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

THE INTERPRETATION OF SOME EXPERIMENTAL DATA ON THE IGNITION OF WOOD

by

P.H. Thomas, D.L. Simms and C.R. Theobald

SUMMARY

The results of some experiments by R.E. Prince[1] on the ignition of wood in an oven are shown to be more satisfactorily correlated by assuming that wood ignites when its surface reaches a certain fixed temperature than by assuming that ignition is primarily determined by exothermic self-heating.

September, 1959.

Fire Research Station,
Boreham Wood,
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1. Introduction

A recent report by the U.S. Department of Agriculture [2] states that its purpose is to indicate "the importance of time in the effect of heat upon wood rather than to present specific values for ignition temperatures or to recommend methods for determining such temperatures". It then goes on to state that a previous investigation by R.E. Prince [1] "demonstrated clearly that what he termed the 'ignition temperature' for wood does not have a fixed value, but is greatly influenced by the duration of exposure".

This report shows that the data are insufficient to warrant these conclusions and that a different interpretation based on a constant ignition temperature is possible; the various times measured then being the times taken to reach the constant ignition temperature in an oven at a given temperature.

In the experiments by Prince [1] oven-dry wood specimens were placed in an electrically heated oven at various elevated temperatures and the time from the moment of insertion until the specimen was ignited by a pilot flame about $\frac{1}{2}$ in. above it was measured. The specimens were 4 in. x $1\frac{1}{4}$ in. x $1\frac{1}{4}$ in. and were of various species and density. Prince's results are given in Table 1.

Table 1

Effect of temperature and time of exposure upon the ignition of wood

Temperature of exposure – $^\circ F$	Duration of exposure before ignition[1] – min.								
	Long-leaf	Red Oak	Tama-rack	Western larch	Noble fir	Eastern hemlock	Red-wood	Sitka spruce	Bass-wood
$^\circ C$									
180	14.3	20.0	29.9	30.8	–	–	28.5	40.0	–
200	11.8	13.3	14.5	25.0	–	13.3	18.5	19.6	14.5
225	8.7	8.1	9.0	17.0	15.8	7.2	10.4	8.3	9.6
250	6.0	4.7	6.0	9.5	9.3	4.0	6.0	5.3	6.0
300	2.3	1.6	2.3	3.5	2.3	2.2	1.9	2.1	1.6
350	1.4	1.2	0.8	1.5	1.2	1.2	0.8	1.0	1.2
430	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.3
Average specific gravity of specimens	0.70	0.68	0.60	0.48	0.46	0.38	0.35	0.34	0.31

[1] In general, the values shown represent the average of two tests.

2. Analysis of experimental data

The thermal balance in an opaque solid receiving heat by radiation and convection and generating heat within itself has been discussed elsewhere [3]. The rise in temperature θ at a depth 'x' below the surface at time t of the specimen in an oven is given approximately* by

$$K \frac{\partial^2 \theta}{\partial x^2} = \rho c \frac{\partial \theta}{\partial t} + q \tag{1}$$

$$q = Q \frac{\partial \omega}{\partial t} = -Q f \omega e^{-E/RT} \tag{2}$$

with the boundary condition at $x = 0$

$$K \frac{\partial \theta}{\partial x} = H(\theta_F - \theta_s) \tag{3}$$

where K is the thermal conductivity

ρ the density

and c the specific heat of the specific heat of the specimen.

q is the rate at which heat is generated chemically.

Q is the heat of reaction per unit volume.

ω is the volume concentration of reactant.

f is the frequency factor.

E the activation energy.

R the universal gas constant.

H is the heat transfer coefficient between the oven and the surface

of the wood

θ_s is the surface temperature of the specimen

θ_F is the oven temperature

T the absolute temperature in the wood.

An analytical solution of these equations is not possible, but useful approximations may be made.

Implicit in the previous discussion[1,2] of Prince's data is the assumption that the surface temperature is immediately the same as the oven temperature.

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*The specimen is assumed to be a semi-infinite solid, that is, that the temperature rise at the centre of the specimen is small and has little effect on the temperature rise of the surface.

The first of two extreme cases is that the material rapidly reaches the oven temperature and then rises above it due to exothermic reactions. The conventional theory of thermal self heating [4] [5] states that a steady state is only possible if the rate of exothermic heating is below a certain value which depends on the size of the specimen. If this value is exceeded the temperature continues to rise leading to an explosion or in this case to ignition. [6,7,8] Provided that the heating conditions are well above the threshold, the theory states that the ignition time is given by

$$t_i \propto e^{+E/RT} \qquad (4)$$

where t_i is the ignition time

Equation (4) states that log t should be linear with respect to $1/T$ and fig 1 shows that the results do, in fact, follow this law but the slope gives an activation energy of 10,000 cal/gm. mole which is between $1/3$ and $1/2$ of the usually accepted values [8,9].

The second extreme condition is where the ignition time is predominantly the time taken by the material to reach a temperature at which chemical reaction becomes very rapid i.e. there is an effective "ignition temperature". The time to reach this temperature is determined by the thermal properties of the material and the heat transfer rate between the oven and the material [10].

