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ON THE SPONTANEOUS IGNITION OF CELLULOSIC MATERIALS BY RADIATION

by

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SUMMARY

The work of the Fire Research Station on the ignition of materials by radiation is summarised. A range of intensities of radiation has been obtained from three different sources and methods of measuring and detecting these intensities have been developed. Three types of ignition have been studied; spontaneous ignition where the flame appears without an external source, pilot ignition where ignition starts about a small flame in the volatile stream, and surface ignition where the pilot flame is on the surface of the irradiated material. A number of factors which affect the onset and occurrence of ignition have been examined; two of particular importance are the size of the area irradiated and the absorptivity of the surface. Dimensional analysis of the thermal balance of the irradiated solid has been used to derive dimensionless groups in which to correlate experimental results. In this way, the empirical use of fixed temperature criteria in the solid has been shown to be adequate for correlating ignition times on cellulosic materials over a wide range of experimental conditions, e.g. intensities of radiation, densities and moisture contents with a different temperature for each type of ignition. In particular, spontaneous transient ignition of thermally thick solids occurs at a fixed <u>surface</u> temperature of about 500°C and the spontaneous sustained ignition of thermally thin solids occurs at a fixed <u>mean</u> temperature also of about 500°C. The method has been extended to a pulse of radiation varying with time, and good agreement has been obtained between the calculated threshold energies for ignition by these pulses and those determined experimentally. From these correlations, the threshold energies for ignition of both thermally thick and thin materials for a range of nuclear explosions have been derived. Correction factors to allow for the effect of different colours are also given.

Correlations based on a fixed temperature criterion break down at low rates of heating, probably because of the limited supply of volatiles and at very high rates of heating probably because the time taken to form a flammable mixture is comparable with the heating time.

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1. Introduction

Radiation is the most important means of heat transfer in fully developed fires in compartments, in forest fires spreading in still air and is potentially one of the great dangers from nuclear explosions.

The ignition of cellulosic materials by radiation has therefore been studied at the Fire Research Station for a number of years(1-9). A number of different kinds of thermal damage have been identified, as well as a number of different factors which affect the onset and occurrence of all or some of them. It is the purpose of the present paper to summarise the experimental methods used, the principal results obtained for spontaneous ignition and the theoretical approach adopted, and to relate them to the problem of predicting the threshold energies at which ignition will occur from nuclear explosions.

2. Experimental Methods

2.1 Apparatus

Three sources of radiation have been used at the Fire Research Station: a gas-fired radiant panel(10) which is a diffuse source, and two sources in which the radiation was focussed by ellipsoidal mirrors; the radiation sources being a tungsten filament lamp(11) and a carbon arc(12). Some comparative details are given in Table 1 below.

Table 1

Characteristics of radiation sources

Source	Power input	Approximate radiating temperature (°K)	Area receiving not less than 90 per cent maximum radiation (cm^2)	Range of intensities ($cal\,cm^{-2}s^{-1}$)	Source of draught passing over volatile stream
Gas-fired radiant panel		1 000	60	0 to 3	spent gases
Tungsten filament lamp - ellipsoidal mirror	1 KW	3 000	0.5	1 to 5	none
Carbon arc - ellipsoidal mirror	22 KW	4 000	3	1.5 to 14	induced by arc flame

The radiation was measured by a series of modified Moll type(13) or Gardon(14) type water cooled radiometers specially designed for each radiation source. The instruments were calibrated by two types of absolute radiometer(15, 16) and checked against the radiation standard at the National Physical Laboratory over the range 0 - 0.5 cal $cm^{-2}s^{-1}$.

2.2 Method

The basic experimental technique was simple; a specimen* was exposed to radiation of a given intensity and whether or when ignition occurs was noted using a stop watch.

The method of exposure varied. With the radiant panel, the specimen was moved rapidly into position along a slide and different intensities of radiation were obtained by setting the sliding mechanism at different distances from the panel. With the tungsten filament lamp, before the specimen was placed at the second focus, a shield was interposed to cut off the radiation; to expose the specimen the shield was removed. Different intensities of radiation were obtained by adjusting the power input to the lamp. With the carbon arc, the specimen was placed in the optimum irradiation plane near the second focus and shielded from the radiation by a venetian blind. The intensity of radiation was adjusted to the required level by opening or closing the shutters of a second venetian blind. The ignition time was recorded automatically by a signal from a flame detector sighted at the region in the volatile stream where the flame first appeared(5, 6); this also served to shut off the radiation at the same time. Alternatively a pulse of radiation could be used. A range of experiments to investigate the variation of ignition time with constant intensities of irradiation with different materials has been carried out on the carbon arc source in order to determine the variation of threshold intensity for ignition with pulse length. The pulse shape, the time to peak intensity t_p, was kept constant, and the peak intensity was reduced until the specimen no longer ignited.

2.3 Preparation of specimens

The majority of the specimens have been tested in an oven-dry condition; specimens have been heated in an oven set between 95 to 105°C and allowed to cool in sealed tins over phosphorus pentoxide. In experiments using different moisture contents, specimens initially oven-dried, were stored over saturated salt solutions giving the relative humidity that would produce the required moisture content.

Most specimens were cut 5 cm x 5 cm in area; specimens of different sizes of up to 30 cm x 30 cm were cut to investigate the effect of area on ignition time. Specimens were normally exposed in their natural condition but, in order to determine the effect of absorptivity on the ignition time of wood, some specimens were coated with carbon black.

3. Factors affecting ignition of materials

3.1 General

Many factors can affect whether and when ignition by radiation occurs; for experimental purposes these may be divided into two groups.

