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JOINT FIRE RESEARCH ORGANIZATION

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ON THE POSSIBILITY OF IGNITION OF MATERIALS BY RADIATION FROM NUCLEAR EXPLOSIONS

by

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SUMMARY

Threshold energies for the ignition of cellulosic materials by various sizes of nuclear weapons have been calculated assuming that the materials are inert and ignite at a fixed temperature. For thermally thick materials ignition occurs when the surface reaches 525°C, for thermally thin materials ignition occurs when the mean temperature reaches 525°C. There is reasonably close agreement between the experimental results and the calculated values. Means for allowing for the effect of different colours are given.

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1. Introduction

It has been shown elsewhere that the assumptions that ignition$^{(1-2)}$ or charring$^{(2)}$ occur at a certain temperature and that the material is effectively inert can be employed to correlate the radiant energies required to produce ignition or charring with the physical properties of materials. This is not necessarily the case, however, at very short ignition times ($\ll 1$s).

In some applications of these experimental results it is more important to correlate the data for conditions at which ignition just occurs, that is, the threshold conditions. When the radiation is constant in time, the threshold condition is given by a constant or critical intensity, but for a pulse varying with time$^{(3)}$ the threshold conditions for a given shape of pulse are a function of two parameters, the peak intensity and the pulse duration. Correlations have been obtained of laboratory results for several materials and these can be used to find the energies from nuclear explosions which just ignite cellulosic materials.

2. Basis of correlation

2.1. Thin materials

Thin materials are defined elsewhere$^{(1)}$ as materials in which there is a linear temperature gradient; the same material can be thermally thin or thick according to the duration of heating. For materials defined in this way as thin, ignition has been found to be sustained once it occurs.

The theoretical correlation for thin homogeneous materials which are effectively inert is of the form$^{(2)(4)}$

$$\frac{aE}{\theta_m \rho c l} = F_1 \left\{ \frac{H t_p}{\rho c l} \right\} \qquad \text{.........} \; (1)$$

where E is the minimum pulse energy to produce ignition

θ_m is the mean temperature of the material at which ignition occurs

ρ is the density
c the specific heat
$2l$ the thickness of the material
t_p is the time at which the intensity reaches its second maximum I_p
H is the surface cooling coefficient
and a is the effective absorptivity of the surface

2.2. Thick materials

Thick materials are defined(1) as materials in which there is no significant temperature rise of the rear surface. The theoretical correlation for thick materials is of the form(4)

$$\frac{aE}{\theta_F \rho c \sqrt{k t_p}} = F_2 \left(\frac{H^2 t_p}{K \rho c} \right) \qquad \text{.........} \; (2)$$

where $k = \frac{K}{\rho c}$

K is the thermal conductivity

and θ_F is the front surface temperature

2.3. Form of impulse radiation function

The form of the radiation impulse is taken as

$$I(t) = I_p \; f\,(^t/t_p) \qquad \text{.........} \; (3)$$

A function applicable to explosions of different sizes is(4)

$$I(t) = e^2 I_p (^t/t_p)^2 e^{-2t}/t_p \qquad \text{.........} \; (4)$$

and it follows from this that E is given by

$$E = \int I(t)dt = e^2/_4 \; I_p \, t_p \qquad \text{.........} \; (5)$$

With this impulse function it may be shown analytically that for thin materials equation (1) takes the form shown in Figure 1; the form of equation (2) (for thick materials) can also be computed and is shown in Figure 2.

3. Correlation of data

The experimental results consist of values of E for various values of t_p and these are plotted in Figures 1 and 2 as the dimensionless variables given by equation (1) for thin materials and equation (2) for thick materials and compared with the solution calculated with 525°C for θ_m and θ_F.

The results are for materials with black surfaces and the effective absorptivity is assumed to be unity. The calculated solution is below the experimental curve for thin materials by a factor of 30 per cent for bombs in the kT range and by less than 15 per cent for those in the megaton range. For thick solids the theoretical curve is less than 15 per cent below the experimental line.

Because the area irradiated in the laboratory is small, the energy required for ignition is greater than for a large area(1); a correction for this would bring the results closer to the theoretical lines. Unfortunately, the data available, although showing the effect is greatest near the threshold condition do not permit any estimate of its magnitude. The theoretical lines may therefore represent the conditions for large areas better than the data suggest.