The temperature rise of the surface may then be obtained in analytical form as [11]

$$\theta_F / \theta_S = \left(1 - e^{\beta^2} \, erfc \, \beta \right) \qquad (5)$$

where

$$\beta = \frac{H}{K} \sqrt{kt}$$

$$k = \frac{K}{\rho c} = \text{thermal diffusivity.}$$

For the purpose of plotting experimental data, it is convenient [3, 10] to re-arrange equation (5) as

$$\frac{H \theta_F t}{\theta_s \rho c \sqrt{kt}} = \frac{\beta}{\left(1 - e^{\beta^2} erfc \, \beta \right)} \qquad (6)$$

$\dfrac{H \theta_F t}{\theta_s \rho c \sqrt{kt}}$ is equivalent to the energy modulus defined elsewhere [10]

$\dfrac{\beta}{}$ "   "   "   "   cooling   "   "   "   "

At short times, β tends to zero, and the value of

$$\frac{H \theta_F t}{\theta_s \rho c \sqrt{kt}} \quad \text{tends to} \quad \frac{\sqrt{\pi}}{2}$$

Hence from the values of $\dfrac{H \theta_F t}{\theta_s \rho c \sqrt{kt}}$ for small values of β, a first approximation to θ_s may be obtained.

The data of Table I have been expressed in terms of the energy and cooling modulus and these have been plotted in fig.2, the best fit between the experimental results and equation (6) is given by a value for θ_s of 210°C obtained by a process of trial and error. Although there is some scatter, there is little sign of any trend with density. The value of 210°C for θ_s may be taken as the "pilot ignition temperature" for the conditions of the experiment, a conclusion at variance with that of Prince [1]. However, since this temperature is slightly higher than the

minimum oven temperature, 180°C found in Prince's experiments[1], chemical
heating played some part in the ignition process but it is clear that it is
of secondary importance compared with the thermal resistance and capacity of
the specimens.

This pilot ignition temperature is applicable to the conditions of this
experiment [1]; it can only be applied with caution to other conditions where,
for example, the flame may be in a different position with respect to the wood
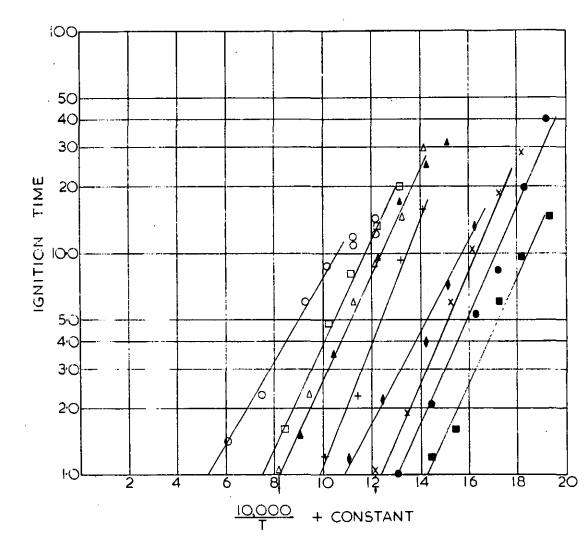surface.

3. Conclusions

An attempt to correlate Prince's data on the basis of an exothermic heat-
ing model succeeds only qualitatively as the activation energies obtained are
much lower than those found elsewhere [8,9]. The assumption that ignition
occurs when the surface reaches a certain temperature 210°C, and then produces
volatiles that can be ignited, gives a more reasonable agreement with the
experimental data, although there is some evidence that chemical heating plays
some part in the ignition process.

Thus for Prince's[1] experimental conditions, the heat transfer to the
specimens is more important than the heat generated chemically.

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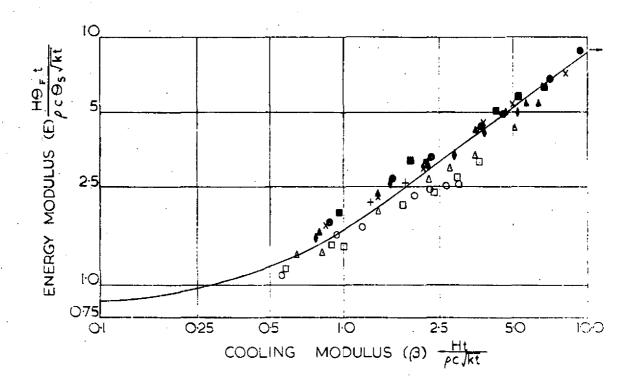   section 24, p.55.

Key :
o Long Leaf
□ Red Oak
△ Tamarack
▲ Western Larch
+ Noble Fir
♦ Eastern Hemlock
x Red Wood
● Sitka Spruce
■ Bass Wood

In this graph the horizontal scale is displaced for each set
of data so that the points and lines are not superimposed
This of course has no effect on linear slopes

FIG. I.   CORRELATION OF IGNITION TIMES
(CHEMICAL MODEL)

ENERGY MODULUS (E) $\frac{H\Theta_F t}{\rho c \Theta_s \sqrt{kt}}$

COOLING MODULUS (β) $\frac{Ht}{\rho c \sqrt{kt}}$

Key: Descending order of densities
o   Long Leaf
□   Red Oak
Δ   Tamarack
▲   Western Larch
+   Noble Fir
♦   Eastern Hemlock
x   Red Wood
●   Sitka Spruce
◻   Bass Wood

Line calculated from equation $E = \dfrac{\beta}{(1-e^{\beta^2} \, erfc\,\beta)}$

Range of exposure temperatures 180–430°C

Range of densities 0·31–0·7 — g/cm³

Range of ignition times 0·3–40 min

Correlating temperature — 210°C

FIG. 2. CORRELATION OF IGNITION TIMES
(THERMAL MODEL)