(a) External factors

These include the intensity of radiation and its variation with time(7), the time of irradiation, the area of uniform energy flux,(5) the form of ignition (4, 17, 18), whether a draught is imposed on the volatile stream(5, 6), and preheating the specimens(9).

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*Ignition may be prevented, or more rarely, delayed by the emitted volatiles being cooled so that the specimen and the volatile stream must be clear of heat sinks(6).

(b) Internal factors

These include the absorptivity of the material,(5) and its diathermancy, the size of the irradiated area(5), its thermal properties(1, 18) thermal conductivity (K) and volumetric specific heat (ρc), its moisture content(20), thickness,(1, 5) homogeneity(2, 3, 21) and the importance of chemical heating(14).

Some of these factors affect both whether and when ignition occurs, others, such as pre-heating and the presence of external draughts, only affect whether it occurs.

3.2 The form of ignition

Three distinct forms of ignition have been identified;(17) in all three the volatiles are emitted from the heated surface at a rate sufficient to form a flammable mixture with the surrounding air. For spontaneous ignition the rate of heating must be high enough for the mixture to reach a temperature at which a flame can appear and flash down to the surface. For pilot ignition, the volatiles are ignited by an independent source of ignition such as a small gas flame or an electric spark, unless the flame is actually on the surface - surface ignition. A material that ignites may or may not continue to burn. Spontaneous ignition followed by continued burning has been called sustained ignition(22); this condition exists when flames are both faces of a slab. Supporting radiation is necessary for flame to persist on one face of a specimen(19).

3.3 The Effect of Absorptivity

The absorptivity of a surface at very low rates of heating is independent of the rate of heating and only varies with the quality of the incident radiation, but in heating a material to ignition, the irradiated surface darkens and the absorptivity depends upon the exposure time. Empirical absorption factors corresponding to different exposure times have been obtained for constant impulses by comparing the intensities of radiation required to ignite the natural material with those required with the artificially blackened material(5). For varying impulses it is more convenient to compare total energies in the pulse for which ignition just occurs. The effective absorptivity for most cellulosic materials is near unity for the radiant panel source, being more than 0.8 for white cotton. It can be less than 0.25 for white filter paper on the carbon arc source at short times, but since the surface darkens the value increases rapidly as the exposure time increases. For the natural wood surfaces tested the absorptivity is always greater than 0.5 on the carbon arc source: on this source changing the surface absorptivity by painting it white can considerably increase the energy required for ignition(21) regardless of whether the paint has fire retardant properties, although such a paint would be better still(2, 3).

3.4 The effect of area of specimen irradiated

As all three sources of radiation produced different areas over which the radiation was uniform to within 90 per cent of the maximum, it was early discovered that the size of the area irradiated affected both the onset and occurrence of ignition. A comprehensive series of experiments using black filter paper (range of areas used 0.8 - 36 cm^2), fibre insulating board (range of areas 1.6 to 930 cm^2*) with its surface blackened to eliminate the effect of absorptivity were therefore carried out, together with some supplementary experiments using white cotton and oak. In the experiments with the carbon arc** some specimens were larger than the area irradiated, others were smaller. It was found that the ignition time of specimens greater than about 3 cm^2 was independent of the size of the specimen. This is about the limits of the

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*With the largest areas of fibre insulating board (230 and 930 cm^2) a 3 ft square radiant panel had to be used(23). Flame appeared at the top of these specimens and rolled down the surface.

**With the smaller specimens of black filter paper the flame descended on to both faces of the specimen; with the larger specimens although the flame normally returned to the irradiated face this was almost immediately followed by the rear surface igniting and flame spreading rapidly over any remaining unburnt material.

90 per cent level of uniformity of the irradiated area (Table 1) and suggests that this is a satisfactory measure of the actual area irradiated. With the radiant panel source,* with the larger areas, the ignition time diminished slowly with increasing size of area irradiated. It was therefore simple to predict the ignition time of infinitely large areas by extrapolating curves of constant intensities.

From these experiments correction factors were obtained to convert the ignition times of specimens of a given area to those of infinite area. For the carbon arc the correction factor is about 0.8 for intensities greater than 3 cal $cm^{-2}s^{-1}$ and for a 25 cm^2 area on the 1 ft square radiant panel the correction factor is negligible above 2 cal $cm^{-2}s^{-1}$ but as large as 0.6 at 1 cal $cm^{-2}s^{-1}$. There was considerable scatter among the original results, but more recent work(20) has shown that this was at least partly due to the different materials used and that the area effect as measured is probably associated with the density of the material.

4. Theoretical studies

4.1 Ignition criteria

Flame first appears in the stream of volatiles issuing from the irradiated surface of the solid and features of their release are known to affect the threshold condition for ignition rather than the ignition time. Again, although a minimum rate of emission of volatiles from the surface of the specimen is clearly necessary before ignition can occur, this, too, appears to affect the occurrence rather than the onset of ignition(5). The probable reason for this is that if the temperature is rising rapidly, the rate of production of volatiles is large compared with the critical rate necessary for ignition. The onset of ignition may, therefore, be discussed in terms of the thermal balance in the solid. However, at very high rates of heating the time to produce a flammable mixture may be comparable with the heating time and the energy required for ignition may increase(7).

4.2 The thermal balance in the solid

A detailed analysis of the heat balance in the dry solid is given elsewhere(7). In the present paper the following simplifications are made: the solid is inert i.e. there is no exothermic heating and no heat transfer by the decomposing volatiles; its surface is totally absorbing and its thermal properties do not change with temperature.

