F.R. Note No. 340/1957
Research Programme
Objective

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

THE HEAT TRANSFER FROM BURNING FABRICS

by

H. Wraight, C. T. Webster and P. H. Thomas

Summary

The rates of heat transfer from burning fabrics to a nearby surface have been measured by two methods for materials of different weights and composition. The maximum heat flux from the flames is about 0·7 cal cm^{-2} sec^{-1} and the total dose increases with the weight of the the fabric, and is about one-third of the calorific value, but all practical fabrics are capable of causing severe burns.

November, 1957

Fire Research Station,
Boreham Wood,
HERTS.

THE HEAT TRANSFER FROM BURNING FABRICS

by

H. Wraight, C. T. Webster and P. H. Thomas

Introduction

Values of the vertical flame speed of burning fabrics have been reported previously (1,2) but there is little data available on how much heat is transferred to a nearby surface from the burning fabrics. This report describes experiments which have been made to determine this heat transfer. Apart from its interest in connection with a possible relation between fabrics and the type of burn that would be caused by them, this work is of general interest in the study of heat transfer from flames.

The heat transfer depends on the properties of the nearby surface, but provided the material used experimentally is, like skin, effectively a total absorber of infra-red, no correction need be applied for thermal properties so long as direct contact between fabric and surface does not occur. This is because the difference between flame and surface temperatures is large and convection and radiation transfer will be independent of the thermal properties of the surface. To apply results to other conditions, allowance for the thermal properties of the material may be necessary.

Two experimental methods were used.

Method 1

Description of apparatus

The apparatus is shown in Fig. 1. $8\frac{1}{2}$ in. (21·6 cm) from the upper edge of an asbestos wood board $\frac{1}{2}$ in. (1·27 cm) thick, 18 in. (45 cm) wide and 3 ft. (91 cm) high, a $\frac{5}{8}$ in. (1·6 cm) diameter hole was drilled in the centre of the board. In this hole a copper disc $\frac{1}{2}$ in. (1·27 cm) diameter and $\frac{1}{4}$ in. (0.63 cm) thick was inserted centrally in the gap and maintained in position by asbestos fibre packing. The disc temperature could be measured by a copper-constantan thermocouple attached to its rear face. The exposed side of the disc was adjusted to be flush with the surface of the board.

On the exposed face of the board two vertical metal strips were fixed parallel and 6 in. (15.2 cm) apart. Asbestos string was tied horizontally between the metal strips at 6 in. (15.2 cm) intervals so that by interlacing the textile between the asbestos strings it was held in position at a constant distance of $\frac{1}{2}$ in. (1.27 cm) from the surface of the board and the copper disc.

The materials tested are listed in Table 1.

Experimental method

Strips of fabrics, 30 in. by 4 in. (76 x 10 cm) were conditioned to 68°F and 65 per cent relative humidity which for cotton fabrics gave a moisture content of about 5 per cent.

The specimen was hung from the top of the board between the metal strips and interlaced through the asbestos string. It was ignited over the whole width of of the bottom edge with a long luminous gas flame. The output from the thermocouple was recorded continuously.

Experimental results

From a direct calibration it was found that the measured temperature had to be increased by 13 per cent to correct for heat loss down the thermocouple wires.

The results of the tests are given in Table 1. The heat dosage received by the disc was calculated from:

$$Q = 1{\cdot}13\, c \rho t \theta \text{ cal cm}^{-2}$$

where t = thickness of disc....................0.63 cm
ρ = density of disc......................8.9 gm cm^{-3}
c = specific heat of disc...............0.10 cal gm^{-1} $^{\circ}C^{-1}$
θ = temperature rise as measured by the thermocouple.

The results are shown in Fig. 2 as a curve of heat dosage against weight per unit area.

Table 1

Heat Dosage - Method I

Material	Weight mg cm^{-2} (mg cm^{-2}x 0.295 = oz.yd^{-2})	Temperature rise of disc °C	Corrected temperature rise °C	Heat dosage cal cm^{-2} Q
Cotton poplin	11.2	25.2 23.2 Av. 24.2	27.4	15.3
Cotton poplin with crease resisting finish	11.8	30.4 22.7 Av. 26.5	30.0	16.8
Cotton poplin with crease resisting finish	14.2	24.6 26.4 Av. 25.5	28.8	16.1
Cotton winceyette	15.3	30.4 28.1 Av. 29.2	33.0	18.5
Cotton winceyette treated with flame-retardant	17.6	7.5 5.2 Av. 6.3	7.1	4.0
Cotton winceyette treated with flame-retardant	17.3	12.4 18.0 Av. 15.2	17.2	9.6
Viscose (spun)	19.3	37.4 32.8 Av. 35.1	39.1	22.2
Viscose (spun), with phosphate added to crease resistant rayon	18.7	28.3 27.0 Av. 27.6	31.2	17.5
Linen canvas	37.0	67.3 72 Av. 69.6	78.6	44.0
Flax canvas	65.0	103 135 Av. 119	134.5	75.5
Cotton	6.4	16.6 20.7 14.5 Av. 17.3	19.5	10.9

Table 1 (contd.)

Material	Weight mg cm^{-2} (mg cm^{-2} x 0·295 = oz.yd^{-2})	Temperature rise of disc °C	Corrected temperature rise °C	Heat dosage cal cm^{-2} Q
Viscose (spun), with phosphate added to crease resistant rayon	18·7	28·3 27·0 Av. 27·6	31·2	17·5
Linen canvas	37·0	67·3 72 Av. 69·6	78·6	44·0
Flax canvas	65·0	103 135 Av. 119	134·5	75·5
Cotton	6·4	16·6 20·7 14·5 Av. 17·3	19·5	10·9
Cotton muslin	3·4	2·6 3·5 3·0 Av. 3·0	3·4	1·9
Wool/Cotton 20/80	12·5	26·9 26·2 30·0 Av. 27·7	31·3	17·5
Wool/Cotton 40/60	11·9	22·0 19·9 19·2 Av. 20·4	23·1	12·9
Wool/Cotton 60/40	14·0	25·7 24·6 22·7 Av. 24·3	27·5	15·4
Wool	12·5	16·5 28·1 25·0 Av. 23·2	26·2	14·7
Wool	13·2	21·4 21·4 26·9 Av. 23·2	26·2	14·7

Method 2

Description of apparatus

Fig. 3 is a diagram of the apparatus which consisted of a sheet iron pipe diameter 15·35 cm (6·05 in.) and wall thickness 0·205 cm (0·08 in.) standing vertically in a concrete base. The internal depth of the cylinder was 46 cm (18·1 in.).

Three 26 S.W.G. constantan wires were soft soldered to the outside of the pipe 5 cm below the top, spaced at 120° arc from each other. A fourth constantan wire was placed round the inside of the pipe at the same level as the external wires and soldered at the three points directly opposite the outside wires. The wires and the pipe then constituted three iron-constantan thermocouples connected in parallel.

The output from this thermocouple system gave the mean temperature difference between the outside and the inside of the wall of the pipe. The response time of this system was very small, thermal gradients and heat flow being effectively proportional to each other in less than 1 sec.

Tests were made with the pipe filled with water to a level of 2 cm (0·79 in.) from the top. The water was stirred as shown in Fig. 3 and its temperature measured by means of a thermocouple.

