F.R. Note No.381. 1959.
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ON THE CORRELATION OF THE THRESHOLD FOR IGNITION BY RADIATION WITH THE PHYSICAL PROPERTIES OF MATERIALS

by

P.H. Thomas, D.L. Simms and Margaret Law

of the

Department of Scientific and Industrial Research and Fire Offices' Committee
Joint Fire Research Organization

This report describes work carried out by the Fire Research Station for the Ministry of Supply under E.M.R. contract 7/tex/104/R3 and any enquiries relating to it should be addressed to the Director of Materials and Explosives Research and Development, Ministry of Supply, Shell Mex House, Strand, London, W.C.2.

SUMMARY

The threshold conditions for ignition by a pulse of thermal radiation from a nuclear weapon have been obtained in terms of the physical properties of the materials.

File No.F.1020/2/11.
January, 1959.

Fire Research Station,
Boreham Wood,
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1. Introduction

Ignition times of different cellulosic materials at different constant levels of irradiation (1 - 15 cal cm^{-2} s^{-1}) have already been correlated in terms of the thermal balance of the solid (1). In some problems, it is more important to correlate the data for the 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 minimum intensity, but for a pulse varying with time(2) the threshold conditions for a given shape of pulse are a function of two parameters, the peak intensity and the pulse duration. Such a correlation is obtained in this paper for laboratory results on one thin and three thick materials and the results have been generalised to a wider application on the assumption that the materials are inert and ignite at a fixed temperature.

2. Experimental method and results

Table 1

Materials tested

Material	Weight/unit area g/cm^2	Density g/cm^3
Black filter paper	0.01	0.53
Oak	0.42	0.66
Western red cedar	0.23	0.37
Fibre insulating board	0.30	0.24

Before testing, the thick materials were blackened on the surface with candle black, all the materials were dried at 95°C and then allowed to cool over phosphorus pentoxide. The apparatus and the method of use are described in detail elsewhere(3). With this apparatus a pulse similar in form to a nuclear explosion can be produced(2).

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In these experiments, both the duration and the peak intensity of the pulse were varied and any ignition was noted. In general, about eight tests were carried out at each peak intensity and each pulse length. Ignition usually occurred after the peak intensity but well before the end of the pulse.

3. Theoretical analysis

The thermal balance method used earlier(1) for constant intensities of radiation assumes that ignition occurs at a certain fixed temperature and that when the material is heated it behaves as if it were inert. Here, the same assumptions are made.

3.1. Differential equations - dimensional analysis

The temperature rise θ at depth x at time t of a slab thickness 2l, irradiated by an intensity varying with time I(t) on one face, losing heat on both sides by Newtonian cooling is given by

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

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

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

where K is the thermal conductivity

ρ the density

c the specific heat of the solid

and H is the Newtonian cooling coefficient.

If dimensional analysis is used, no particular form to I(t) need be assumed. For any given pulse shape, two parameters are required. For convenience the peak intensity I_p, and the time to peak intensity t_p have been chosen

$$I(t) = I_p f\left(\frac{t}{t_p}\right) \qquad \ldots\ldots(4)$$

where f is a shape function

Let $k = \frac{K}{\rho c}$ the thermal diffusivity

$\frac{t}{t_p} = \tau$

$x/l = \lambda$

$\frac{H\theta}{I_p} = \psi$

Substituting and rearranging equations (1, 2 and 3) give

$$\frac{k t_p}{l^2} \frac{\partial^2 \psi}{\partial \lambda^2} = \frac{\partial \psi}{\partial \tau} \qquad \text{......(5)}$$

$$\frac{\partial \psi}{\partial \lambda} = -\frac{Hl}{K}\psi + \frac{Hl}{K} f(\tau) \qquad \lambda = +1 \qquad \text{......(6)}$$

$$\frac{\partial \psi}{\partial \lambda} = \frac{Hl}{K}\psi \qquad \lambda = -1 \qquad \text{......(7)}$$

The solution may be rewritten as

$$\frac{H\theta}{I_p} = F_1\left[\frac{Hl}{K}, \frac{k t_p}{l^2}, \tau\right] \qquad \text{......(8)}$$

where F_{1-n} are unknown functions. The maximum temperature is given by

$$\frac{H\theta_{max}}{I_p} = F_2\left[\frac{Hl}{K}, \frac{k t_p}{l^2}\right] \qquad \text{......(9)}$$

so that the threshold conditions are

$$\frac{H\theta_i}{I_p} = F_3\left[\frac{Hl}{K}, \frac{k t_p}{l^2}\right] \qquad \text{......(10)}$$

where θ_i is the effective ignition temperature.