The temperature rise, θ at depth x at time t of such a slab, of thickness, 21, irradiated on one face by an intensity varying with time I(t) and losing heat on both sides by Newtonian cooling is given by

$$K\frac{\partial^2\theta}{\partial x^2} = \rho c\frac{\partial\theta}{\partial t} \qquad t > 0 \qquad (1)$$

The boundary conditions are

$$K\frac{\partial\theta}{\partial x} = -H\theta + I(t) \qquad t > 0,\ x = +1 \qquad (2)$$

and

$$K\frac{\partial\theta}{\partial x} = H\theta \qquad t > 0,\ x = -1 \qquad (3)$$

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[*] With thermally thin materials at low intensities of irradiation, the volatiles which formed the flammable mixture appeared to be emitted from the rear surfaces and ignition therefore occurred at intensities below those expected(5).

The initial condition is

$$\theta = 0 \text{ when } t = 0$$

where K is the thermal conductivity

ρ the density

c the specific heat of the material

and H is the Newtonian cooling constant

A radiation pulse varying with time may be described functionally as

$$I(t) = I_p \lambda\ ({}^t/t_p) \qquad (4)$$

where I_p is the peak intensity

t_p the time to the peak

and λ is a shape function

A function$^{(24)}$ amenable to analytical treatment and applicable to explosions of different sizes is given in equation 5

$$I(t) = e^2\, I_p\, ({}^t/t_p)^2 \exp(-\frac{2t}{t_p}) \qquad (5)$$

and

$$\Sigma = e^2/4(I_p\, t_p) \qquad (6)$$

where Σ is the total energy in the pulse. At this stage it is most profitable to use dimensional analysis

Put

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

$$t/t_p = \tau \quad \text{dimensionless time}$$

$$z = \frac{x}{l} \quad \text{dimensionless distance}$$

and

$$\Theta = \frac{H\theta}{I_p} \quad \text{dimensionless temperature}$$

Substituting and rearranging equations 1 - 4 gives

$$\frac{kt_p}{l^2}\frac{\partial^2\Theta}{\partial z^2} = \frac{\partial\Theta}{\partial\tau} \qquad (7)$$

$$\frac{\partial\Theta}{\partial z} = -\frac{Hl}{K}\Theta + \frac{Hl}{K}\lambda(\tau), \quad z = +1 \qquad (8)$$

and

$$\frac{\partial\Theta}{\partial z} = \frac{Hl}{K}\Theta \qquad , \quad z = -1 \qquad (9)$$

Hence
$$\frac{H\theta}{I_p} = F_1 \left[\frac{Hl}{K}, \frac{kt_p}{l^2}, \frac{x}{l}, \frac{t}{t_p} \right] \tag{10}$$

where F_{1-n} represent unknown functions.

It is usual to express results using the energy modulus, defined as $\frac{Ip}{\rho cl} \frac{tp}{\theta}$ or $\frac{\Sigma}{\rho cl\ \theta}$. Equation 10 may therefore be rewritten as

$$\frac{\Sigma}{\rho cl\ \theta} = F_2 \left[\frac{Hl}{K}, \frac{kt_p}{l^2}, \frac{x}{l}, \frac{t}{t_p} \right] \tag{11}$$

Equation 11 may be simplified further provided that the values of $\frac{kt}{l^2}$ and $\frac{Hl}{K}$ lie within certain ranges$^{(5)}$.

Two of these approximations are the semi-infinite solid (thermally thick materials) where $\frac{kt}{l^2}$ is small*, and the slab with a linear temperature gradient (thermally thin materials) where $\frac{kt}{l^2}$ is large*.

4.2.1 The semi-infinite solid

For the semi-infinite solid, the thickness is of no importance in determining the front surface temperature, θ_F, and eliminating it from equation 11 leads to

$$\frac{\Sigma}{\rho c\sqrt{kt}\ \theta_F} = F_3 \left[\frac{H^2t}{K\rho c}, \frac{t}{t_p} \right] \tag{12}$$

If $\frac{H^2t}{K\rho c}$, the cooling modulus, is small, surface heat losses may be neglected$^{(25)}$.

For a constant pulse of radiation, equation 12 becomes

$$\frac{\Sigma}{\rho c\sqrt{kt}\ \theta_F} = F_4 \left[\frac{H^2t}{K\rho c} \right] \tag{13}$$

and an analytical solution$^{(24)}$ to equation 13 is

$$\frac{\Sigma}{\rho c\sqrt{kt}\ \theta_F} = \frac{\gamma}{1 - \exp\gamma^2 \operatorname{erfc}\gamma} \tag{14}$$

where
$$\gamma = \left(\frac{H^2t}{K\rho c}\right)^{\frac{1}{2}}$$

For a pulse of radiation varying as in equation 5, equation 12 becomes

$$\frac{\Sigma}{\rho c\sqrt{kt_p}\ \theta_F} = F_5 \left[\frac{H^2t_p}{K\rho c} \right] \tag{15}$$

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*The actual value depends upon $\frac{Hl}{K}$

No analytical solution for this equation has been found, but it has been computed using the modified Schmidt method and is shown in figure 1. (It is possible to use a more complete non-linear formula allowing for radiative and convective surface heat losses).

4.2.2 The slab with linear temperature gradient

For a slab in which a quasi-stationary state exists there is a linear temperature gradient through the slab. The mean temperature of the slab, θ_m, which has been found to be useful for correlating experimental results for sustained ignition, can be expressed without using the thermal conductivity. The mean temperature rise, θ_m, is given by

$$\frac{\Sigma}{\rho cl\,\theta_m} = F_6\left[\frac{t}{t_p}, \frac{Ht}{\rho cl}\right] \qquad (16)$$

If $\frac{Ht}{\rho cl}$, the cooling modulus, is small, surface heat losses may be neglected(5).