4. Application of results

In the absence of field data, therefore, it is assumed that the minimum energy necessary to ignite cellulosic materials from nuclear explosions of any size greater than 20KT may be calculated for thin materials from Figure 1 and for thick materials from Figure 2, using the theoretical lines.

4a. Thin materials

For values of $\frac{Ht_p}{\rho cl}$ between 0.2 and 2.0 the equation of the theoretical line in Figure 1 is given by

$$E = 1.16 \times 10^3 \rho cl + 2.46\, t_p \qquad \text{..........} \tag{6}$$

assuming $H = 1.4 \times 10^{-3}$ cal cm^{-2}s^{-1} deg C^{-1}

and $\theta_m = 525^\circ C$

Since $t_p = 0.032\sqrt{W}^{(3)}$ .... (7)

where W = yield in kilotons

equation (6) may be written as

$$E = 0.20\, m + 0.08\sqrt{W} \qquad \text{..........} \tag{8}$$

where $m = 2\rho l$ = mass per unit area-mg/cm^2

and $c = 0.34$ cal g^{-1}degC^{-1}

Equation 8 is plotted in Figure 3 for different values of m. Outside the experimental limits the lines are shown dotted. For a paper of density 0.5 g/cm^3 and thickness 0.020 cm (the paper used in the experiments) m would have the value 10 mg/cm^2 (3 oz/yd^2). For large values of W, equation (8) reduces to

$$E = 0.08\sqrt{W} \qquad \text{..........} \tag{9}$$

Equation (9) can be derived directly as follows

The cooling loss from a vertical surface at 525°C may be taken as 0.72 cal cm^{-2}s^{-1} and for long exposure times threshold ignition of thin materials can be predicted by assuming that the peak intensity is just sufficient to balance the heat loss from front and rear surfaces at 525°C

$$\text{i.e. } I_p = 1.44 \text{ cal cm}^{-2}\text{s}^{-1} \qquad \text{..........} \tag{10}$$

Combining equation (10) with equations (5) and (7) then gives equation (9).

Equation (9) does not involve the thermal properties of the material and can be used for any thin material with an ignition temperature of 525°C. It gives the energy for ignition of an infinitely thin material and is an asymptote to the curves for materials of finite thickness. Equation (9) is also shown in Figure 3.

4b. Thick materials

For values of $\frac{t_p}{K\rho c}$ between 10^4 and 3.3×10^5 the equation of the theoretical line for thick woods in Figure 2, is given approximately by

$$\frac{E}{K\rho c} = 350 \left(\frac{t_p}{K\rho c}\right)^{0.62} \qquad \text{..........} \tag{11}$$

Substituting for t_p as before gives

$$E = 42\, W^{0.31} (K\rho c)^{0.38} \qquad \text{..........} \tag{12}$$

Equation (12) is plotted in Figure 4 for three types of wood. Where the lines extend outside the range of the experiments they are shown dotted.

4c. Effect of colour

Correlations similar to the one shown in Figure 1 have been obtained for white, yellow and green paper. For light colours higher values of threshold energy are needed for ignition; the extra energy needed depends on the exposure time since the surface darkens in colour prior to ignition thus reducing the effect of the initial colour. For very large bombs, therefore, the threshold ignition energy may be considered independent of colour.

By drawing smooth curves through the experimental results for the coloured papers it has been possible to compare the ignition energy E_c for coloured paper with the ignition energy E for black paper. The factor $\frac{E_o}{E}$ found in this way is shown in Figure 5 in terms of yield of the bomb and mass per unit area of paper. Thus the value of E_c for a coloured paper may be found by taking the value of E for black paper from Figure 3 and multiplying it by the factor $\frac{E_o}{E}$ given in Figure 5. For $\frac{W}{m^2}$ greater than 500 kiloton $mg^{-2}cm^4$ (5,000 kiloton $oz^{-2}yd^4$) the effect of colour is not significant.

The effects of colour, mass per unit area and size of bomb are illustrated in Table 1.

