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

ON THE PILOT IGNITION OF WOOD BY RADIATION

by

D. L. Simms

Summary

Results on the pilot ignition of wood by radiation may be correlated
using simple heat transfer theory from a different effective threshold
surface temperature for each different position of the pilot flame. The
correlations are not complete because a small variation between densities
remains and the behaviour of fibre insulation board is anomalous, probably
because self-heating is significant under some experimental conditions.

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Introduction

In an earlier paper[1] an attempt was made to correlate experimental results on the pilot ignition of thick wood* by radiation and an empirical relation was derived of the form

$$(I - I_0)t^{\frac{2}{3}} = 0.025 \times 10^6 (K\rho c = 68 \times 10^{-6}) \quad \dots\dots\dots\dots(1)$$

where I is the intensity of irradiation

I_0 is the critical intensity of radiation at which ignition is theoretically just possible

t is the ignition time

K is the thermal conductivity

ρ the density

and c the specific heat of the wood

A similar empirical relation was also obtained for spontaneous ignition[1]. It has since proved possible to correlate the results for spontaneous ignition in terms of a simple heat transfer theory[2] which leads to

$$\frac{It}{\rho c \sqrt{Kt}\,\theta_F} = \frac{Ht}{\rho c \sqrt{Kt}} (1 - e^{\beta^2} \operatorname{erfc}\beta) \quad \dots\dots\dots\dots(2)$$

where θ_F is the surface temperature at ignition

H the corresponding Newtonian cooling coefficient

$k = \dfrac{K}{\rho c}$, the thermal diffusivity

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

and $\operatorname{erfc}\beta = \dfrac{2}{\sqrt{\pi}}\displaystyle\int_{\beta}^{\infty} e^{-z^2}\,dz$

To obtain this correlation the irradiated material was assumed to be opaque, totally absorbing and inert; it was assumed to ignite when the surface reached a fixed temperature, there being no significant temperature rise of the rear surface. A correction to the experimental results was applied to allow for the effect of the finite size of the specimens irradiated.**

Pilot ignition occurs when a flammable mixture of volatiles and air reaches the pilot flame. The ignition time has been found[3] to depend on the position

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*A thick wood is one in which there is no significant temperature rise of the rear

**The size of the irradiated area affects the ignition time: the smaller the area irradiated and the lower the intensity of irradiation, the longer the specimen takes to ignite. Values of the correction required for spontaneous ignition are available[5] but none for pilot ignition have been published. What information there is, suggests that the effect is smaller than for spontaneous ignition.

of the pilot flame, so there must be variations in concentration within the volatile stream. The value of the surface temperature at ignition, θ_F, in a correlation of the type given by equation (2) will therefore vary with the position of the pilot flame.

Experimental results

Two series (1) and (2) of experimental results are available. In series (1) three woods (3) were subjected to a range of levels of radiation from 0.025 - 1.5 cal $cm^{-2}s^{-1}$, from a gas fired radiant panel in the presence of a burning gas flame of length 1.25 cm, placed 0.62 cm, 1.25 cm, and 1.9 cm in front of the surface of the specimen, with the tip of the flame level with the surface (fig 1a), and the ignition times noted. The properties of the materials used in this series of experiments are given in table 1.

TABLE 1

Thermal properties of woods tested in series (1)

Wood	K cal $cm^{-2}s^{-1}$ deg C^{-1} $\times 10^5$	ρ g/cm^3	c cal gm^{-1} deg C^{-1}
Fibre insulation board	8.8	0.25	0.34
Columbian Pine (Taxifolia pseudosuga)	30	0.5	0.34
Oak (Quercus spp)	40	0.7	0.34

In series (2) a number of woods ranging in density from 0.25 to 0.7 g/cm^3 were ignited in a similar way by radiation in the presence of a similar pilot flame but placed 1.25 cm above, and in front of, the specimen surface (fig. 1b). The thermal properties of the woods tested are given in table 2.