For a constant pulse of radiation, equation 16 becomes

$$\frac{\Sigma}{\rho cl\,\theta_m} = F_7\left[\frac{Ht}{\rho cl}\right] \qquad (17)$$

The analytical solution to equation 17 is

$$\frac{\Sigma}{2\rho cl\,\theta_m} = \frac{Ht}{\rho cl} \Bigg/ \left[1 - \exp\left(-\frac{Ht}{\rho cl}\right)\right] \qquad (18)$$

For an impulse of radiation varying as in equation 5, equation 17 becomes

$$\frac{\Sigma}{\rho cl\,\theta_m} = F_8\left[\frac{Ht_p}{\rho cl}\right] \qquad (19)$$

The solution to this equation may be obtained analytically and is shown plotted in Figure 2.

4.3 Correlation of the data

It has been found that results for the spontaneous ignition time of semi-infinite solids can be correlated in terms of the surface temperature and results for the sustained ignition time of slabs with linear temperature gradients in terms of the mean temperature.

4.3.1 Semi-infinite solid-constant pulses

The experimental results consist of the ignition times (2-100s) for different values of I, the intensity of radiation (1-12 cal $cm^{-2}s^{-1}$) of different species of wood (density 0.24 - 0.66 g/cm^3). The best fit between the experimental data(20) and equation 15 is given by $\theta_F = 525^\circ C$, in reasonable agreement with the values given by other workers(26, 27). Similar correlations have been obtained for pilot ignition(5) and surface ignition(28).

4.3.2 Semi-infinite solid - varying impulse

The experimental results consist of values of Σ for a large range in values of t_p corresponding to 10 KT to 10^2 MT for three woods, (density 0.24 - 0.66 g/cm^3) with blackened surfaces. These are plotted in figure 1 in terms of the dimensionless variables given by equation 15 and compared with the solution calculated for θ_F as 525°C. The calculated curve is less than 15 per cent below the experimental line.

4.3.3 Slab with linear temperature gradient - constant pulses

The experimental results consist of the sustained ignition times (1-20s) for a range of values of the intensity of radiation (1-14 cal cm^{-2}s^{-1}) for a number of papers and fabrics (thickness 0.02-0.065 cm). The best fit between the experimental data and equation 18 is given by θ_m = 525°C.

A similar correlation has been obtained for Sauer's experiments(29) on black α-cellulose paper (thickness 0.06-0.08 cm with a range of intensities of radiation (3-15 cal cm^{-2}s^{-1}) and ignition times (0.3-4.0s). However, the mean temperature found was 650°C, the rather higher value for θ_m found in this way may be due to Sauer's choosing the critical exposure time so that ignition occurred about 80 per cent of the time, as opposed to the 50 per cent level chosen in the other experiments.

4.3.4. Slab with linear temperature gradient-varying impulses

The experimental results consist of values of for a large range in values of t_p - corresponding to 10 KT to 10^3 MT-for black and white filter paper (wt/unit area 12 mg/cm^2) and for dark green, yellow and white blotting paper (wt/unit area, 30 mg/cm^2). The results for black filter are plotted in figure 2 in terms of the dimensionless variables given by equation 19 and compared with the solution calculated for θ_m taken as 525°C. The calculated curve is about 30 per cent below the experimental line for low values of t_p and less than 15 per cent below for high values of t_p.

5. Application of results to nuclear explosions(24)

5.1 General

The area of the specimens irradiated is small (c. 3 cm^2) and this is too small to be representative of the areas likely to be exposed. Unfortunately the data available, although showing the effect is greatest near the threshold do not permit any accurate estimate of its magnitude. The theoretical lines may therefore represent the conditions for large areas better than the experimental data suggest. The theoretical lines have therefore been used to calculate the threshold energies necessary to ignite cellulosic materials from nuclear explosions of size greater than 20 KT.

The threshold energy required for ignition increases with increasing size of the bomb and increasing time of irradiation because

(a) for longer times of irradiation, cooling losses are relatively more important

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

(c) on the other hand the effect of colour becomes less marked at longer times.

5.2 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

$$\frac{\Sigma_i}{K\rho c} = 350\left(\frac{t_p}{K\rho c}\right)^{0.62} \qquad (20)$$

where Σ_i is the energy required for ignition

Since(30)

$$t_p = 0.032\ W^{\frac{1}{2}} \tag{21}$$

where W is the yield in kilotons

Subsituting equation 21 in equation 20 gives

$$\Sigma_i = 42\ W^{0.31}\ (K\rho c)^{0.38} \tag{22}$$

Equation 22 is plotted in figure 3 for three types of wood, oak (Quercus sp., $\rho = 0.66$ g/cm^3), cedar (Thuja plicata, $\rho = 0.37$ g/cm^3) and fibre insulating board ($\rho = 0.24$ g/cm^3). Outside the experimental limits the lines are shown dotted.

5.3 Thin materials

For values of $\frac{Ht_p}{\rho cl}$ between 0.2 and 2.0 the equation of the threshold line in figure 2 is given by

$$\Sigma_i = 4 \times 10^2 \rho l + 2.46\ t_p \tag{23}$$

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

$\theta_m = 525^\circ$C

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

Substituting equation 21 in equation 23 gives

$$\Sigma_i = 0.20\ m + 0.08\ W^{\frac{1}{2}} \tag{24}$$

where $m = 2\rho l$, the weight per unit area mg/cm^2

Equation 24 is plotted in figure 4 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 has the value 10 mg/cm^2 (3 oz/yd^2).