Table 1

Threshold energy for ignition of materials

MATERIAL			ENERGY - cal/cm^2		
Paper	Mass/unit area		Yield of bomb		
	mg/cm^2	oz/yd^2	100 MTon	50 MTon	10 MTon
Black	5	1.5	27	19	9
	20	6.0	29	22	16
White	5	1.5	27	19	9
	20	6.0	35	34	26
Wood (Black)	Density g/cm^3				
Oak	0.66		40	33	20
Cedar	0.37		27	22	13
Fibre Insulating Board	0.24		20	16	10

The increase in threshold energy for ignition with larger bombs is due to two reasons.

(i) for longer times of irradiation cooling is more important

(ii) as the pulse duration increases ignition occurs relatively earlier so that the "useful" portion of the pulse decreases.

For very short irradiation times some materials which are physically thin are not thermally thin as defined earlier and these may not continue to burn once ignited; the thermally thin materials will certainly continue to burn and the flame will spread to unburnt material.

The presence of moisture increases the energy required to ignite the material and raises the threshold level for ignition. For the present purpose, the energy required to ignite a specimen of a given moisture content may be calculated from the energy required to ignite the equivalent dry specimen added to the energy required to evaporate the moisture(5)(6).

The method should have general application to any kind of thermal damage for which a fixed temperature criterion may be used.

References

1. SIMMS, D. L. Ignition of cellulosic solids by radiation. Combustion and Flame, 1960, 4, (4) 293-300.

2. SIMMS, D. L. Damage to cellulosic materials by thermal radiation Combustion and Flame, 1962, 6, (4) 303-18.

3. GLASSTONE, S. (Ed.). The effects of nuclear weapons. United States Department of Defense and United States Atomic Energy Commission 1957. United States Government Printing Office, Washington, 25.

4. THOMAS, P. H., SIMMS, D. L. and LAW, Margaret. On the correlation of the threshold for ignition by radiation with the physical properties of materials. Joint Fire Research Organization F.R. Note No. 381/1958.

5. THOMAS, P. H., SIMMS, D. L. and LAW, Margaret. The effect of moisture content on the spontaneous ignition of wood by radiation. Joint Fire Research Organization F.R. Note No. 280/1955.

6. PICKARD, R. W. and WRAIGHT, H. The effect of moisture on the ignition and flame propagation of thin cellulosic materials. Joint Fire Research Organization F.R. Note No. 450/1961.

