not require oxygen will lead to a steady rate of propagation of the reaction zone in burning wood if lateral heat losses are prevented. This is a limiting value when the burning has proceeded a long time. Its value depends on a parameter about which there is some uncertainty, but the values calculated are of the same order as those measured in experiments and fire tests if values of Q found for decomposition in air are taken, so that it is important to obtain reliable experimental values for the heat of reaction. There is evidence, discussed by Byram(14), that this heat of reaction varies with the rate of decomposition, so that the kinetics of the reaction cannot be completely represented by a first order single step reaction of the kind used in this paper so that more information is also required of the kinetics of decomposition before a satisfactory theory can be established. However, provided the reactions taken together are exothermic and independent of oxygen supply, a steady rate will occur under conditions of no heat loss and be calculable by methods or developments of the methods used for calculating laminar flame speeds.

As has been pointed out it must be remembered that the experimental values of burning rate referred to in this report do not correspond to the ideal conditions postulated in the theory though the experimental conditions may be said to tend towards them. There is therefore a need for additional experimental data and a transient theory before the agreement can be regarded as significant.

*This value is for decomposition in air and would be unsuitable if the heat release of the reaction depended on the oxygen concentration and the oxygen concentration at the reaction zone were much below its value in air.

**A value of 30 cal/gm may be too low to give a sharp self ignition temperature such as Akita himself has observed(16)

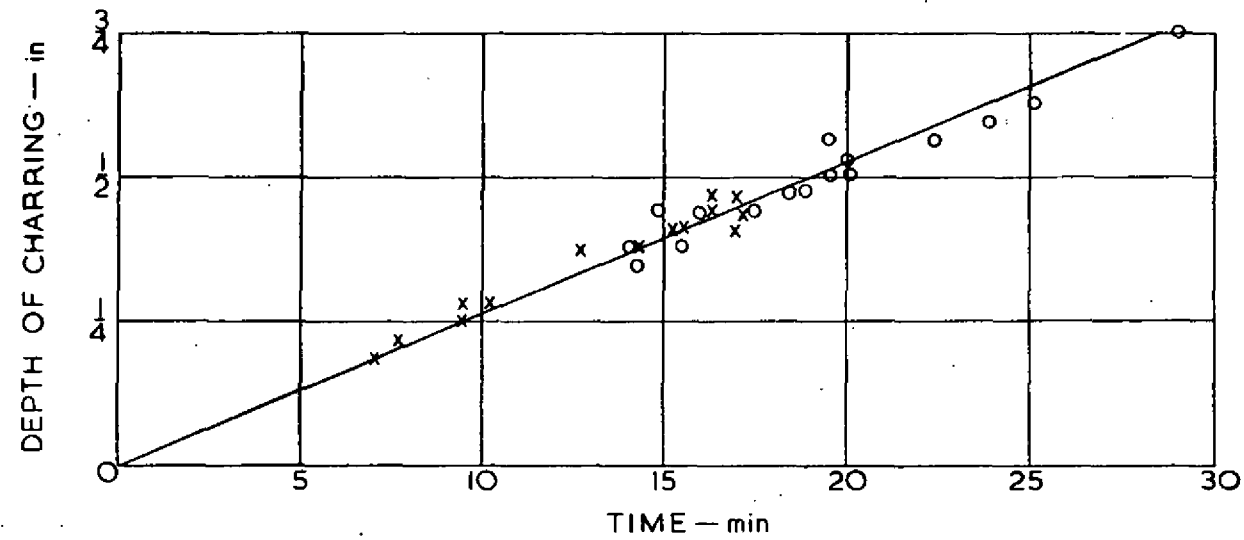
Recommendations for future work

- (1) A study of the effect of various heat transfer rate on various wood surfaces as required. e.g. The rate of loss of weight at various times when the surface is subjected to radiation should be studied.
- (2) This should be done in air and in an inert atmosphere, e.g. nitrogen. In the case of air some sampling of the oxygen concentration at the surface or in a large crack may be desirable.
- (3) Some thick samples of wood should be used so that the burning can proceed a long time before the rear surface is heated and the effect of initial conditions overcome.
- (4) The effect of preheating, which might be expected to change the subsequent exothermic heating should be studied.