TABLE 2

Thermal properties of woods tested in series (2)

Wood	K cal $cm^{-2}s^{-1}$ deg C^{-1} $\times 10^5$	ρ g/cm^3	c cal gm^{-1} deg C^{-1}
Fibre insulating board	8.5	0.24	0.34
Western red cedar (Thuja plicata)	21	0.36	0.34
American whitewood (Liriodendron tulipifera)	28	0.47	0.34
African mahogany (Khaya ivorensis)	32	0.56	0.34
Freijo (Cordia goeldiana)	33	0.58	0.34
Oak (Quercus robur)	35	0.61	0.34
Irok (Chlorophora excelsa)	41	0.72	0.34

All specimens were 1.9 cm thick*, except for the fibre insulation board which was 1.25 cm thick and were cut 5 cm square, so that the faces were parallel with the grain. They were dried for 24 hours in an oven at 95°C and, after drying, they were allowed to cool over phosphorous pentoxide. The densities were obtained from the volumes and weights when oven-dry. These samples were all in the natural state (unblackened) but the reflectivity of their surface for infra-red radiation is low, and although wood is partly diathermanous the effect of this is undoubtedly small in present conditions[4], so that the surfaces may be assumed to have an absorptivity of unity without introducing a significant error.

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*There is no significant temperature rise of the rear surface under the conditions of these experiments[2] ($h\ell \sim 10$).

Correlation of Data

The results for any one position of the pilot flame have been correlated in terms of the dimensionless groups of equation (2). When the cooling modulus $\frac{Ht}{\rho c \sqrt{kt}}$ tends to zero, equation (2) becomes

$$\frac{It}{\rho c \sqrt{kt}\,\theta_F} \rightarrow \frac{\sqrt{\pi}}{2} \qquad\qquad \cdots\cdots\cdots\cdots (3)$$

Hence from values of the energy modulus, $\frac{It}{\rho c \sqrt{kt}\,\theta_F}$, for small values of the cooling modulus, a first approximation to θ_F may be obtained and an appropriate value chosen for that temperature range for the Newtonian cooling constant, H. The value of θ_F is then adjusted to give the best fit between the experimental points and equation (2).

The results for series 1 for the different positions of the pilot flame are shown in Figs (2-4), and tend to follow a similar pattern. The values of θ_F giving the best fit are 300°C for the pilot flame at 0.62 cm, 380°C at 1.25 cm and 410°C for the 1.9 cm. The results for oak tend to lie below the theoretical curve, those for columbian pine appear above the curve, whilst those for fibre insulating board tend to be above the line for low values of the cooling modulus and below it for high values. The combined results are plotted in Fig.5 where the same pattern is repeated, but the effect of the different positions of the pilot flame has been eliminated by using the best fitting values of surface temperature corresponding to each position of the flame in the energy modulus.

The results for series 2 for a wide range of densities are correlated in Fig.6 with a surface temperature of 340°C. The effect of density has not been entirely eliminated as the less dense woods tend to be above and the denser below the theoretical curve. This may be because the rate of production of volatiles is not a unique function of the temperature but depends on a number of other physical and chemical constants including the density itself. No similar effect was found with spontaneous ignition[3]. The surface temperature at ignition is then higher, about 525°C, the rate of production of volatiles is much higher and therefore less critically important. For pilot ignition, the behaviour of fibre insulating board is anomalous. At the lower intensities (high values of $\frac{Ht}{\rho c \sqrt{kt}}$) the results leave the curve completely and the material continues to ignite at intensities of irradiation well below the critical intensity of the woods[1] (0.35 cal cm^{-2} s^{-1}) and ignition has resulted at intensities of radiation below 0.1 cal cm^{-2} s^{-1}. This suggests that at the higher rates of heating the production of volatiles occurs at roughly the same rates as for wood but that at lower rates there may be significant self-heating[6,7]. In some previous experiments[8] when fibre insulating board was irradiated at an intensity of about 0.35 cal cm^{-2} s^{-1} significant quantities of heat were liberated.

Critical intensity for pilot ignition

The critical intensity of irradiation at which ignition is theoretically just possible is, in effect the rate at which heat is lost from the surface at the temperature calculated[1], i.e.

$$I_o = H\,\theta_F \qquad\qquad \cdots\cdots\cdots\cdots (4)$$

Because this temperature has been found to increase with increasing distance of the pilot flame from the surface it would be expected that the critical intensity, I_o, would also increase, but the method developed earlier[1], viz, of plotting I against $1/\sqrt{t}$ and extrapolating to the abscissa, t is equal to zero, does not appear to be sufficiently sensitive to detect these differences[3].