For large bombs and low values of m the first term in equation 23 may be neglected and Σ_i becomes a function of $W^{\frac{1}{2}}$, viz

$$\Sigma_i = 0.08\ W^{\frac{1}{2}} \tag{25}$$

Since equation 25 does not involve the thermal properties of the material it can be used for any thin material with an ignition temperature of 525°C. It gives the energy for sustained ignition of an infinitely thin material and is the asymptote to the other curves for materials of finite thickness and is shown in figure 4. It may be derived directly as follows. The cooling loss from a vertical surface at 525°C is about 0.72 cal cm^{-2}s^{-1}. Hence the threshold intensity for ignition of thin materials is given by the intensity just sufficient to balance the heat loss from front and rear surfaces, both taken to be at 525°C, i.e.

$$I_p = 1.44 \text{ cal cm}^{-2}\text{s}^{-1} \tag{26}$$

Combining equation 26 with equations 6 and 21 gives equation 25.

5.4 The effect of colour

Similar correlations to that in figure 2 have been obtained for the white, yellow and green papers. The lighter the colour, the higher the values of threshold energy needed for ignition, but the increase depends on the exposure time since the surface darkens prior to ignition thus reducing the effect of the initial colour.

The threshold ignition energies for the coloured papers, $\sum c$, have been compared with the threshold ignition energy for black paper, $\sum i$. The factor $\frac{\Sigma_c}{\Sigma_i}$ found in this way has been plotted in figure 5 as a function of yield of the bomb, W and mass per unit area, m. For $\frac{W}{m^2}$ greater than 500 KT mg^{-2} cm^4 (6000 KT oz^{-2} yd^4) the effect of colour is not significant. A similar effect will be found with surfaces painted white or any other light colour.

5.5 The effect of moisture content

Increasing the moisture content increases the time taken for spontaneous ignition. The amount of the increase has been accounted for satisfactorily by using the values of the thermal properties appropriate to the different moisture contents, and allowing for the effect of the heat of wetting and the latent heat of evaporation within the term for specific heat(20). For present purposes, the energy required to ignite a specimen of a given moisture content may be calculated from the sum of the energy required to ignite the equivalent dry specimen and the energy required to evaporate the moisture.

5.6 The sustained fire

Thermally thin materials once ignited will continue to burn, and for all but very short irradiation times, materials which are physically thin may be taken to be thermally thin. Whether thick materials continue to burn depends upon their shape and orientation and whether there is any supporting radiation. Experiments at the Fire Research Station tended to show that the shape did not affect the ignition time but that tetrahedral corners of fibre insulating board were much more likely to continue to burn than flat pieces.

6. Conclusions

A number of factors have been shown to effect the onset and occurrence of spontaneous ignition by radiation. These include the absorptivity of the irradiated surface and the size of the irradiated area of the specimen. If corrections are applied for these effects and the solid is treated as an inert, totally absorbing material, then the onset of ignition for both constant and varying pulses of radiation may be calculated from the thermal properties, thermal conductivity and volumetric specific heat, assuming a fixed temperature criterion for ignition. This criterion corresponds to a surface temperature of 525°C for thermally thick materials and to a mean temperature criterion of 525°C for thermally thin materials. Once these thin materials are ignited they will continue to burn (sustained ignition) and flames will spread to any unburnt material. At low intensities, the correlations fail and ignition may not occur because of the limited supply of volatiles in the surface of thermally thick solids. They also fail at high intensities of radiation where the time to form a flammable mixture may be comparable with the heating time.

The correlating temperatures for thin and thick materials have been used to compute the threshold energies for ignition from nuclear explosions. Factors to allow for the effect of colour and for moisture content have also been obtained. The energy required for ignition increases with increasing size of explosion because cooling losses are more important and as the pulse duration increases ignition occurs relatively earlier so that the 'useful' portion of the pulse decreases; the effect of colour becomes less marked at longer times.

The method employed should have general application to any kind of thermal damage, e.g. charring or thermal destruction, and to any kind of material e.g. wool, which has a low rate of exothermic heating.