3.2. Simplification of problem

Two approximations used in the earlier paper[1] are considered. The first, the slab with a linear temperature gradient, the second the semi-infinite solid.

3.2.1. Slab with linear temperature gradient

The mean temperature rise of such a slab is independent of the thermal conductivity, K.

Eliminating[4] K from equation (10) and substituting $\overline{\theta_i}$ the mean temperature for θ_i gives

$$\frac{H\overline{\theta_i}}{I_p} = F_4\left[\frac{Ht_p}{\rho c l}\right] \qquad \text{......(11)}$$

Since the energy E in the pulse is proportional to $I_p \cdot t_p$, equation (16), the relation can be written as

$$\frac{E}{\rho c l \overline{\theta_i}} = F_5\left[\frac{Ht_p}{\rho c l}\right] \qquad \text{......(12)}$$

$E' = \frac{E}{\rho c l \overline{\theta_i}}$ is similar in form to the energy modulus obtained for constant intensities of irradiation[1] but represents the ratio of the heat in the pulse to the heat absorbed.

$\frac{Ht_p}{\rho c l}$ is a modulus connected with the size of the bomb. It represents the ratio of the energy lost in the time up to the maximum to the energy absorbed at ignition.

3.2.2. Semi-infinite solid

The solution for the semi-infinite solid is independent of the thickness $2l$, so on eliminating l from equation (10) and writing θ_F for the front surface ignition temperature.

$$\frac{H\theta_F}{I_p} = F_6\left[\frac{H\sqrt{t_p}}{\sqrt{K\rho c}}\right] \qquad \text{......(13)}$$

Similarly

$$\frac{E}{\theta_F \rho c \sqrt{k t_p}} = F_7\left[\frac{H^2 t_p}{K\rho c}\right] \qquad \text{......(14)}$$

Acknowledgment

The work described in this report was only made possible by the generous assistance of Messrs. I.C.I. Ltd., in providing the tank and laboratory facilities. The Fire Service Department of the Home Office also helped with the supply of pumping equipment.

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2. FRENCH, R. J. and HINKLEY, P. L. The Production of Foam for Injection at the Base of Petrol Tanks. Department of Scientific and Industrial Research and Fire Offices' Committee Joint Fire Research Organization F.R. Note No. 271, September 1956.