From the effective temperatures calculated the critical intensity might be expected to vary from about 0.25, to 0.33 cal cm^{-2} s^{-1} for the different positions, being about the same for the different species.

The minimum intensity at which ignition occurs is higher than the critical intensity: this is because the estimate of critical intensity neglects the fact that the supply of volatiles is limited. Any factor tending to prolong the period between the surface reaching the temperature at which volatiles are emitted and the surface reaching that at which ignition takes place, tends to increase the possibility of the volatile supply being exhausted and may increase the minimum intensity required for ignition. Such factors include the size of area irradiated, the moisture content and the density. The minimum intensity for spontaneous ignition may be shown[2] to vary with the first two, but insufficient experimental evidence was available for examining the effect of density on the exhaustion of the volatiles. In the present experiments[1], the increase in minimum intensity for pilot ignition with density - excluding fibre insulating board - is significant, and is shown in Fig.7 for the woods given in Table 2 with the pilot flames as in Fig.1b.

Discussion and conclusions

It is possible to correlate results for the ignition by radiation of different woods at various positions of the pilot flame in terms of simple heat transfer theory. There is, however, some residual variation in the results for different density and the behaviour of fibre insulating board is anomalous. At the higher intensities of radiation (0.4 cal cm^{-2} s^{-1}), its behaviour is not dissimilar from the other woods, but at lower intensities, it ignites sooner than would be expected from the correlation and it continues to ignite at intensities of radiation well below the critical intensities of the other woods, which appear to be independent of species but dependent upon the position of pilot flame. A possible reason for the anomalous behaviour of fibre insulation board is that there is significant self-heating.

The critical intensities for the ignition of these seven woods (excluding fibre insulating board) have an average value close to 0.3 cal cm^{-2} s^{-1}. This value has been used as the maximum permissible radiation level for buildings exposed to fire.

References

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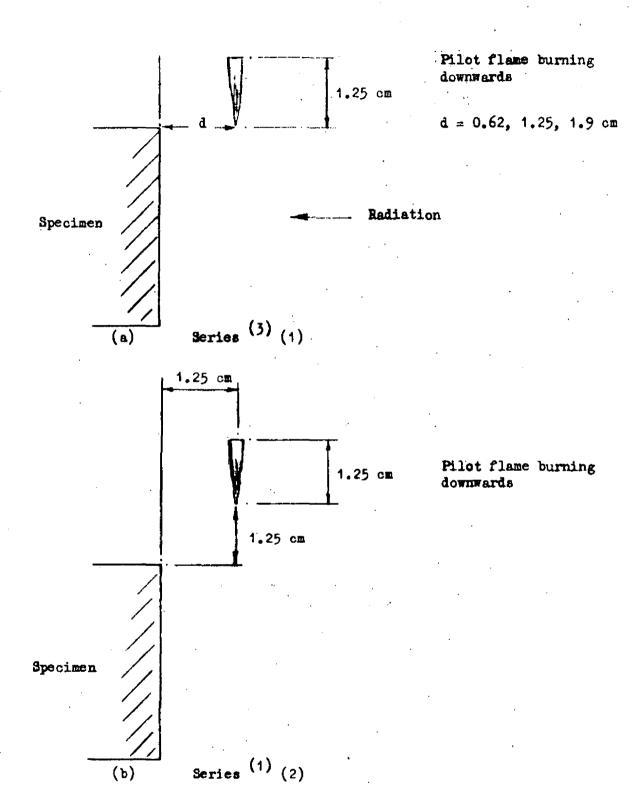
Pilot flame burning
downwards
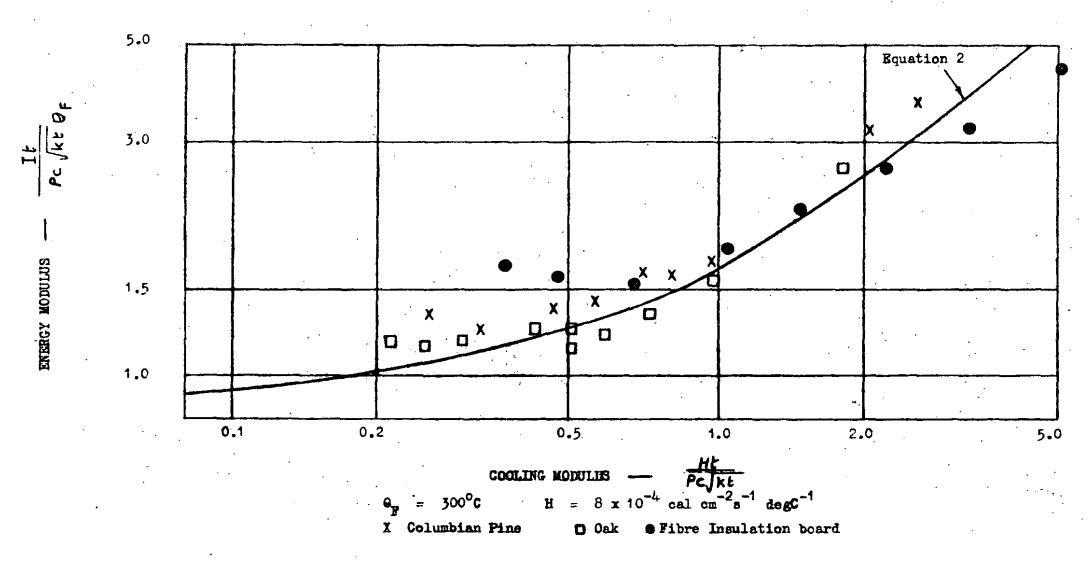
d = 0.62, 1.25, 1.9 cm