References

1. FOLK, F. Experiments in fuel extinguishment. Quart. Nat. Fire Prot.Ass. 1937, 31, (2) 115.
2. BRYAN, J. Scale effects in the burning of wood. Civil Defence Research Committee Sub-Committee F, RC(F) 64. July, 1943.
3. FISCHL, C. F. The rate of combustion of timbers. Joint Fire Research Organization F.P.E. Note 76, 1951.
4. LAWSON, D. I., WEBSTER, C. T. and ASHTON, L. A. Fire Endurance of Timber Beams and Floors. Department of Scientific and Industrial Research and Fire Offices' Committee Joint Fire Research Organization National Building Studies Bulletin No.13. London, 1951. Her Majesty's Stationery Office.
5. WEBSTER, C. T. and ASHTON, L. A. Investigation on building fires, Pt.IV. Fire resistance of timber doors. Department of Scientific and Industrial Research, Building Research Station, Building Studies Technical Paper No.6, London, 1951. Her Majesty's Stationery Office.
6. WEBSTER, C. T., WRAIGHT, H. and THOMAS, P. H. The burning of fires in rooms, Part I. Joint Fire Research Organization, F. R. Note No.398/1959.
7. STAMM, A. J. Ind. Eng. Chem. 1956. 48 (3) 413.
8. BAMFORD, C. H., CRANK, J. and MALAN, D. H. The combustion of wood. Proc. Camb. Phil Soc. 1946 (42) (2) 166.
9. SPALDING, D. M. Combustion and Flame, 1957, 1 287-307.
10. FRIEDMAN, R. and BURKE, E. J. Chem. Phys. 1953, 21 (4) 710.
11. BOWES, P. C. Private Communication.
12. GROSS, D. and ROBERTSON, A. F. J. Res. Nat. Bureau of Standards 1958, 61 413.

13. AKITA, K. Bull. Fire Prevention Soc. Japan, 1956, 5 43.
14. BYRAM, G. H. Thermal properties of forest fuels. U.S. Department of Agriculture Forest Service, Division of Fire Research, Oct. 1952.
15. THOMAS, P. H. and BOWES, P. C. "Some Aspects of the Self Heating and Ignition of Solid Cellulosic Materials". (To be published).
16. TODÉS, O. M. and MELENTIEV, P. B. J. Phys. Chem. (Moscow) 1939 13 1594.



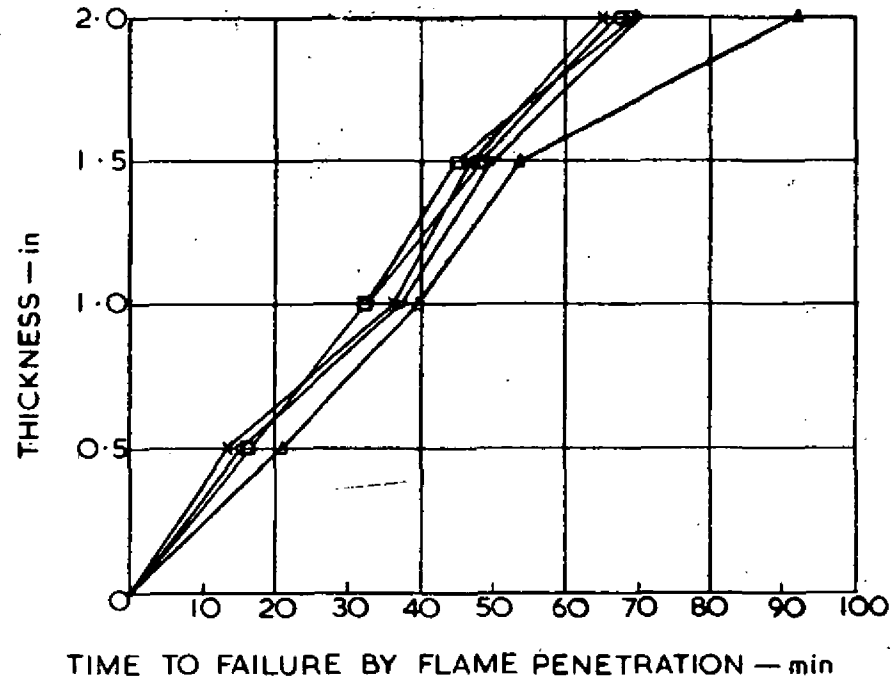
o Experimental results of Lawson et al for beams between $1\frac{3}{4}$ " and 2" thick