The pipe was surrounded by a cage of vertical 26 S.W.G. chromel wires stretched from a perforated ring at the top to a series of screws in the concrete base. This cage served as a support for the fabric and it held it at a constant distance of 2 cm (0·79 in.) away from the pipe. The cage was encircled by a movable ring of $\frac{1}{4}$ in. gas pipe with a number of holes in its inner side to serve for gas jets. When the gas was lighted it provided a ring of flame at the base of the fabric which ignited the specimen evenly all round. The gas flame was extinguished immediately the fabric was lighted.

Calibration of the apparatus

In view of the heat conduction loss down the thermocouple leads, it was not possible to use the apparatus absolutely.

The method of calibration consisted of applying heat to the outside of the pipe for a known time, measuring the temperature difference across the wall of the pipe with the iron constantan thermocouples and the rise in temperature of the water in the pipe. Flames from the gas ring were in contact with the pipe over a depth of water of 3 cm (1·18 in.) and the heat was assumed to enter the water only over this depth. The pipe thermocouples were inside this region and their output was continuously recorded during the application of the gas flame. A series of tests were made at different gas pressures. The final steady value of the output from the pipe thermocouples and the maximum value of the water temperature were measured after the flame had been applied for one minute. These enabled the mean rate of heat supply per unit area to the water to be calculated.

The value of this rate of heat flow H and the associated output from the pipe thermocouples are given in Fig. 4 as the best fitting line through 19 points with 95 per cent confidence limits. Within the limits of experimental error the heat transfer is proportional to the thermo-e.m.f. The assumption that heat entered the water over a constant depth of 3 cm and that the heat transfer as measured by the thermocouples was typical of the mean value appears justified in view of the calibration being effectively linear between thermocouple output and water temperature.

Experimental method

Fabrics were conditioned at 70° ± 3°F and 61 ± 3 per cent relative humidity which for cotton fabrics gives a moisture content of about 5 per cent. A sample, size 46 x 61 cm (18 x 23 in.) of fabric was hung around the apparatus on the wire cage, the top edge of the fabric level with the water surface.

The specimen was ignited all round its lower edge by means of the gas ring. The output from the iron-constantan thermocouple system was continuously recorded and the test was regarded as over as soon as the output fell to an insignificant value. At this stage, the fabric was burnt away except in some tests when a carbon skeleton remained. The rise in temperature of the water was noted and this provided a check on the thermocouple system, since integration of the flux-time curve should enable an estimate to be made of the rise in temperature of the water.

After each test the pipe was wiped clean and dry and an interval of 30 minutes allowed. Four or six specimens of each fabric were tested.

Experimental results

A summary of the results of the tests are given in Table 2. A mean curve of the variation in heat flow with time was plotted for the several specimens tested of any one fabric and the area A under the heat flux-time curve measured, to obtain "Q" the total heat passing to the surface, i.e. the heat dosage. The mean curves for heat transfer against time are shown in Figures 5-8.

Table 2
Heat dosage and maximum rate of heat transfer Method II

Materials	Fig. No. for heat flux-time curve	Weight per unit area mg cm^{-2} (mg cm^{-2} x 0·295 = oz.yd^{-2})	Heat dosage "Q"	Maximum rate of heat transfer cal cm^{-2} sec^{-1} H max
Cellulose materials				
Viscose rayon Net C	5	1·6	0·7	0·22
Viscose rayon Net D	5	2·5	1·3	0·28
Muslin	5	3·4	2·9	0·18
Cotton Net A	5	4·4	1·1	0·31
Newspaper	7	5·5	6·7	0·60
Cotton No. 1	6	6·5	8·7	0·73
" " 2	6	7·8	10·2	0·75
" " 3	6	13·5	17·2	0·68
Viscose locknit rayon	7	15·5	9·0	0·28
Wool mixture materials				
20% Wool 80% Cotton	8	12·7	15·5	0·75
40% Wool 60% Cotton	8	11·8	8·6	0·65
60% Wool 40% Cotton	8	13·8	11·2	0·71
100% Wool*		19·0	-	0·29

*Very irregular burning.

Within the limits of experimental error no systematic discrepancy was found between the predicted and the measured rise in temperature of the water, so that the calibration curve can be regarded as satisfactory.

The heat dosage, measured by method II is plotted against weight per unit area in Figure 2, together with the results obtained by Method I.

Heat transfer

After the fabric is ignited the flame increases in size and the heat transfer rate increases up to the time when the thermocouples are passed by the base of the flame. The curves for heat transfer against time, Figs. 5 - 8, show a peak corresponding to the point at which the base of the flames passes the thermocouple. There is a rapid rise up to the peak value followed by cooling.

With the light fabrics such as nets, the peak in the curve appears soon after they are lit but with heavier textiles the peak is preceded by a shoulder. This is presumed to be because the flames reached a limiting size before passing the thermocouples. This is particularly noticeable with the wool-cotton mixtures, whereas with the faster burning light weight materials an equilibrium flame speed may not have been reached. The viscose locknit rayon gave a low maximum heat transfer which appeared to be associated with a smaller volume of flame compared with the other fabrics.

For cellulosic materials the time to burn unit length is directly proportional to the weight (1). If the time from ignition to the appearance of the peak on the curves is regarded as the time to burn unit length then the curve for weight against time to peak should be a straight line. This is shown in Fig. 9 to be so for the cellulosic materials as a group.

From Fig. 2 it may be seen that heat dosage is proportional to weight per unit area, though the nets and muslin do not evolve so much heat for their weight compared with the other fabrics. The distribution of points shows good agreement between the two experimental methods of measurement of heat dosage. The heat transferred amounts to about 1·2 cal/cm^2 for every mg/cm^2 (0·3 oz/yd^2) of fabric. This corresponds to a rate of heat transfer of 1,200 cal/g of fabric burnt. In other words, about one-third of the heat of combustion is transferred to the surface.

Fig. 10 shows the maximum value of the heat flux. Relations of proportionality between weight per unit area and time to peak heat flux and also between weight per unit area and total dosage imply that so long as the shapes of the flux-time curves are the same, the peak heat flux is independent of the weight per unit area. This is so for all the materials tested, except the four nets and the locknit rayon, these materials producing a significantly lower heat dosage than would be expected from their weight.

The maximum heat flux is approximately 0·7 cal cm^{-2} sec^{-1}. This agrees with other data (3).

Wool-Cotton Mixture

At the end of Table 1 there are some results for wool and wool-cotton mixtures, these tests were made to see if the heat transfer from burning wool was different from that of cellulosic materials, but the results show no difference between the two types of fabric, see Figure 2. Although burning around the pipe was not always even for any material, it appeared to be less so for wool than for cotton.

Fabrics treated with flame retardant

Two of the treated fabrics gave a significantly lower heat dosage than untreated cotton. This may be contrasted with the behaviour of untreated materials. The heavier they are the slower they burn, but the greater the heat dosage.

Flame resistance rating

Flame resistance rating is directly proportional to weight for cellulosic materials (1), (2). It follows that heat dosage is generally proportional to flame resistance rating, with the exception of very light weight materials, and a scale of flame resistance rating parallel to the weight axis is drawn in Figure 2.

Burns

It is shown in Figure 9 that the time to peak intensity is proportional to weight per unit area, and in Figure 2 that heat dosage is proportional to weight. Figure 11 is a curve for heat dosage against time, this is compared with curves of heat dosage against exposure time for coagulation burns (Hinshaw *et al*) (4) and for unbearable pain (Buettner) (5). The line denoting the heat output from fabrics is always above the limiting curve for burns except for fabrics having a weight of about $\frac{1}{3}$ oz/yd^2 (6).