1.25 cm

d

◄------- Radiation

Specimen

(a)   Series (3) (1)

1.25 cm

1.25 cm

1.25 cm

Pilot flame burning
downwards

Specimen

(b)   Series (1) (2)

FIG. 1.   POSITION OF PILOT FLAME

FIG. 2. PILOT FLAME 0.62 cm FROM SURFACE
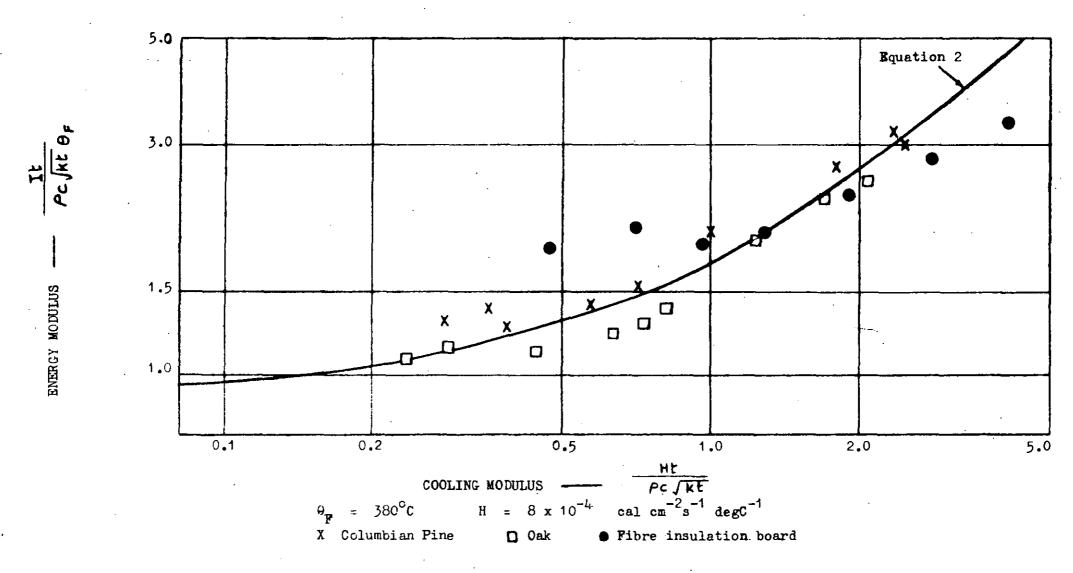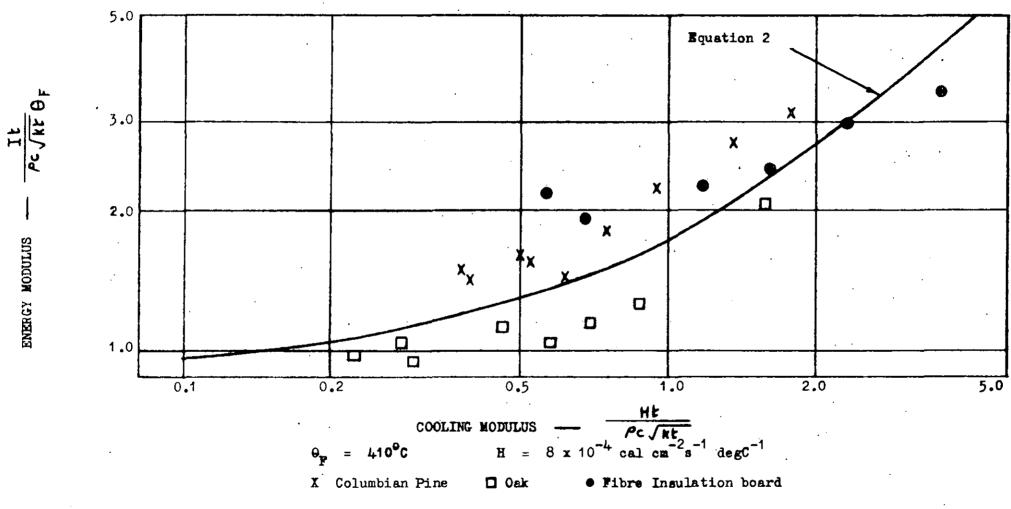
FIG. 3.   PILOT FLAME 1.25 cm FROM SURFACE