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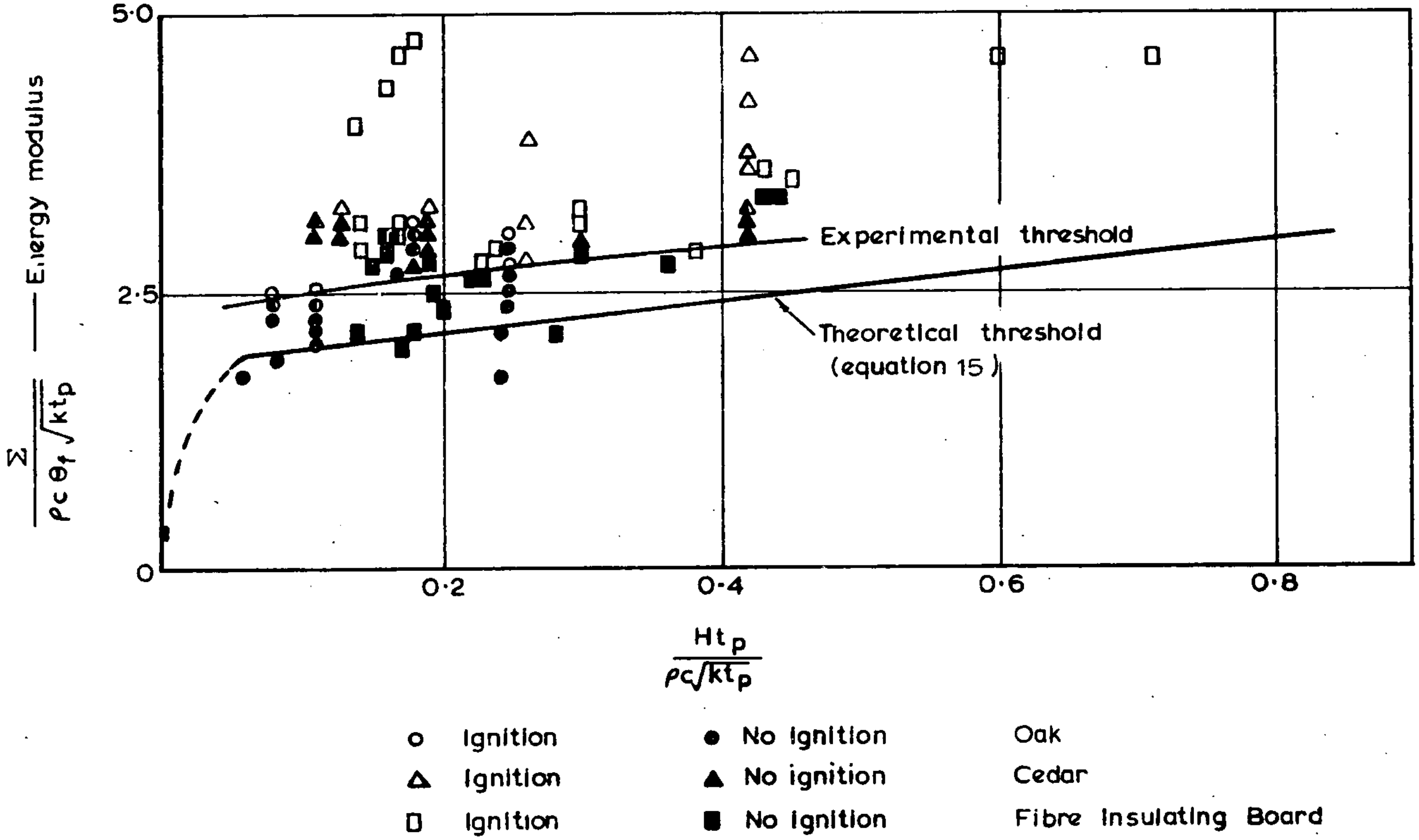

FIG. 1. THRESHOLD ENERGY IN PULSE FOR IGNITION OF THICK MATERIALS (CELLULOSE)

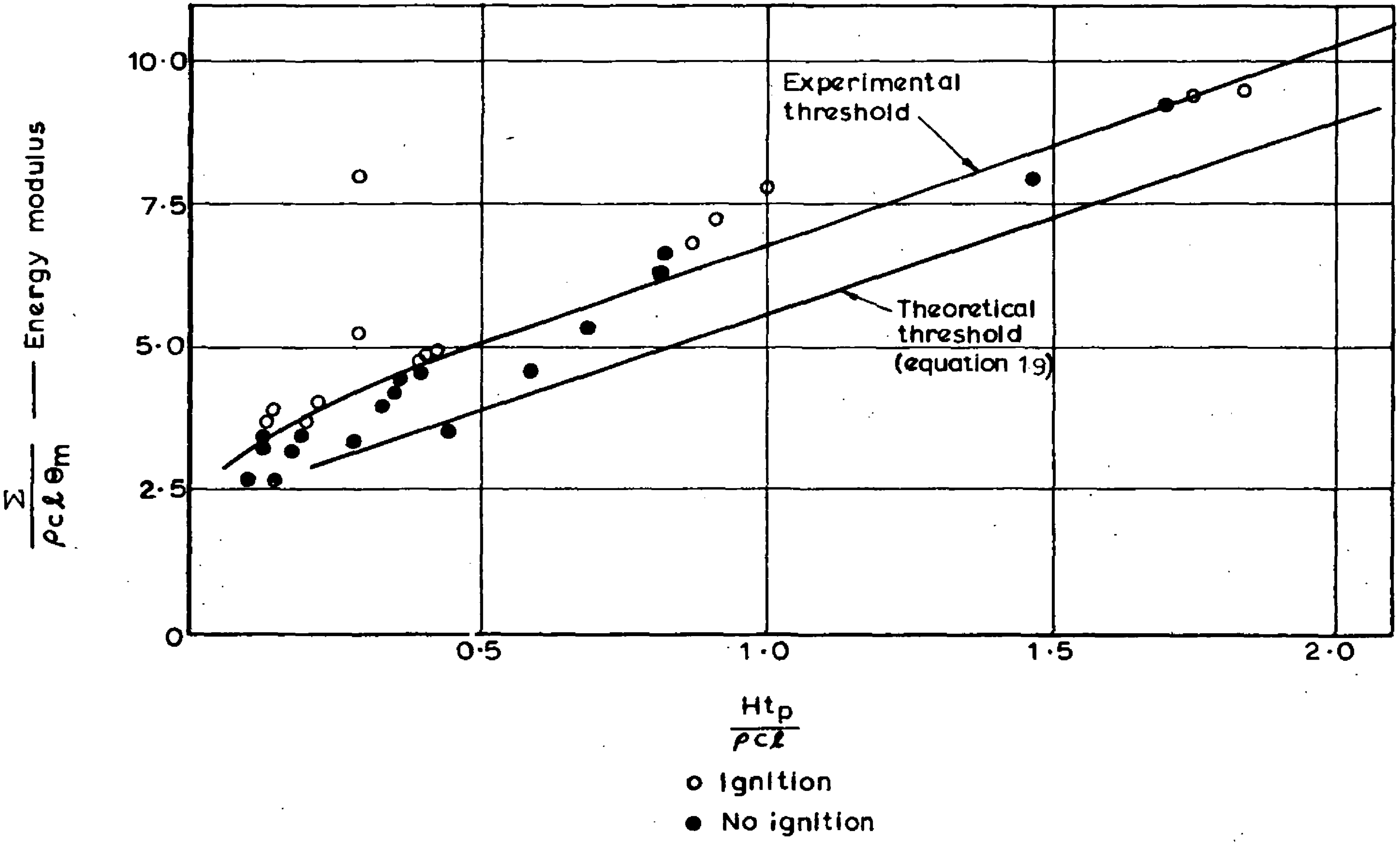

FIG. 2. THRESHOLD ENERGY IN PULSE FOR IGNITION OF THIN MATERIALS (CELLULOSE)