It should be mentioned that whereas the curve of heat output from burning fabrics is approximately triangular in shape with respect to time, the experiments of Buettner and Hinshaw were conducted with square pulse radiation; the effect of this would be to reduce the amount of heat from the fabric required to produce a given degree of damage. The figure of $\frac{1}{3}$ oz/yd^2 may, therefore, be optimistic.

Conclusions

The heat transfer to a nearby surface by burning fabrics is about one-third of their calorific value, no marked differences being observed between wool and cotton.

The heat dosage, although increasing with the weight of the fabric, is even for normal light weight fabrics considerably above the minimum value that will cause severe burns.

The maximum heat flux from the flames to the surface is about 0.7 cal cm^{-2} s^{-1}.

References

(1) Lawson, D. I., Webster, C. T., Gregsten, M. J. The flammability of fabrics. Journal Text. Inst. 1955, 46, T453-T463.

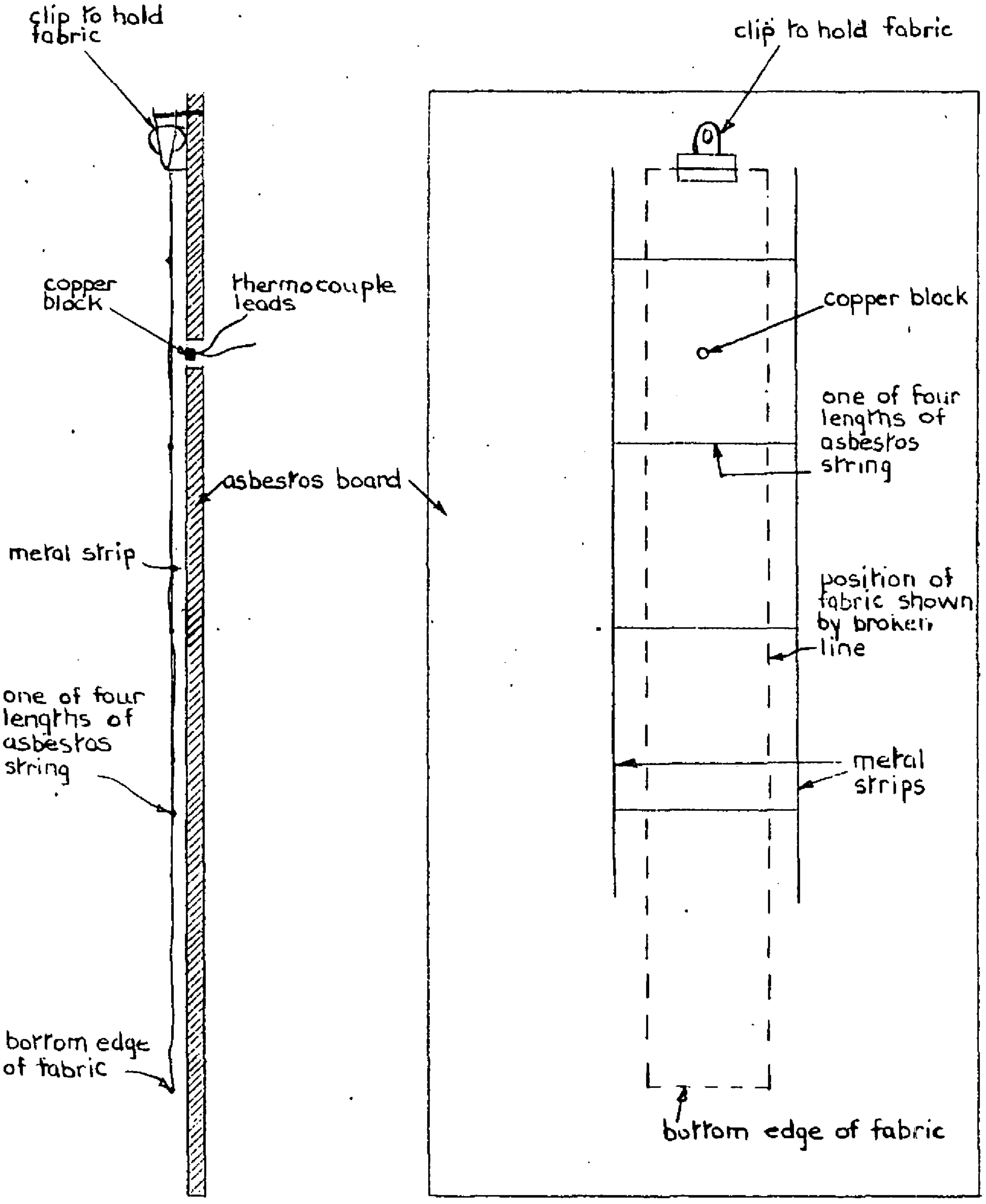
(2) British Standards Institution. P.D. 2777-1957. The flammability of apparel fabrics in relation to domestic burning accidents.

(3) Hinkley, P. L., Simms, D. L., Millar, D. W. Materials suitable for clothing aircraft crash rescue workers. Part II. F.R. Note 220/1955.

(4) Bales, H. W., Hinshaw, J. R. and Pearse, H. E. A comparison of the effects of radiant thermal energy on bare blackened and whitened pig skin. U.S. Atomic Energy Commission UR-438. University of Rochester, 1956.

(5) Buettner, K. Effects of extreme heat and cold on human skin. II Surface temperature, pain and heat conductivity in experiments with radiant heat. J. Appl. Physiol. 1951, 3 (12) 703-13.

(6) Lawson, D. I. "The Contribution of Apparel and Household Textiles to Fire Accidents". Textile Institute Conference Paper. Oct. 1957.