$$\text{ENERGY MODULUS} \quad \longleftarrow \quad \frac{It}{\rho c \sqrt{\kappa t}\,\theta_F}$$

$$\text{COOLING MODULUS} \quad \longleftarrow \quad \frac{Ht}{\rho c \sqrt{\kappa t}}$$

$\theta_F = 410°C$ $H = 8 \times 10^{-4} \text{ cal cm}^{-2}\text{s}^{-1} \text{ degC}^{-1}$

X Columbian Pine   □ Oak   ● Fibre Insulation board

FIG. 4.   PILOT FLAME 1.9 cm FROM SURFACE
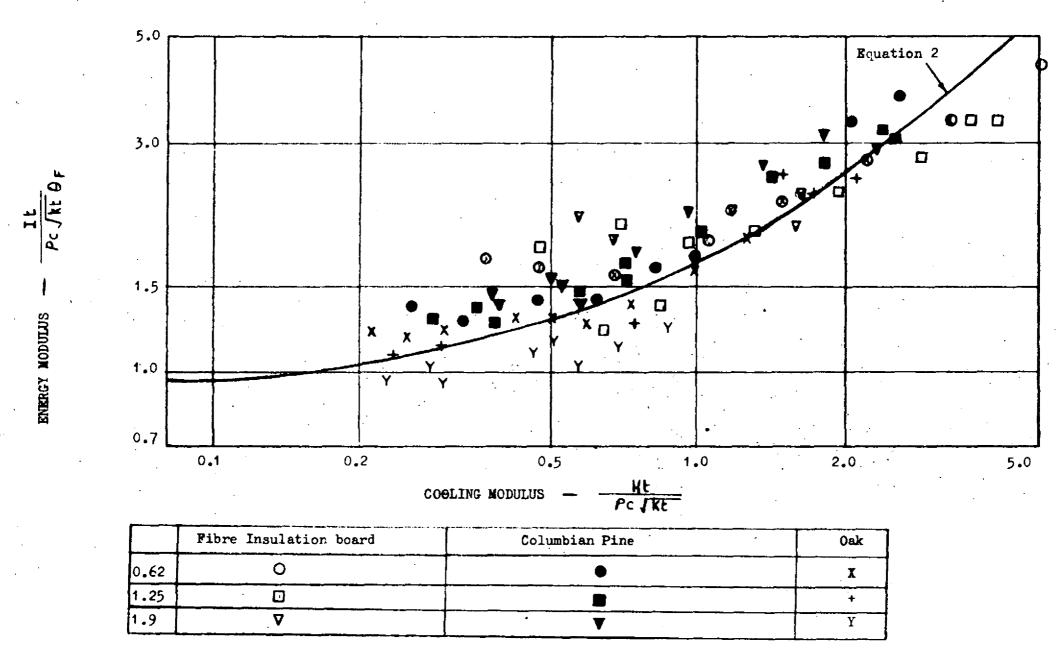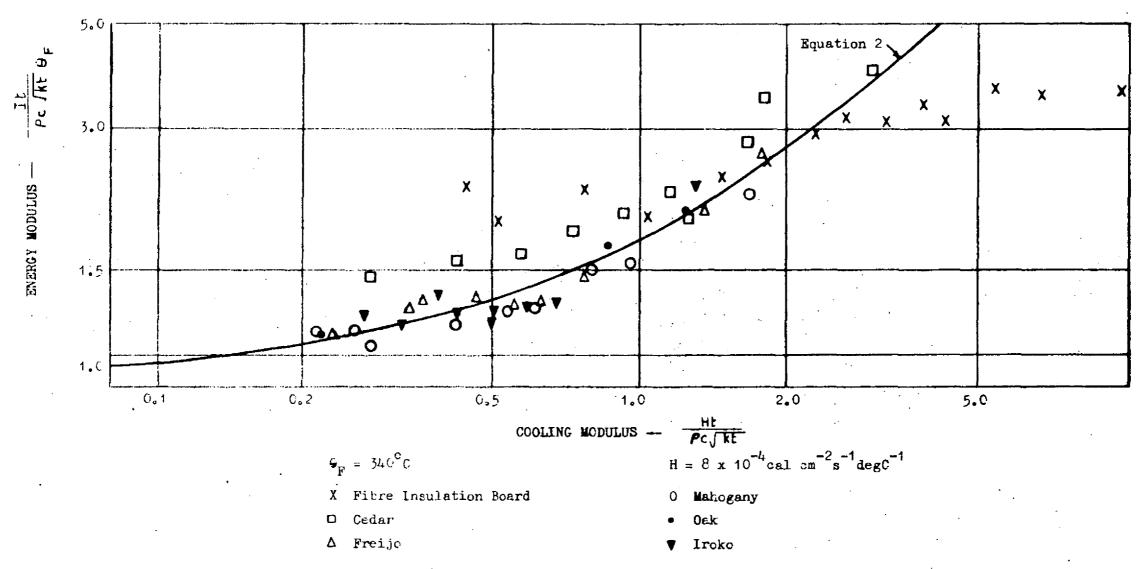