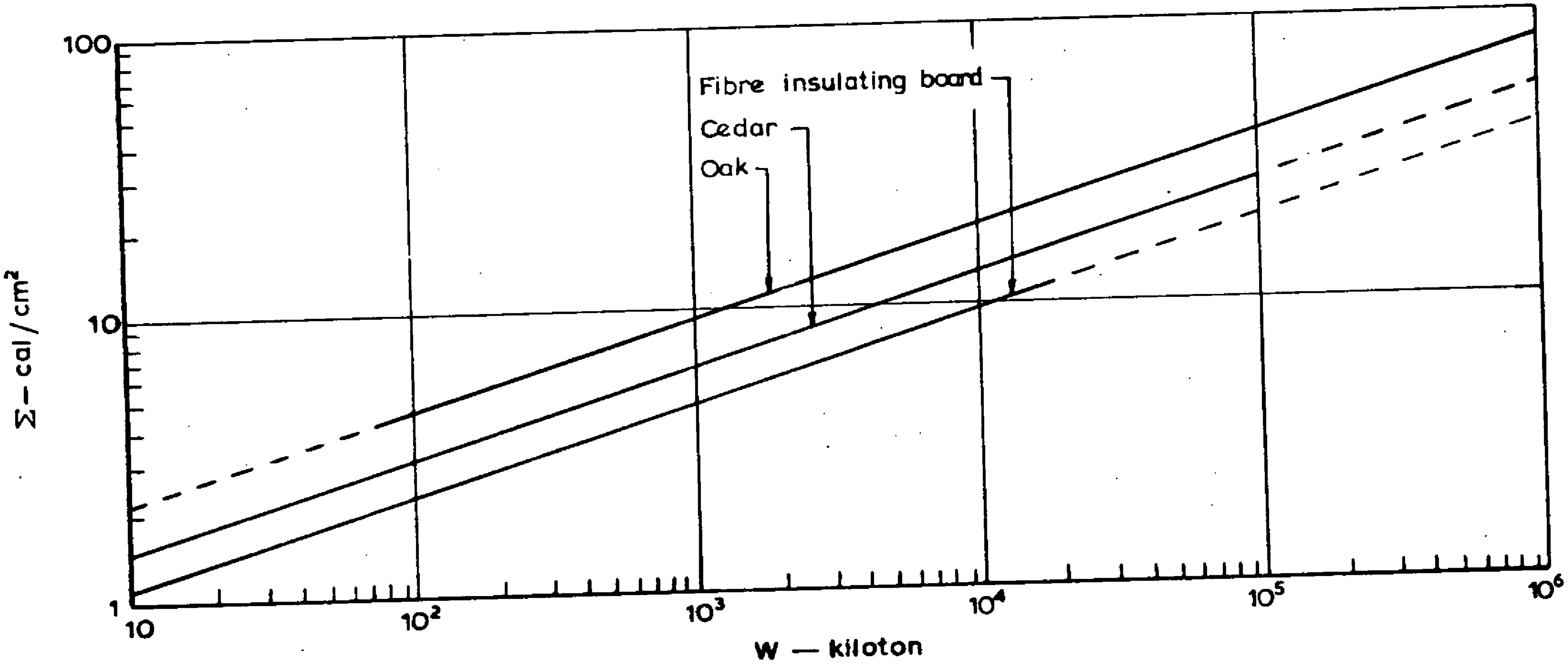

FIG. 3. THE IGNITION THRESHOLD OF THICK WOODS

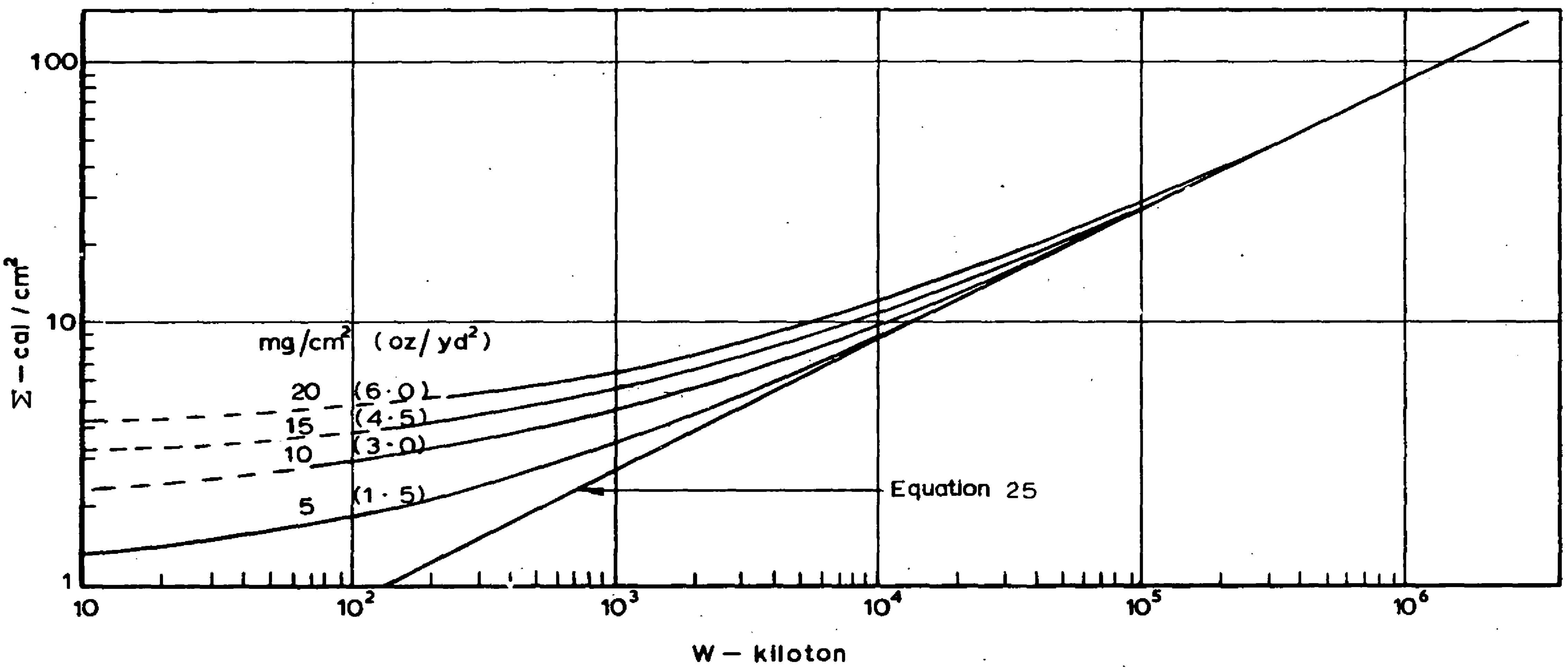