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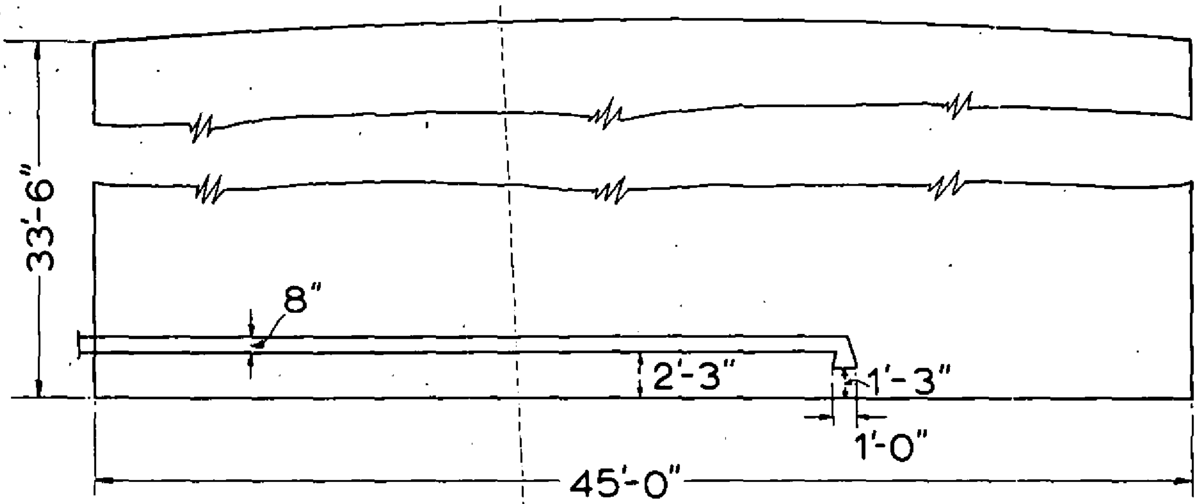
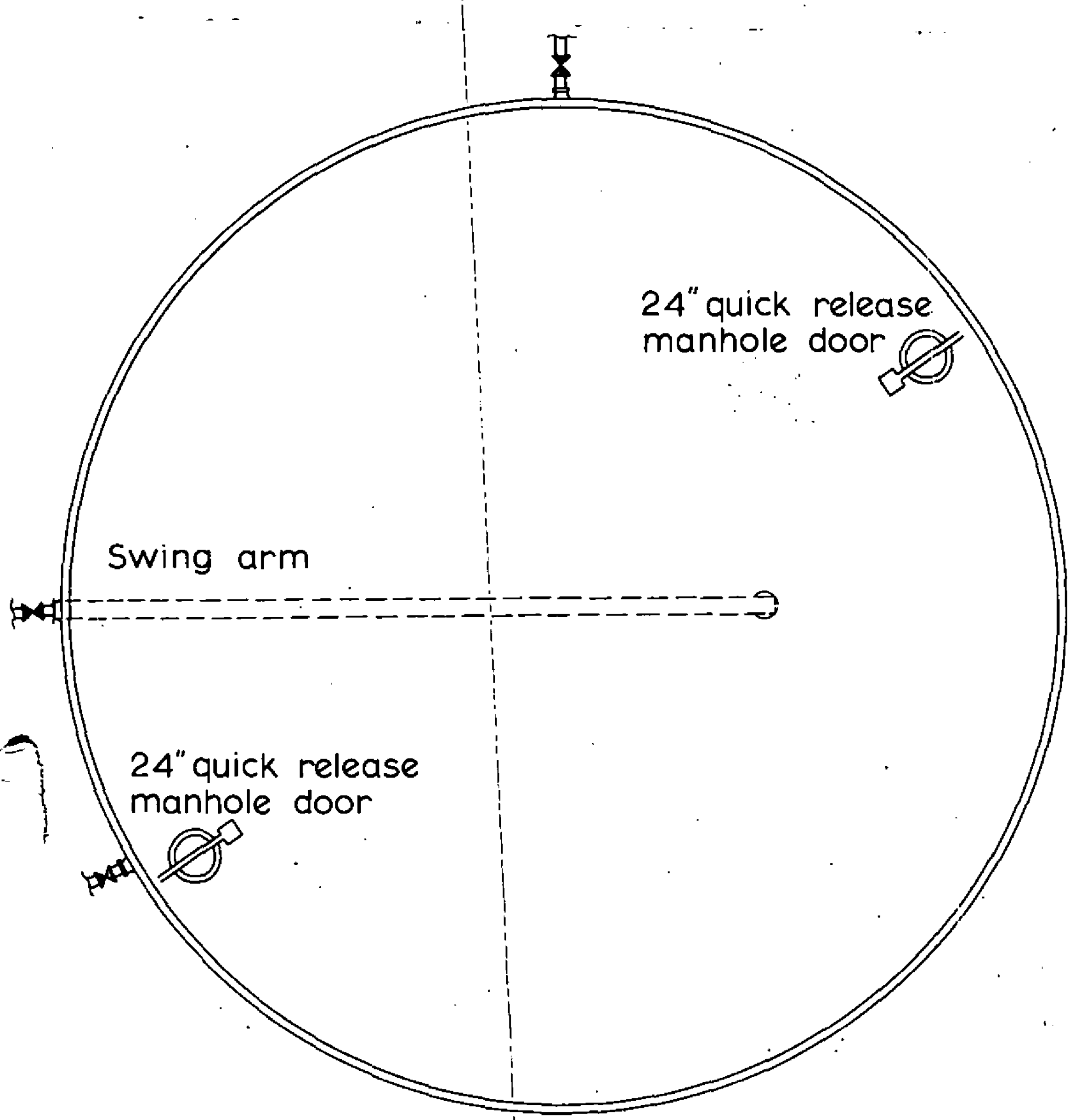