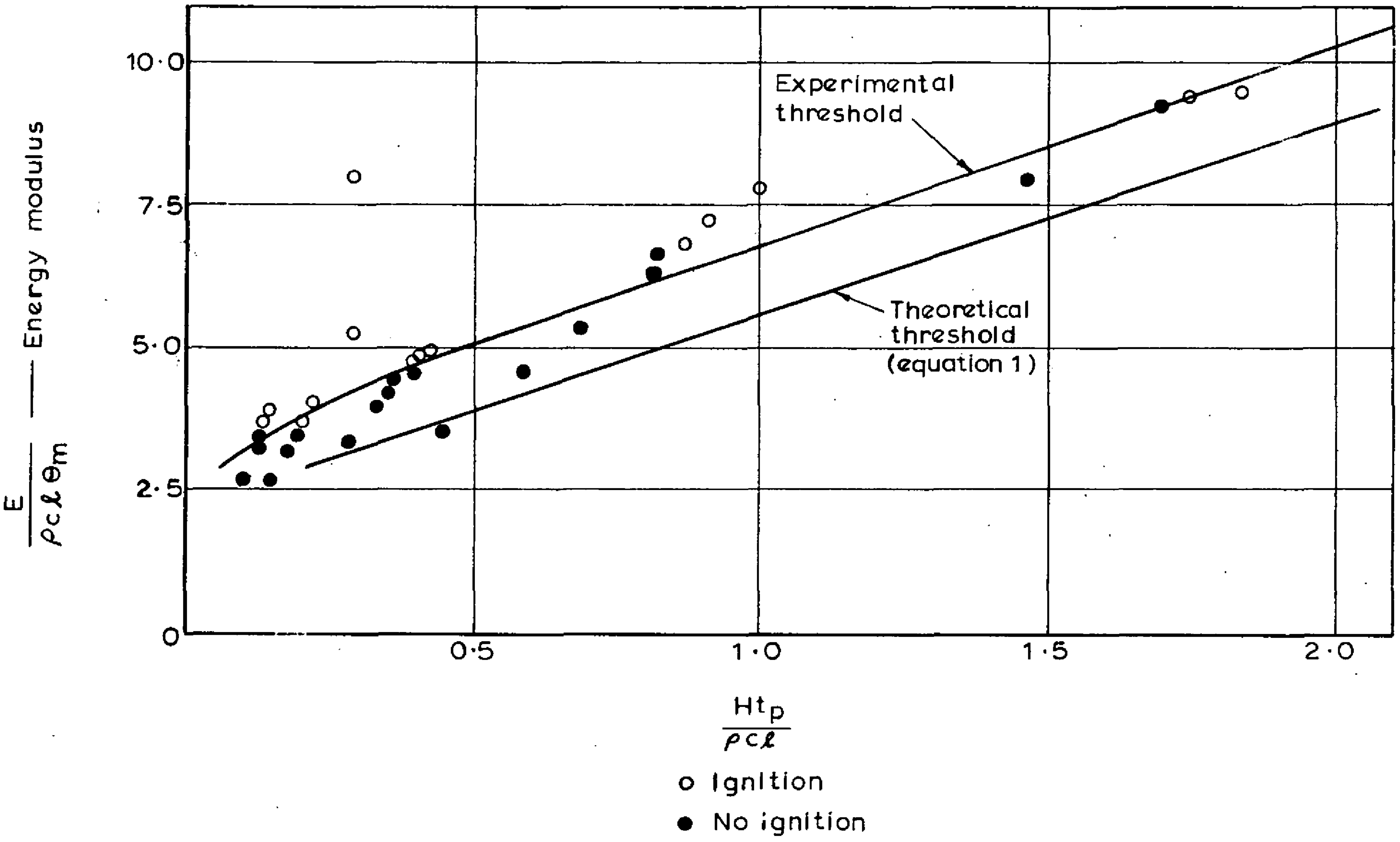

FIG.1. THRESHOLD ENERGY IN PULSE FOR IGNITION OF THIN MATERIALS (CELLULOSE)