SIDE ELEVATION

FRONT ELEVATION

FIG.1. DIAGRAM OF APPARATUS USED IN METHOD I

F.R.340. 1/2912

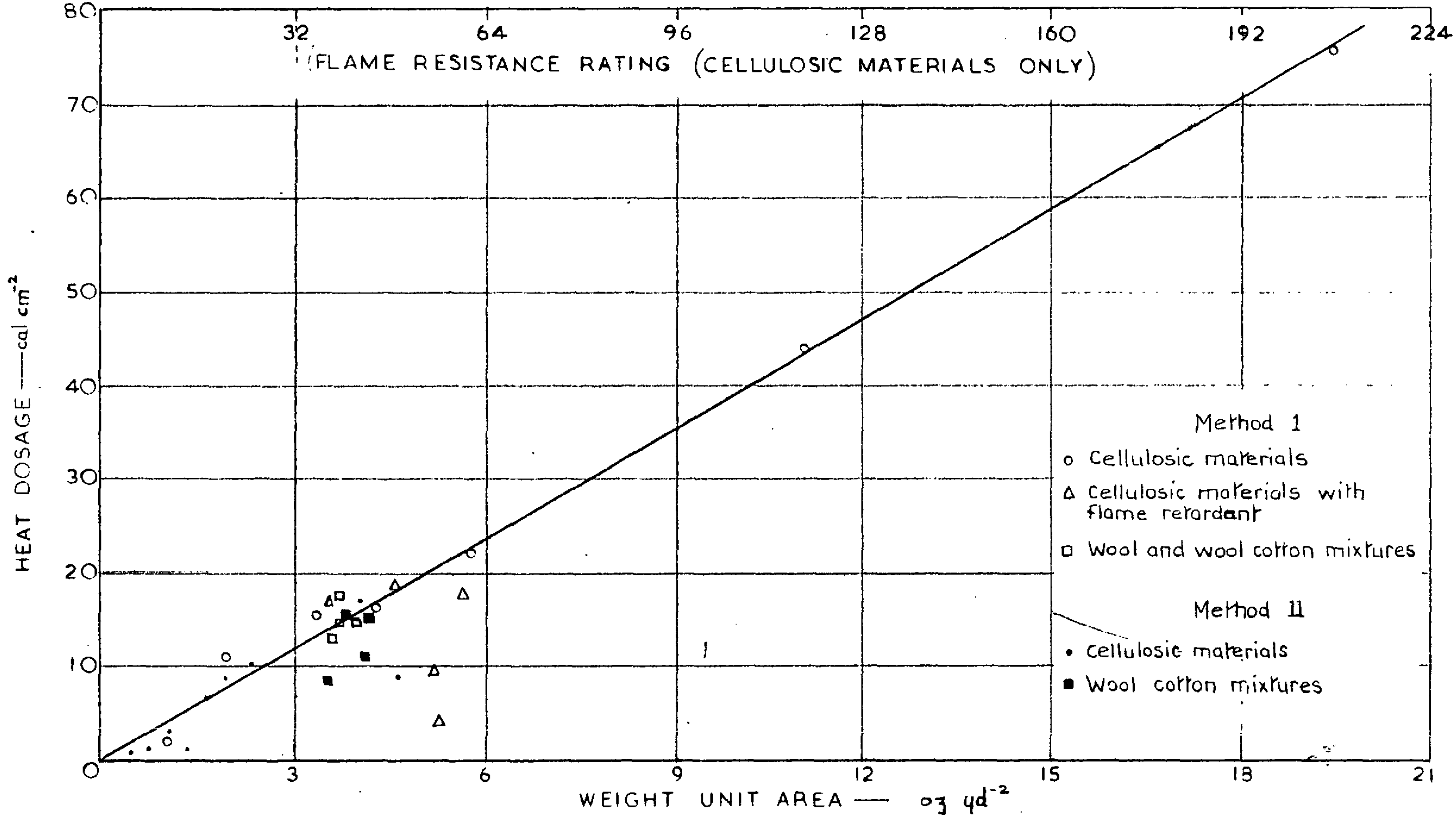


FIG. 2. HEAT DOSAGE AS A FUNCTION OF WEIGHT PER UNIT AREA AND FLAME RESISTANCE RATING