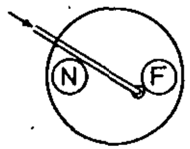
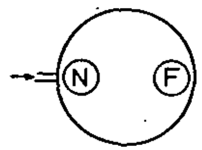
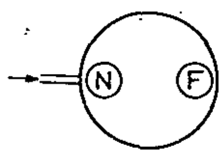
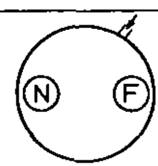
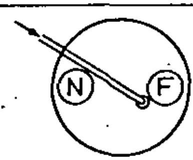
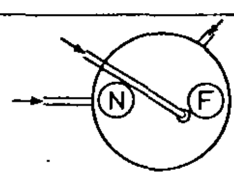
PART ELEVATION



PLAN

Fig. 1 ARRANGEMENT OF SWING ARM AND SIDE INLETS

TABLE 2

TEST No.	POINT(S) OF INJECTION	METHOD OF PRODUCTION	RATE OF INJECTION gl/ft²/min	SHEAR dyne/cm²	25% DRAINAGE TIME (min.)	PETROL PICK-UP AT N (% by volume)	PETROL PICK-UP AT F (% by volume)	EXPANSION AT SURFACE AT N	EXPANSION AT SURFACE AT F
1		Generator + centrifugal pump	0·074 (Generator operating at 135 lb/in²)	125	8-10	4·4	1·8	6·0	5·8
2		Generator + centrifugal pump	0·08	125	8-10	7·7	25·3	6·3	7·3
3		Small generator + centrifugal pump	0·04	125	8-10	7·6	22·2	5·8	6·5
4		Generator + centrifugal pump	0·08	125	8-10	14·8	20·8	6·8	6·7
5		Generator only	0·08	70	2	7·8	12·0	8·2	8·4
6		Generator + centrifugal pump	0·08	125	8-10	40·9	30·8	6·7	6·6

The similarity between equations (12) and (14) is that $\sqrt{ktp}$ which has the dimensions of length and is a measure of the depth of penetration of the heat replaces l whilst θ_F, the surface temperature, replaces $\bar{\theta_i}$ the mean temperature.

3.3. Analytical solutions

It is only possible to solve equations (12) and (14) completely with a knowledge of the form of $f(\tau)$.

3.3.1. The form of $f(\tau)$

A function amenable to analytical treatment and applicable to explosions of different sizes is shown in Fig.1 and given in equation (15).

$$I(t) = e^2 I_p \left(\frac{t}{t_p}\right)^2 e^{-\frac{2t}{t_p}} \qquad \text{......(15)}$$

and

$$E = \frac{e^2}{4} I_p t_p \qquad \text{......(16)}$$

where e is the exponential function

and E is the total energy in the pulse.

Equation (15) is a better fit than an equation of the form

$$I(t) = e I_p \left(\frac{t}{t_p}\right) e^{-t/t_p} \qquad \text{......(17)}$$

with which it is compared in Fig.1.

3.3.2. The slab with a linear temperature gradient

An analytic solution to the mean temperature rise can now be obtained (Appendix I) by the elimination of the term 'C' between

$$E' = \frac{\frac{1}{2}(2\omega-1)^3}{2\omega^3 e^{-C} - \omega^3 e^{-2\omega C}\left[C^2(2\omega-1)^2 + 2C(2\omega-1)+2\right]} \qquad \text{......(18)}$$

and

$$E' = \frac{\frac{1}{2} e^{2\omega C}}{\omega^3 C^2} \qquad \text{......(19)}$$

where $$E' = \frac{E}{\rho c l \bar{\theta}_i} = \frac{e^2 I_p t_p}{4 \rho c l \bar{\theta}_i}$$

and $$\omega = \frac{\rho c l}{H t_p}$$

The solution to these equations is shown in Fig.2. and is of the form

$$E' = \frac{E}{\rho c l \bar{\theta}_i} = F_8 \left[\frac{H t_p}{\rho c l} \right] \qquad \text{......(20)}$$

which is similar to the general form of equation (13)

3.3.3. Semi-infinite solid

No solution in terms of elementary functions has been obtained for the semi-infinite solid. However, a solution has been obtained by using an electrical analogue[5] and the form of equation[14] is shown in Fig.3.