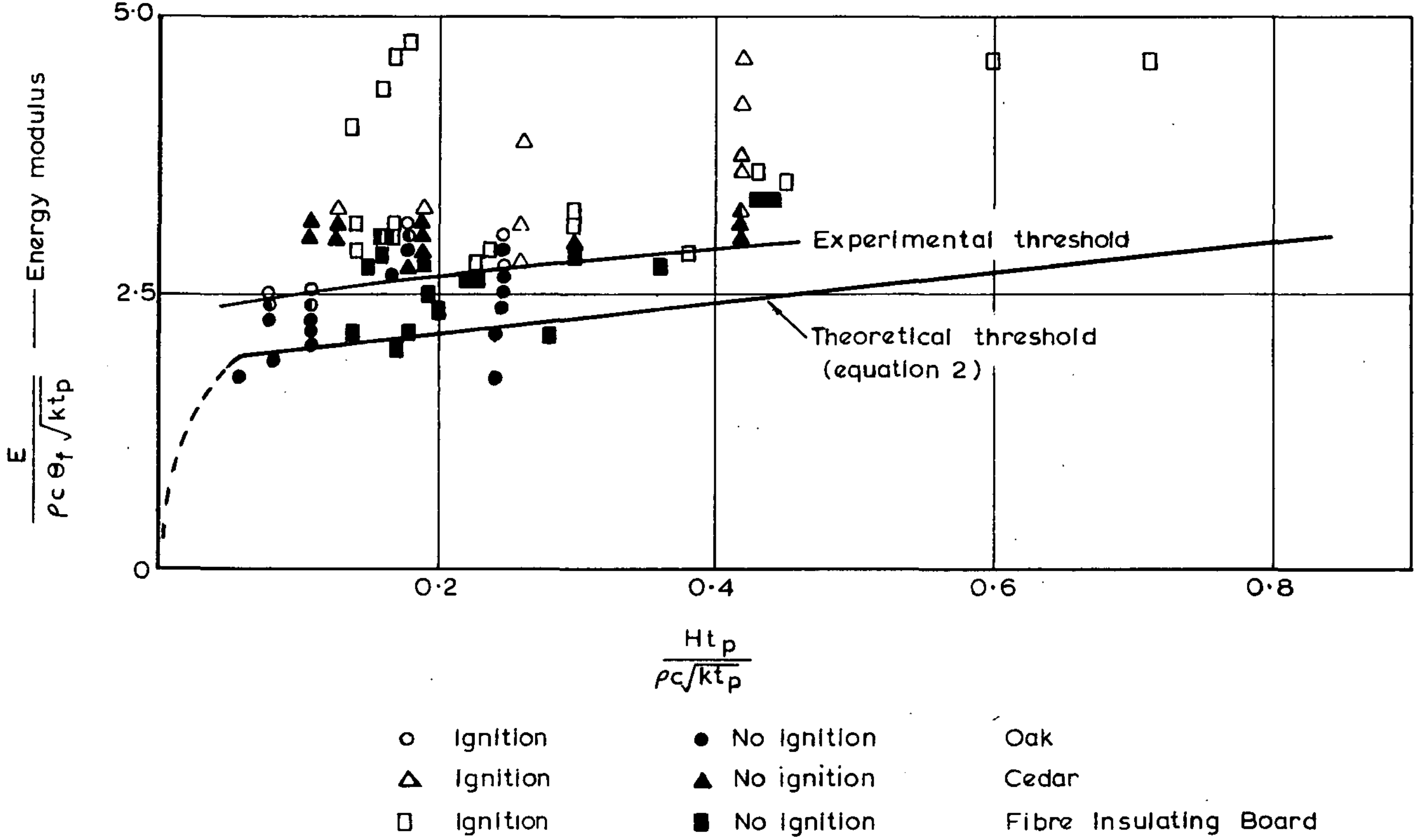

FIG. 2. THRESHOLD ENERGY IN PULSE FOR IGNITION OF THICK MATERIALS (CELLULOSE)