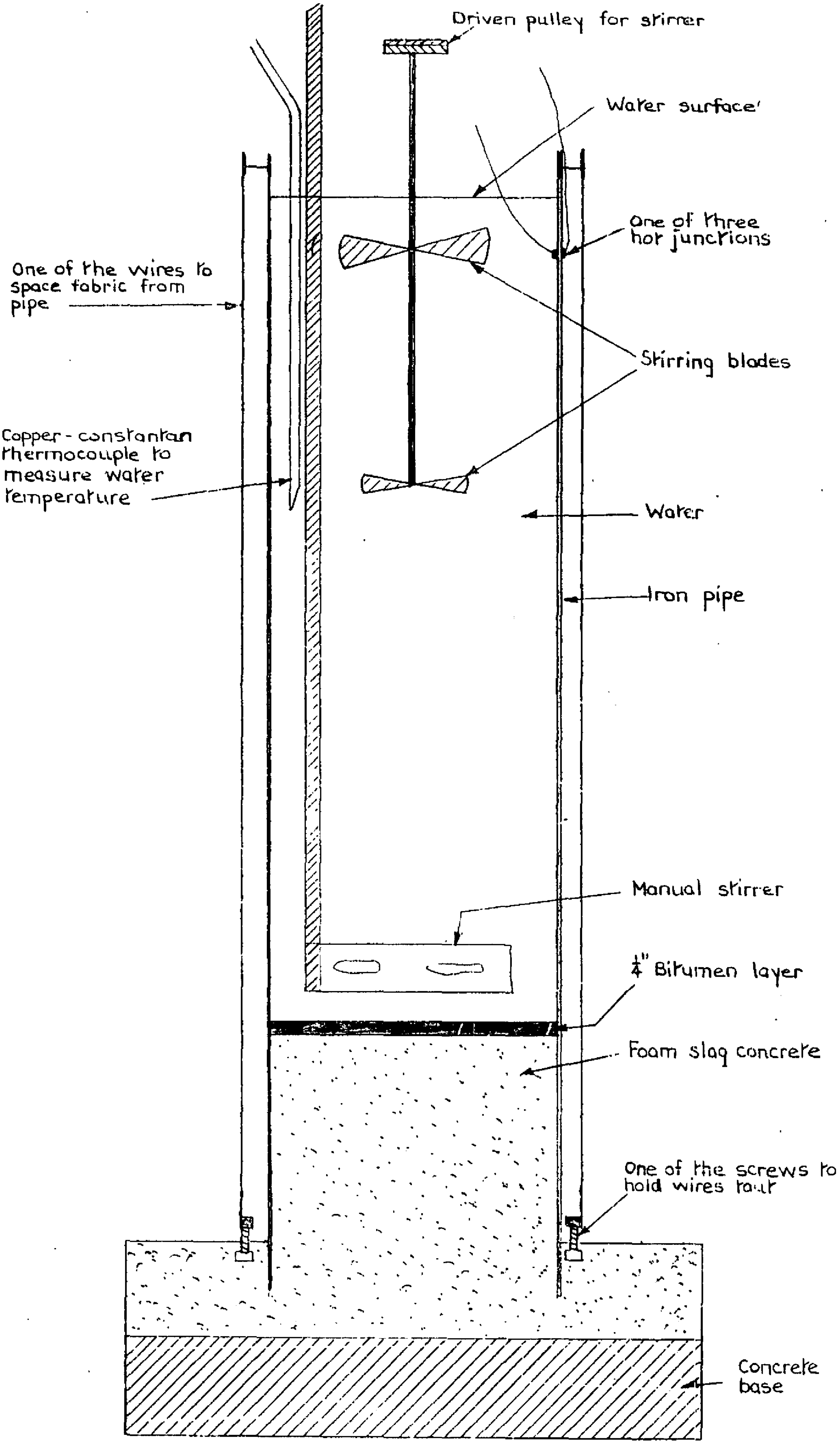


FIG. 3. CROSS SECTION OF APPARATUS USED IN METHOD II

F.R 343 1/2913

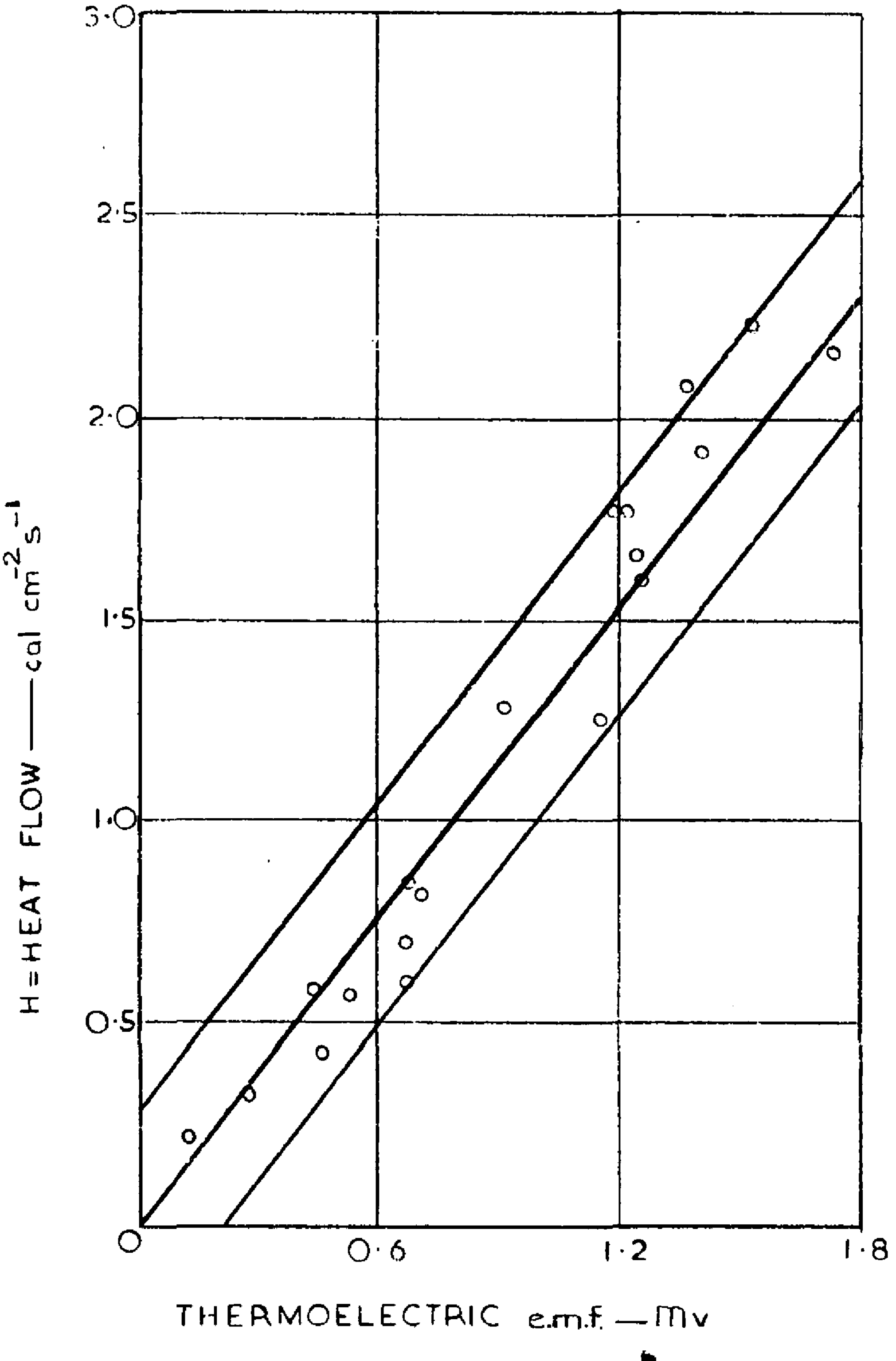


FIG. 4. CALIBRATION OF THERMOELECTRIC e.m.f WITH HEAT FLUX AND 95 per cent CONFIDENCE LIMITS