FIG. 5. CORRELATION OF RESULTS FOR DIFFERENT POSITIONS
OF PILOT FLAME

$\theta_F = 340^\circ C$

$H = 8 \times 10^{-4} cal\ cm^{-2} s^{-1} degC^{-1}$

X   Fibre Insulation Board

O   Mahogany

□   Cedar

●   Oak

△   Freijo

▼   Iroko

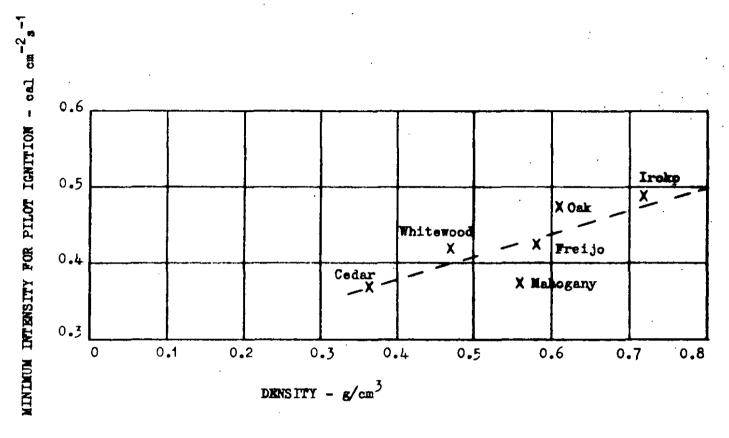FIG. 6.   CORRELATION OF RESULTS FOR DIFFERENT DENSITIES

FIG. 7. VARIATION OF MINIMUM INTENSITY FOR
PILOT IGNITION WITH DENSITY
(PILOT FLAME AS IN FIG. 1A)