5. Correlation of data

The experimental results consist of values of E for various values of t_p and these are plotted in Fig.2 and 3 as the dimensionless variables given by equation (12) and compared with the analytic solution of equations (18) and (19) for the slab with the linear temperature gradient and as the dimensionless variables of equation (14) with its solution for the semi-infinite solid.

The value chosen for $\bar{\theta}_i$ was 525°C as obtained previously[1] and it gives a curve which is below the experimental line for the slab by a factor of 30 per cent for low values of $1/\omega$ (kiloton range) and by less than 20 per cent for high values (megaton range), and a curve 40 per cent below the experimental line for the semi-infinite solid.

6. Discussion and conclusions

The effect of density in the ignition of thick solids varying in density by about $2\frac{1}{2}$: 1 is accounted for satisfactorily by the dimensionless correlation employed and it is probable that for thin and thick cellulosic materials these correlations can be used generally using an ignition temperature of 525°C.

All the materials tested in these experiments have been totally absorbing. Predictions for materials which reflect some of the incident radiation may be estimated from values of absorptivity given elsewhere.

Because the area irradiated in the laboratory is less than the area irradiated in the field, the energy required in the laboratory is greater than the energy required in the field. Unfortunately, the data available for the effect of area[7,8], although showing the effect is greatest near

near the threshold condition does not permit an estimate of its magnitude closer than 20-40 per cent. Thus the theoretical lines may represent the field conditions better than the figures suggest.

In the absence of field data for ignition it is predicted, on the basis of laboratory tests and calculation , that it is probably satisfactory to assume that

$$E_{laboratory} = a\ E_{field}$$

where a is 1.3 for thin

and 1.45 for thick materials.

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(1) Simms, D.L. The correlation of ignition time with the physical properties of materials. Part I The spontaneous ignition of cellulosic materials. Joint Fire Research Organization F.R. Note No.319/1958.

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Appendix I

Calculation of the Threshold Condition for Ignition

The mean temperature rise θ_m of a slab with a linear temperature gradient, thickness 2l, losing heat from both sides by Newtonian cooling is given by

$$2\rho c l \frac{d\theta_m}{dt} + 2H\theta_m = e^2 I_p \left(\frac{t}{t_p}\right)^2 e^{-2t/t_p} \qquad \ldots\ldots(21)$$

Integrating equation (21) and assuming ignition occurs at time t_i when $\theta_m = \bar{\theta}_i$ the ignition temperature, then

$$\bar{\theta}_i = \frac{e^2 I_p}{\rho c l t_p^2}\left[\frac{t_i^2 e^{-2t_i/t_p}}{(z-2/t_p)} - \frac{2t_i e^{-2t_i/t_p}}{(z-2/t_p)^2} + \frac{2e^{-2t_i/t_p}}{(z-2/t_p)^2} - \frac{2e^{-zt_i}}{(z-2/t_p)^3}\right] \qquad \ldots\ldots(22)$$

where $Z = \frac{H}{\rho c l}$

or

$$E' = \frac{\frac{1}{2}(2\omega-1)^3}{2\omega^3 e^{-C} - \omega^3 e^{-2\omega C}\left[C^2(2\omega-1)^2 + 2C(2\omega-1) + 2\right]} \qquad \ldots\ldots(23)$$

where $C = \frac{Ht_i}{\rho c l}$

The threshold intensity is that which is just sufficient to bring the material to a mean temperature $\bar{\theta}_i$. At this point, $\frac{d\theta_i}{dt}$ is zero and equation (23) becomes

$$E' = \frac{e^{2\omega C}}{\omega^3 C^2} \qquad \ldots\ldots(24)$$

The locus of the threshold intensity for ignition is given by the equation which satisfies both equations (23) and (24).