FR. 340 1/2914

F.R.340 1/2915

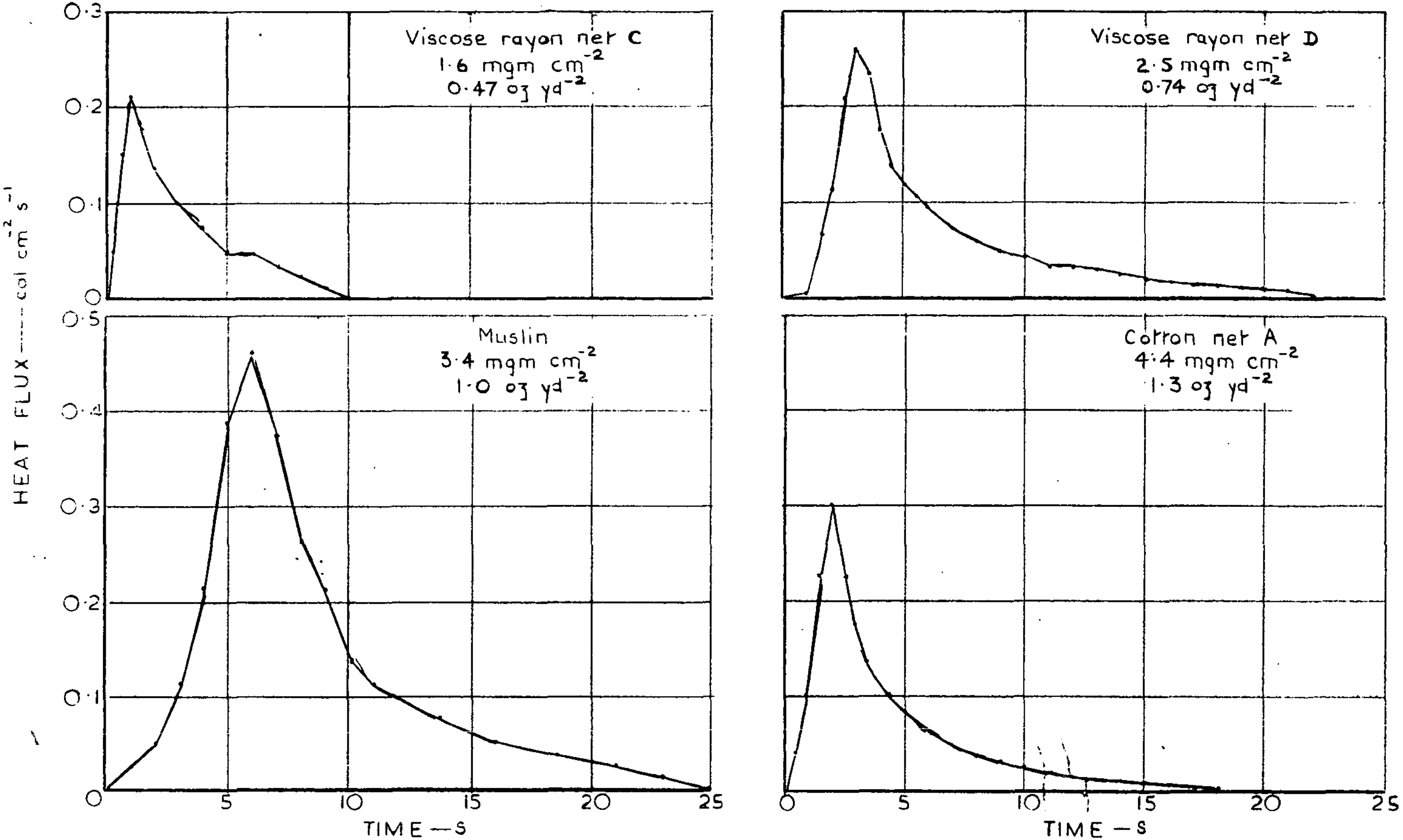


FIG. 5. VARIATION OF HEAT FLUX WITH TIME

F.R. 340 1/2916

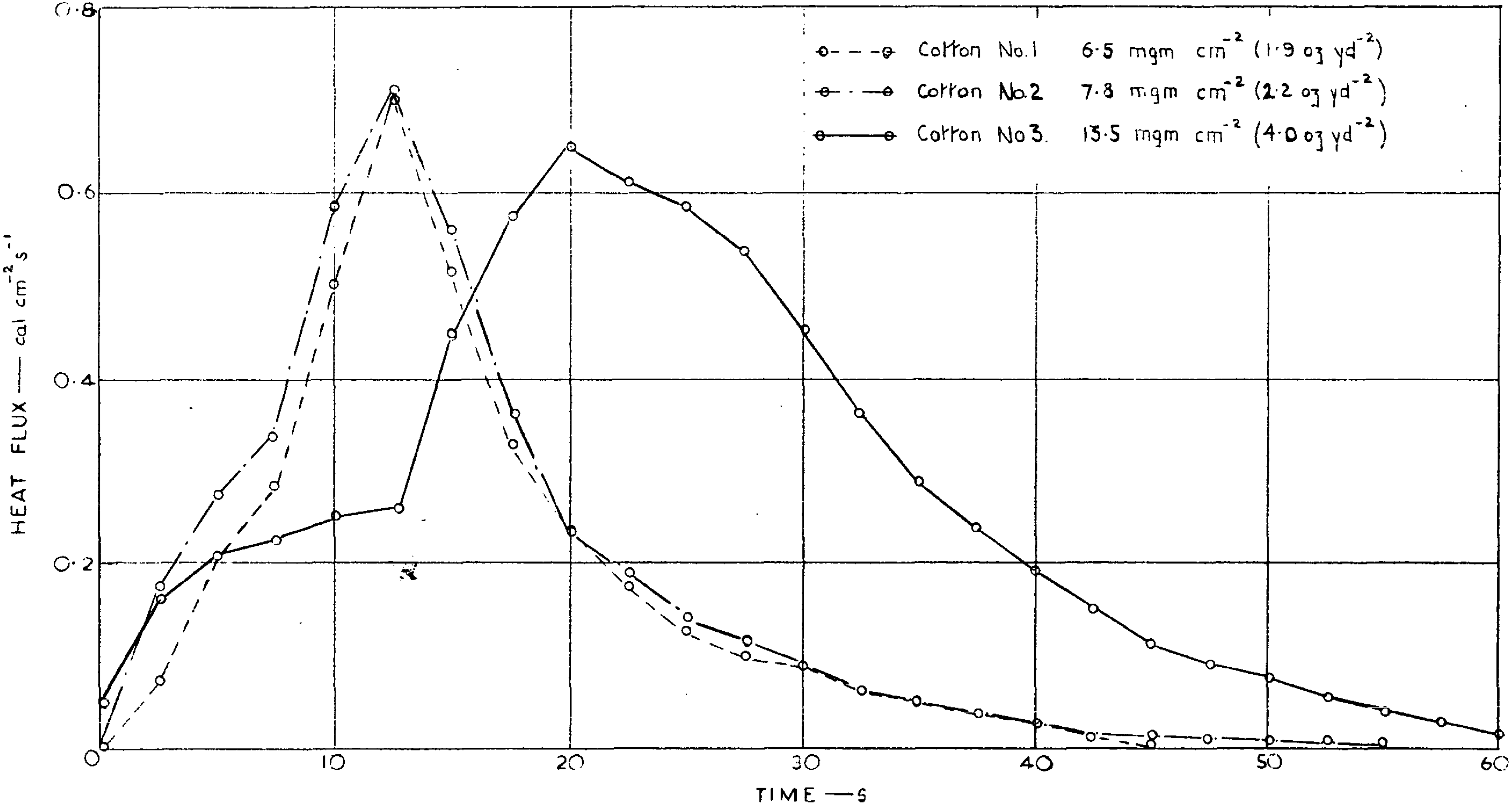


FIG. 6. VARIATION OF HEAT FLUX WITH TIME

F.R.340. 1/2917.