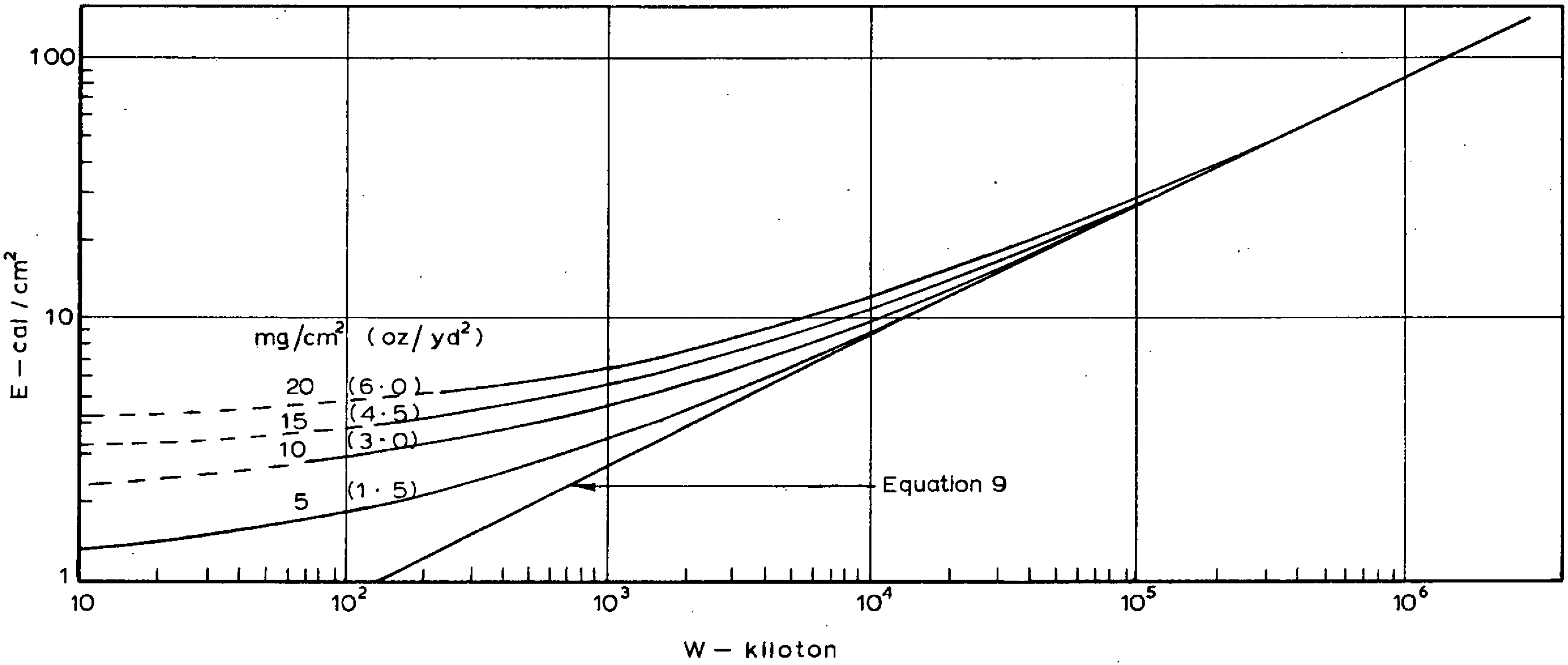

FIG.3. THE IGNITION THRESHOLD OF THIN PAPERS

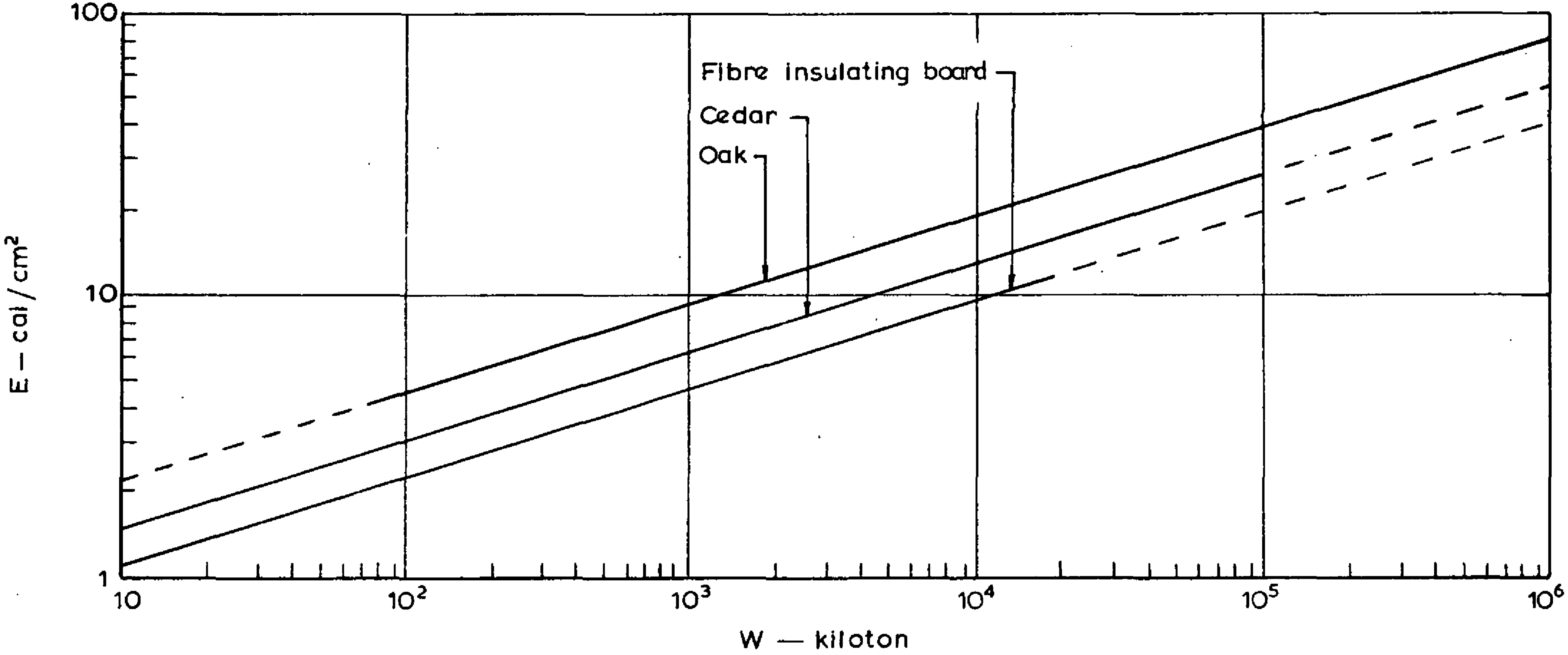