File No.F.1020/2/11.
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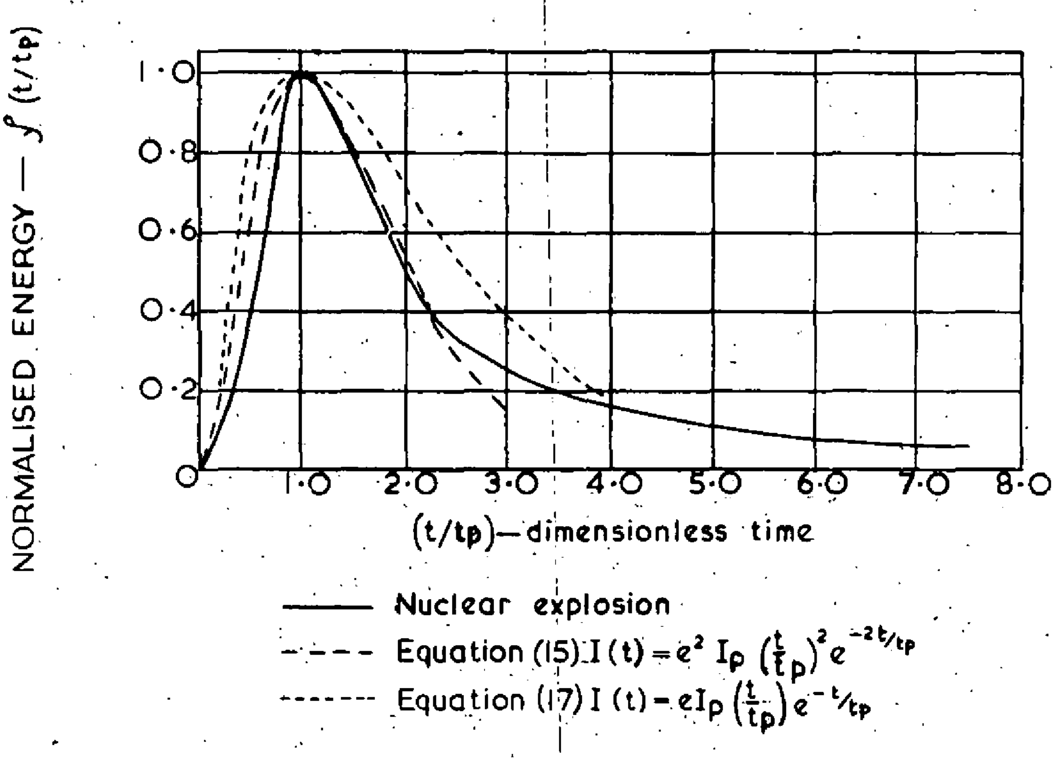