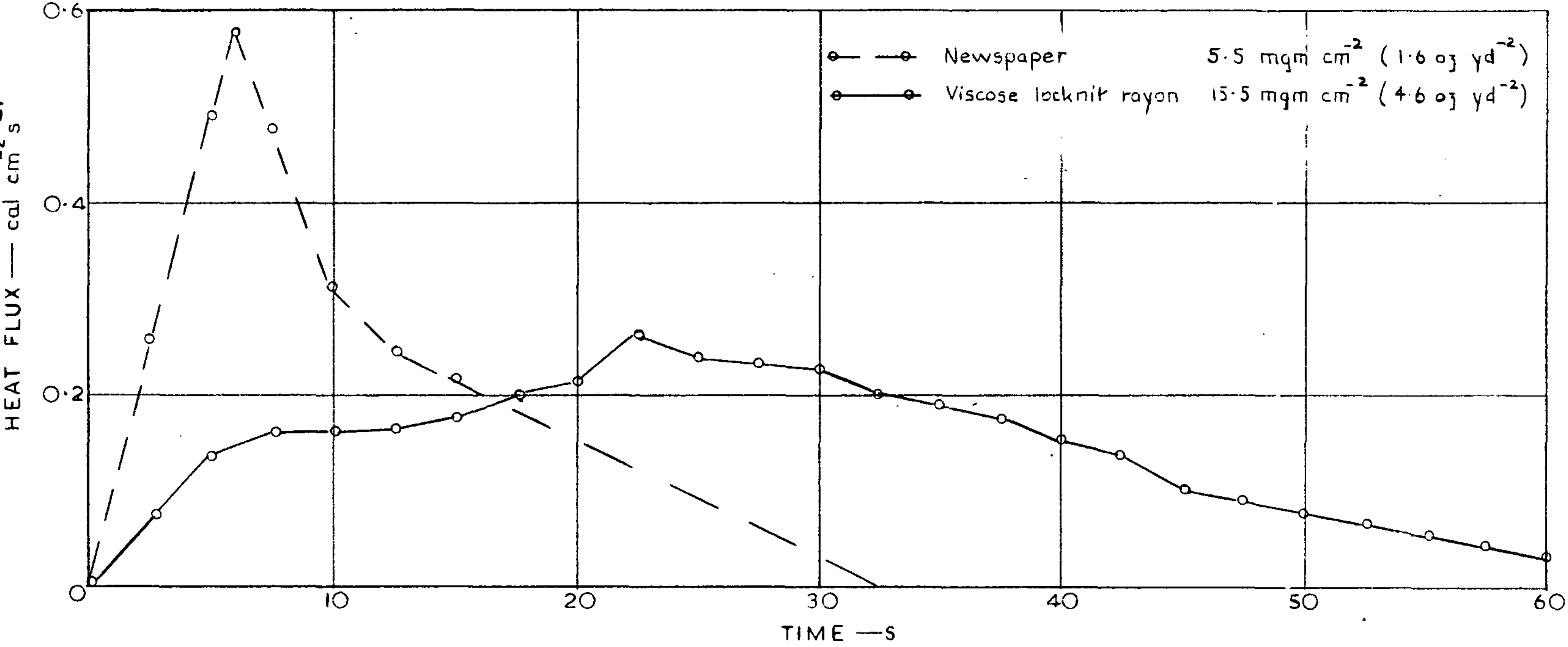


FIG. 7. VARIATION OF HEAT FLUX WITH TIME

FR340 1/2918

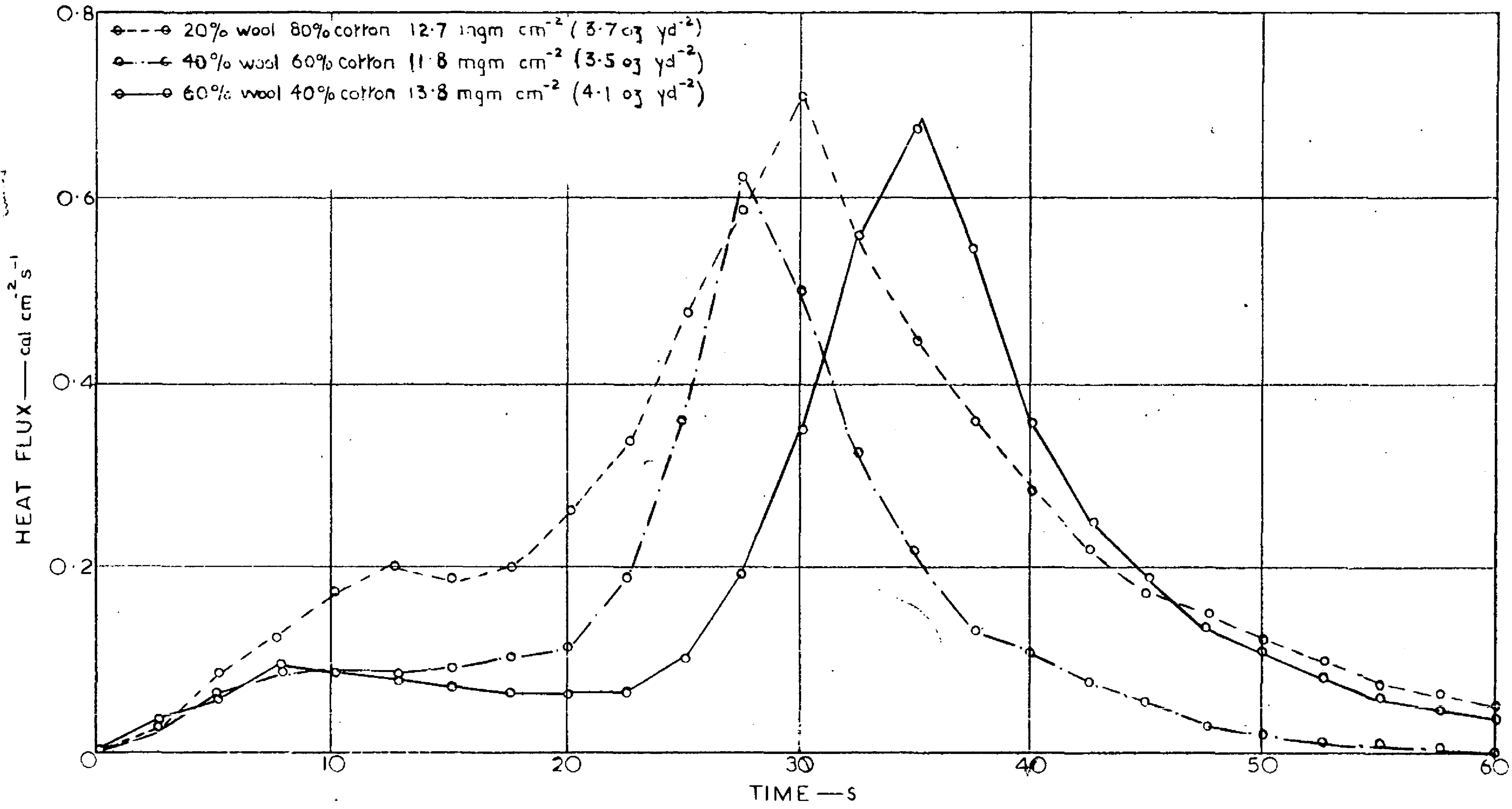


FIG. 8. VARIATION OF HEAT FLUX WITH TIME

F.R.340 1/2919

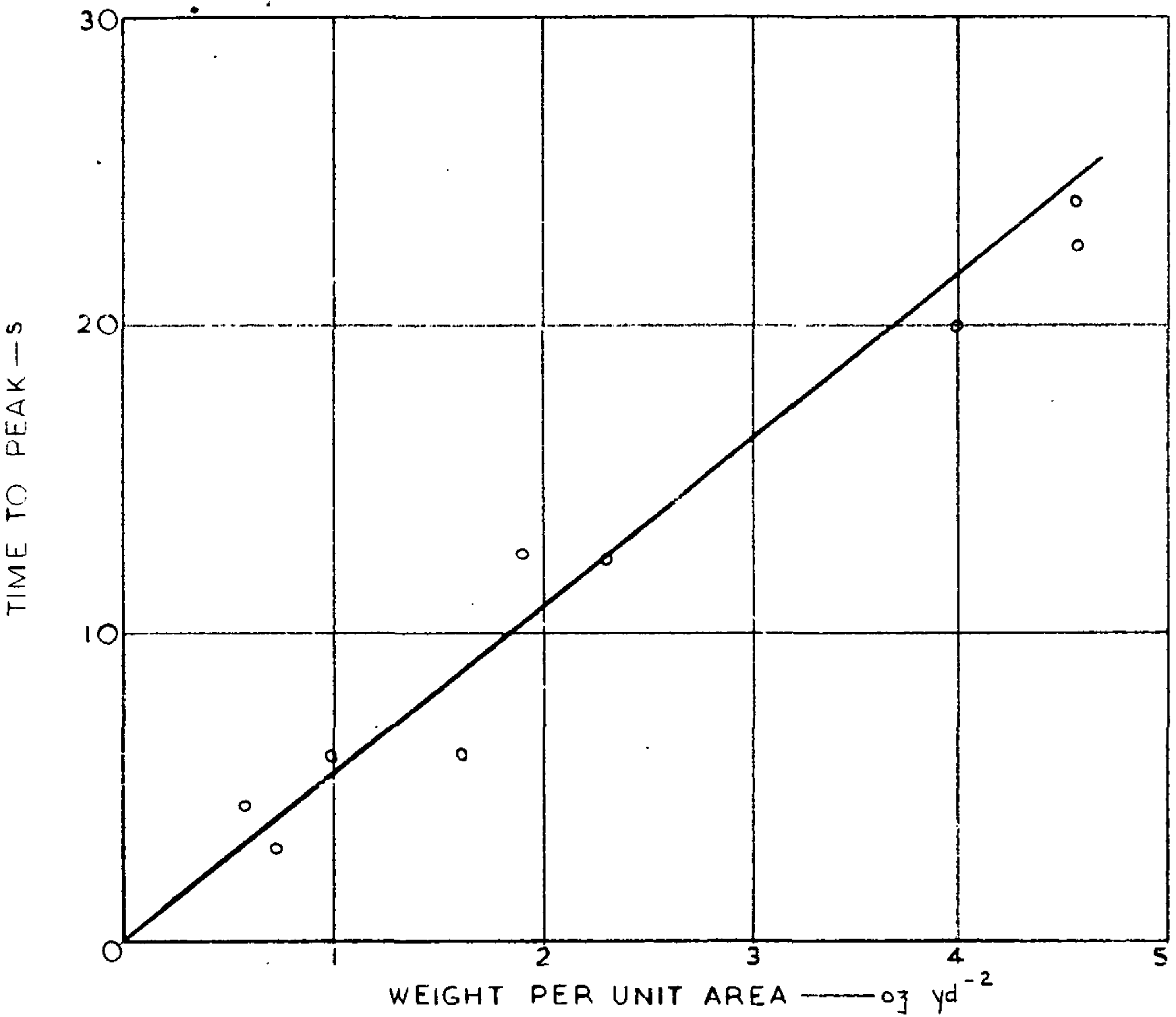


FIG. 9. TIME TO PEAK INTENSITY AS A FUNCTION OF WEIGHT PER UNIT AREA FOR CELLULOSIC MATERIALS