FIG.4. THE IGNITION THRESHOLD OF THICK WOODS

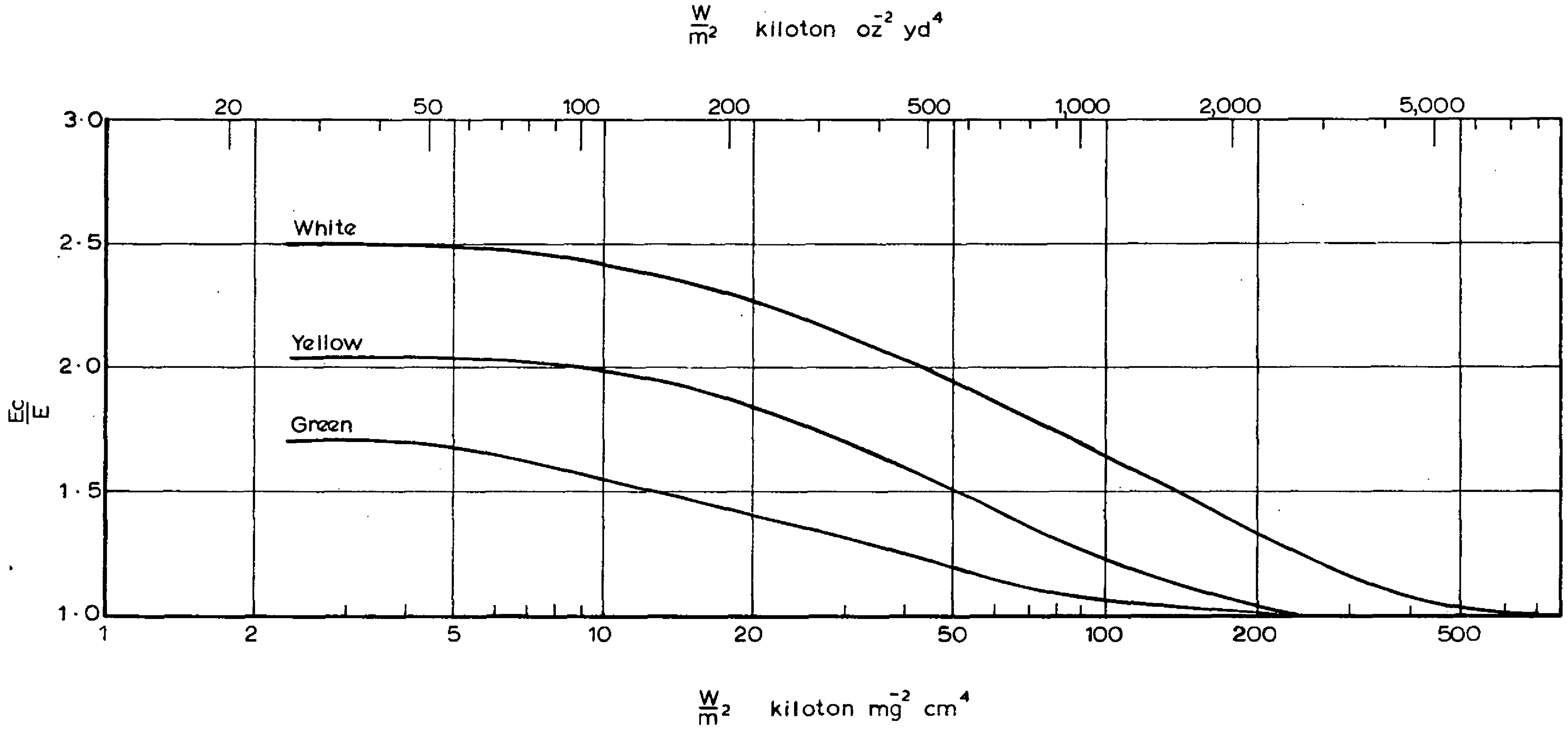

FIG.5. THE EFFECT OF COLOUR ON IGNITION THRESHOLD OF THIN MATERIALS