FIG. 1. PULSE SHAPE NUCLEAR EXPLOSION

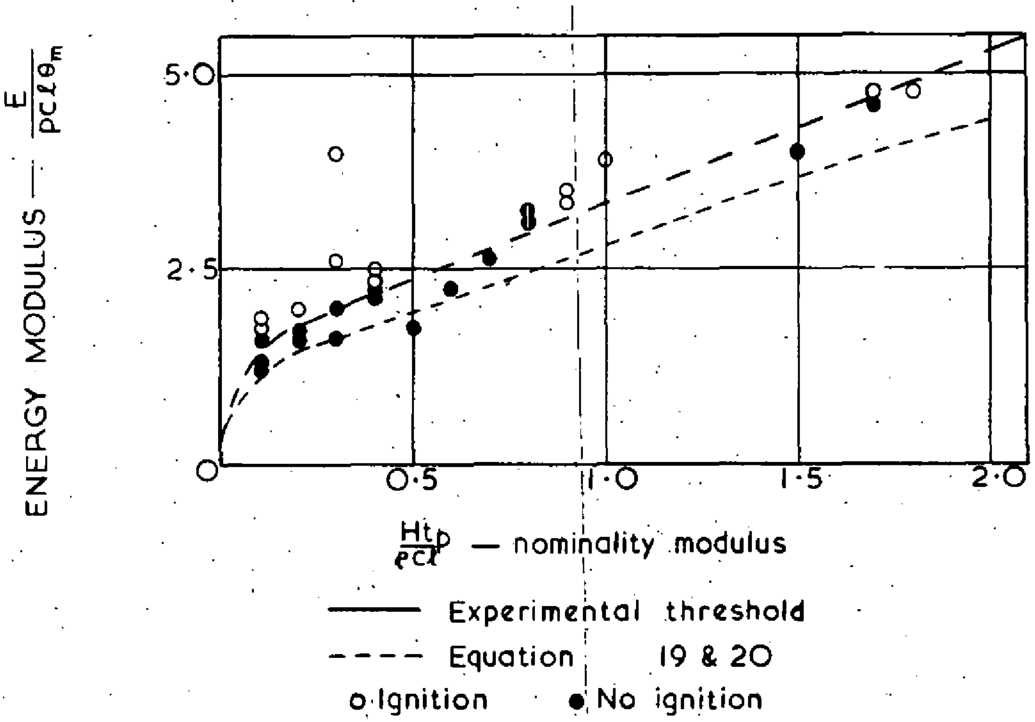

FIG. 2. IGNITION ENERGY CORRELATION FOR SLAB WITH LINEAR TEMPERATURE GRADIENT

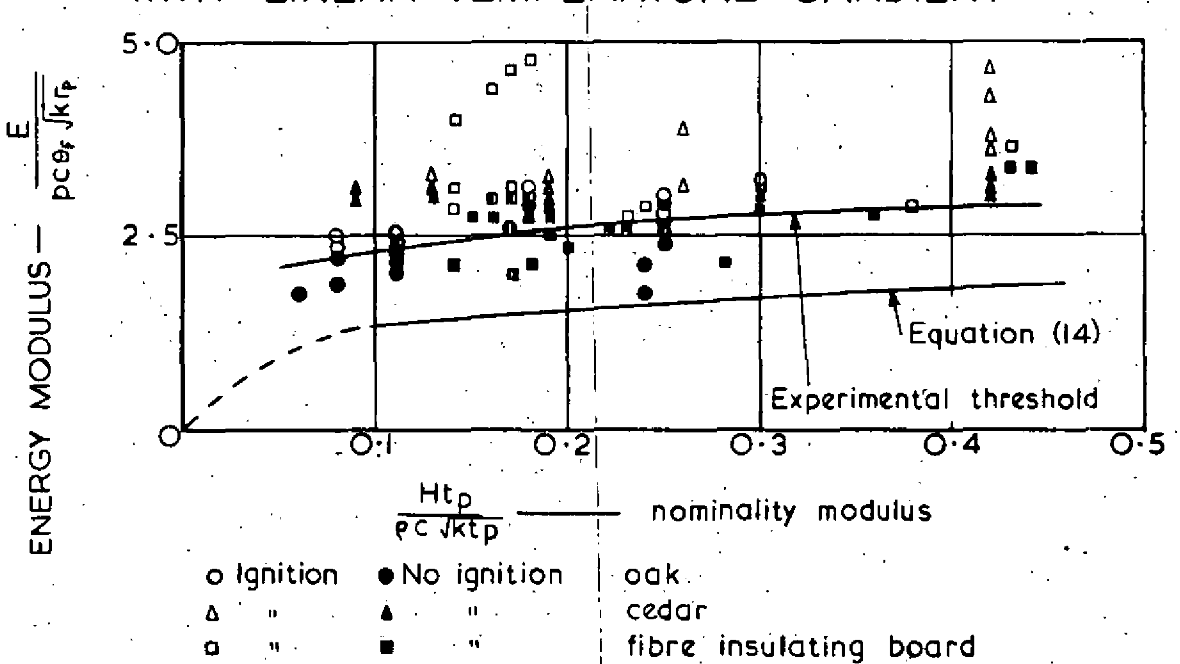

FIG. 3. IGNITION ENERGY FOR THICK SOLID