FIG. 4. THE IGNITION THRESHOLD OF THIN PAPERS

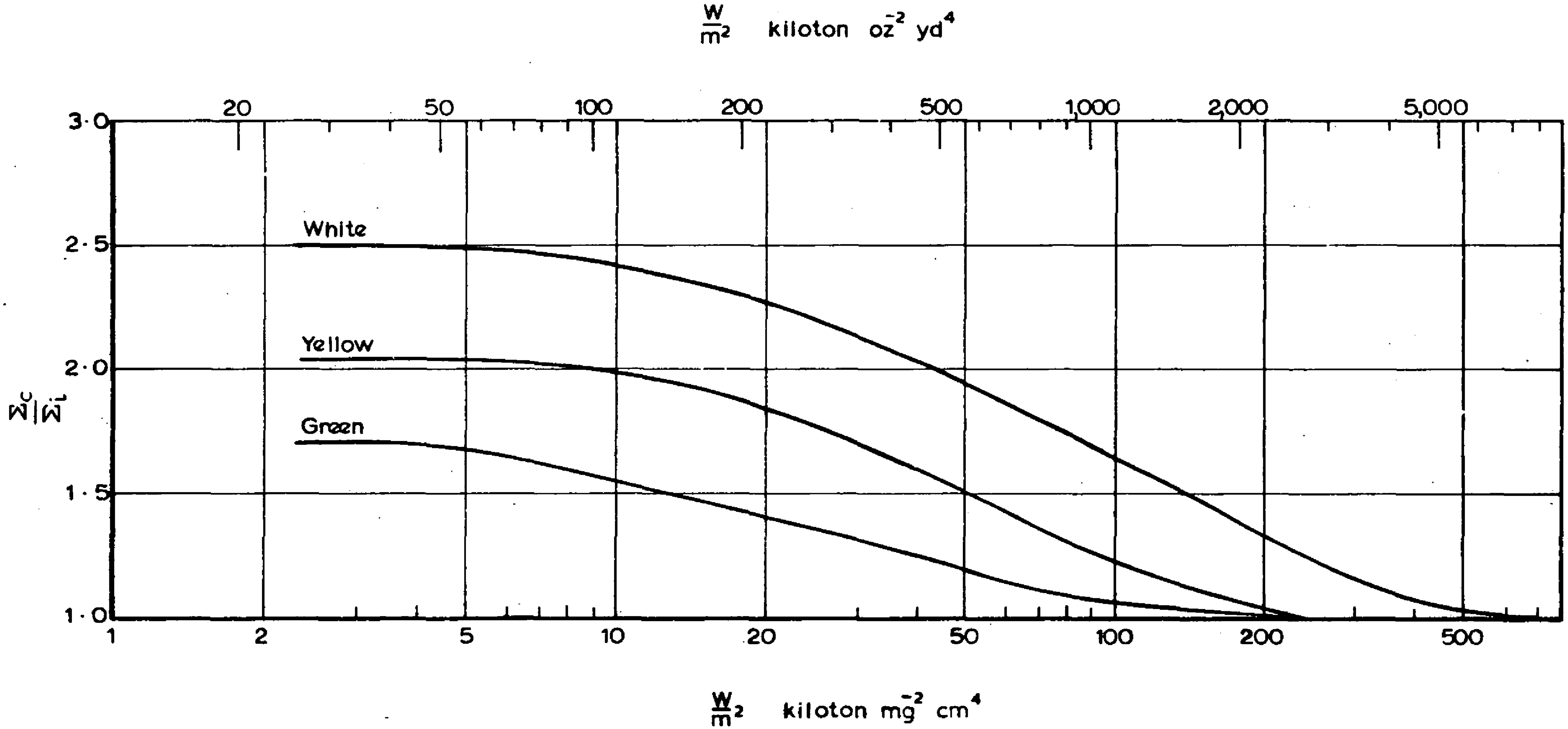

FIG.5. THE EFFECT OF COLOUR ON IGNITION THRESHOLD OF THIN MATERIALS