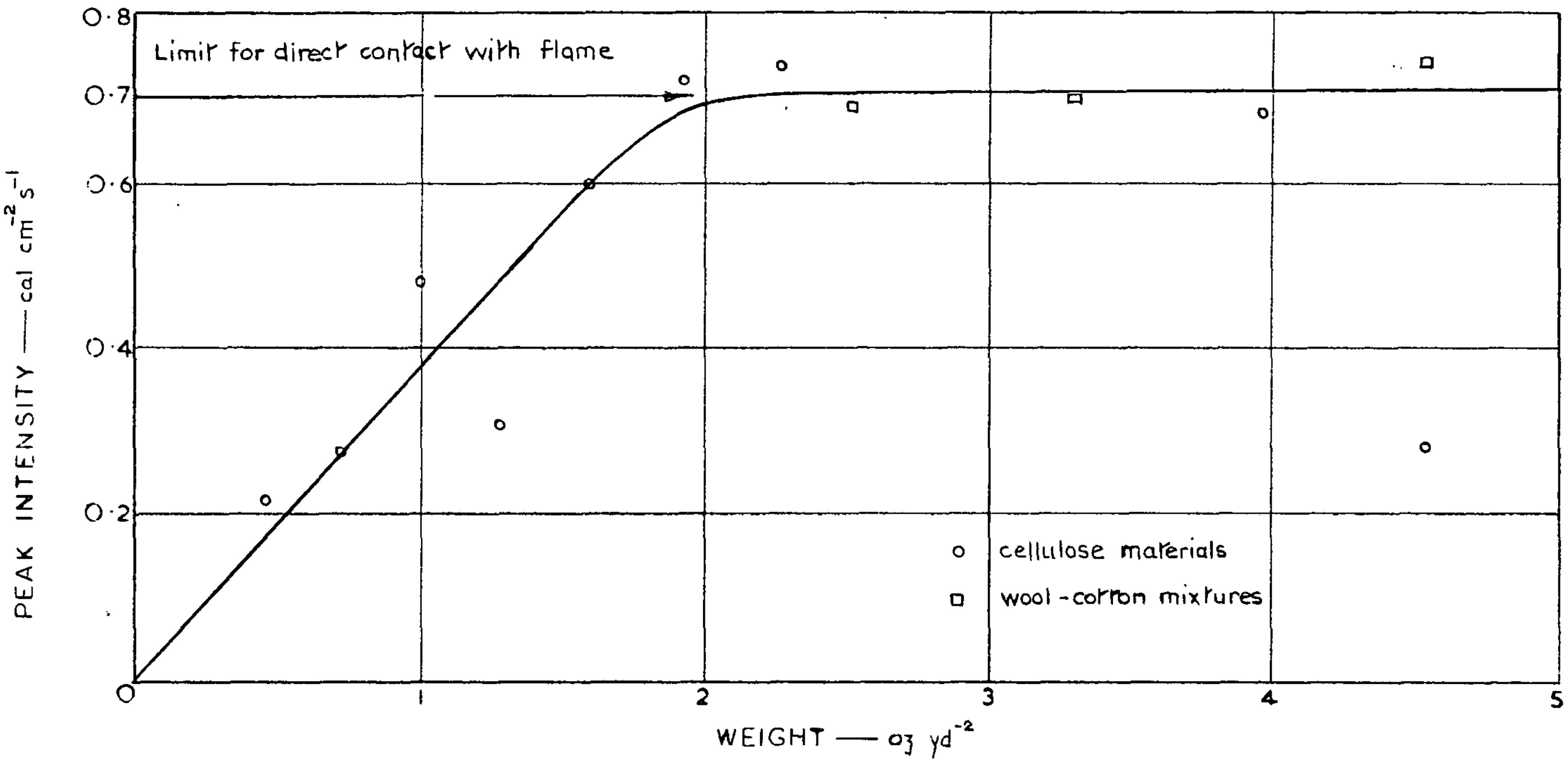


FIG. 10. MAXIMUM HEAT FLUX AS A FUNCTION OF WEIGHT/UNIT AREA

1/2789

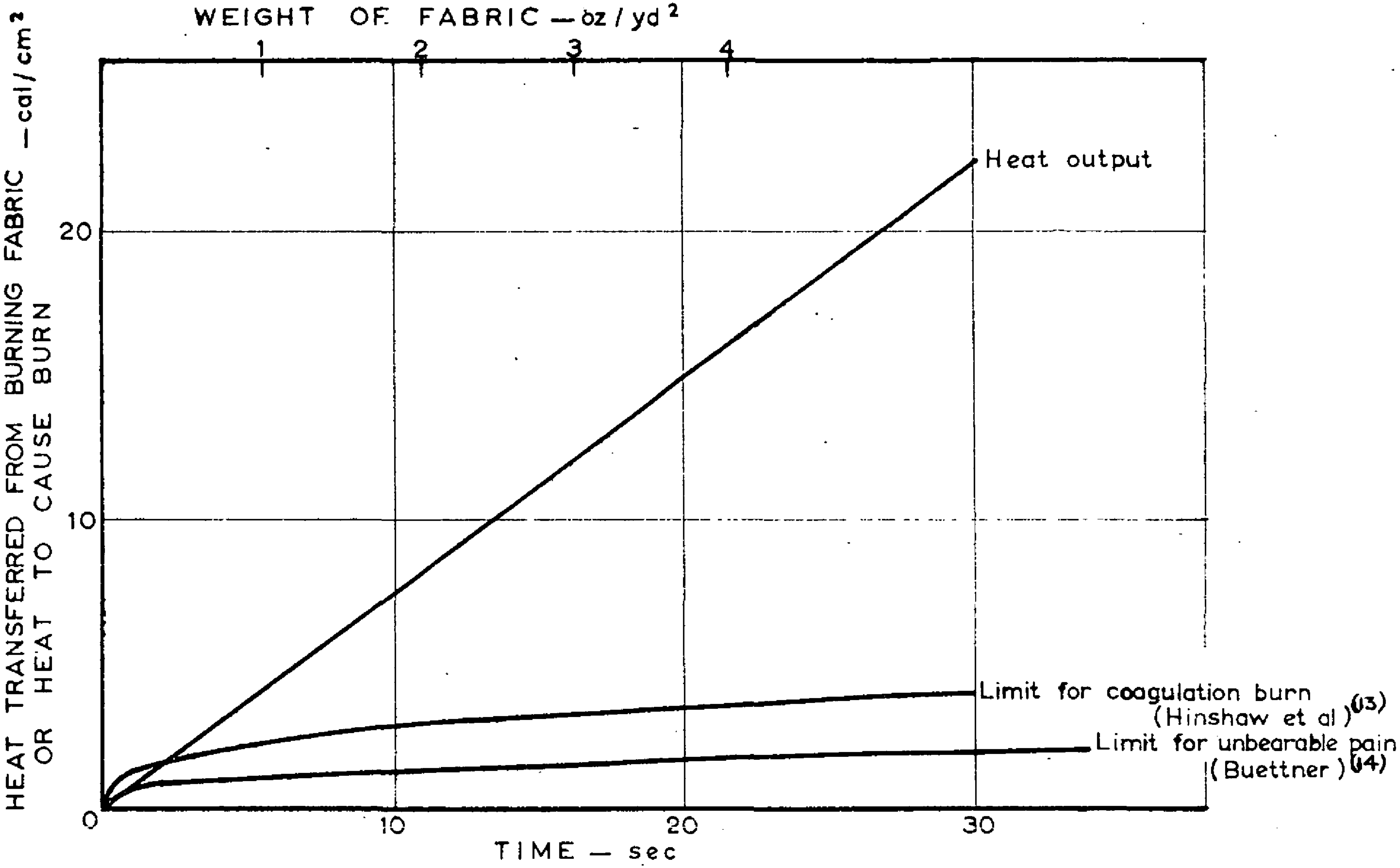


FIG. 12. COMPARISON OF HEAT DOSE FROM BURNING FABRIC AND HEAT DOSE CAUSING BURNS FOR DIFFERENT EXPOSURE TIMES