x Experimental results of Lawson et al for beams between $1\frac{3}{16}$ " and $1\frac{7}{16}$ " thick

Beams with a knot in the face or sloping grain are omitted

— Line calculated from Bryan's full-scale experiment

FIG. 1. EXPERIMENTAL RESULTS FOR CHARRING DEPTH



Note 2" teak panels 8" wide, remainder 9" wide

- x Soft wood (Baltic Redwood)
- o Hard wood (Gurjun)
- Impregnated soft wood
- Soft wood (Spruce)
- Δ Hard wood (Teak)

FIG.2. TIME FOR FLAME PENETRATION — B.S.476 TEST

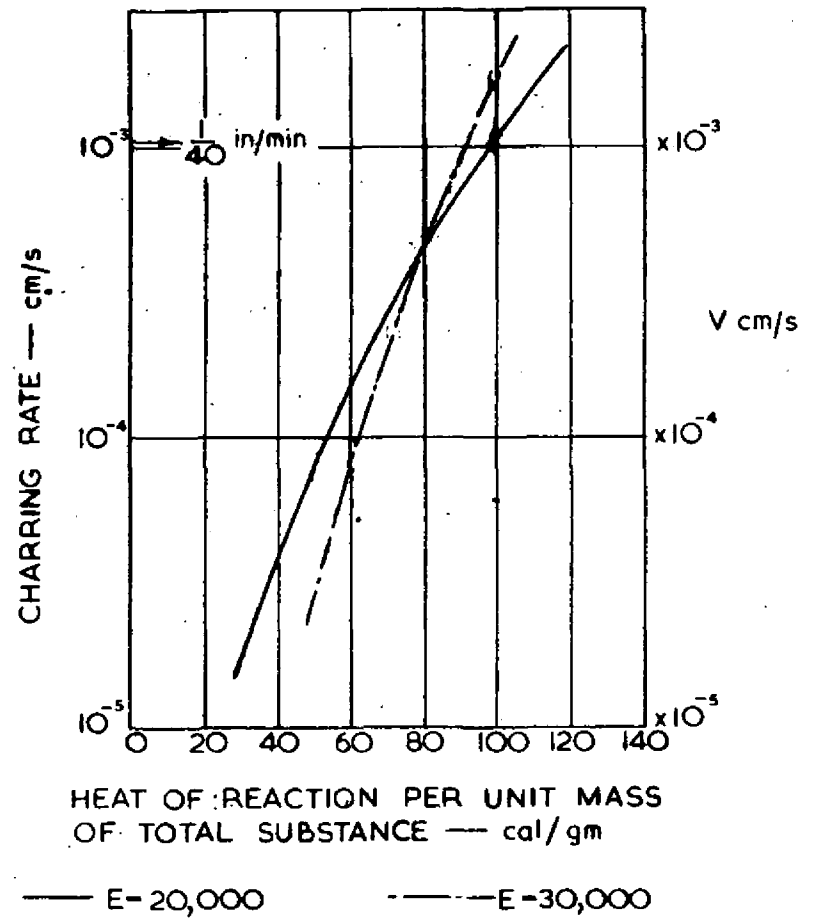


FIG.3. EFFECT OF HEAT OF REACTION AND ACTIVATION ENERGY ON CHARRING SPEED