F.R. Note No. 398/1959

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

THE BURNING OF FIRES IN ROOMS

PART I - SMALL SCALE TESTS WITH CRIBS AND HIGH VENTILATION

by

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

Summary

This report describes experiments to study the burning of fires in a simple well-ventilated enclosure. These, the first in a programme covering various aspects of this subject, were made in a one foot cube with ventilation through one side. The combustible material was wood in the form of a crib and the rate of burning was obtained by continuous weighing. Measurements were made of the flame height, the radiation from the opening and the flames. The effect of different crib designs and weights of wood on these was studied. Only for 1 inch wood, the largest section used, was the effect of crib design negligible in these particular experimental conditions. The results will be discussed in detail when further data from tests in larger models are available.

May 1959

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Boreham Wood,
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1. Introduction

This report deals with certain aspects of the burning of fires in rooms, in particular the maximum rate of burning and the transfer of heat from the flames to the room above by radiation through the window. The combustible material consisted of sticks of wood built into a crib. This was done to obtain a standard fire for which the properties of total weight, surface area and internal ventilation could be independently varied. No attempt was made to study the growth of the fire, the object of this study being the fully developed fire burning at approximately constant rate. Small scale tests have been made in a 1 ft cube box. The work is continuing with similar boxes 2 ft and 3 ft cube and other degrees of ventilation. The present report is, however, only concerned with the preliminary tests on the 1 ft box. Later reports will contain a fuller discussion of the results, when the work on larger scales is completed.

2. Experimental Arrangements

2.1. Weight measurements

The burning box which is shown in Fig. 1 was suspended from the end of a steel cantilever, the strain in which was a measure of the total weight.

The cantilever consisted of a $\frac{1}{2}$ in. square section of mild steel bar with 5 in. grouted into a wall and 49 in. projecting from the wall. Two resistance strain gauges were secured to the bar, one on the upper and the other on the lower face, both about 1 in. from the wall.

The gauges constituted the two arms of a Wheatstone bridge. In the other two arms of the bridge two fixed resistances and a variable resistance were used. In the position normally taken by a galvanometer, a D.C. amplifier was connected to a recorder. The circuit of the bridge is given in Fig. 2. The bridge could be balanced by a precision type single wire variable resistance so that there was a stable output from the amplifier. With a constant test load this system gives a stable output to within ±1% for at least 3 hours. A calibration curve of weight against output (mv) for the cantilever is shown in Fig. 3. This is, as expected, a straight line. The overall response time of the equipment was less than one second.

2.2. Radiation measurements

During a fire the levels of radiation from the open side of the box, and from the flame above, were measured. The general arrangement of the apparatus is shown in Fig. 4, Plates I + II. For the measurement of the radiation from the open side of the box, a copper asbestos disc radiometer (1) was used. The disc was located on the central horizontal axis of the model, and 6 in. in front of the plane of the open side. In order to obtain some measure of the radiation that would enter a room immediately above a burning room, the radiation from the flame above the box was measured by means of a copper asbestos disc and a bright gold disc 1 in. away in the same plane connected in opposition. This arrangement was found necessary to balance out the convective transfer from the hot gases passing over the box and on to the copper disc. The copper asbestos gold disc combination was calibrated against a standard radiometer in front of a surface combustion radiation panel; the curve is shown in Figure 5. This disc combination was placed at a height of 6 in. above the top of the box in a plane parallel to the opening and 2 in. behind it, and centrally with respect to the sides of the opening. A bright aluminium sheet was laid on top of the box to reduce the radiation from the top.

2.3. Design of cribs

Table 1 shows the various designs of wood cribs used in these experiments. The sticks used in the experiments were all square sections and all pieces were 10 in. long.

TABLE I

TYPES OF CRIBS USED IN TESTS

Weight lb.	Average Density of Wood gm/cc	Size in.	Packing Densities				
9	0.53	1	100				
5	0.53	1	100	50	$33\frac{1}{3}$		
3	0.53	1	100	50	$33\frac{1}{3}$	25	
5	0.46	$\frac{1}{2}$	100	50	$33\frac{1}{3}$		
3	0.46	$\frac{1}{2}$	100	50	$33\frac{1}{3}$	25	
$1\frac{1}{2}$	0.46	$\frac{1}{2}$	100	50	$33\frac{1}{3}$	25	20
5	0.40	$\frac{3}{8}$	100				
5	0.43	$\frac{1}{4}$	100				

The packing densities given in Table 1 are computed as the thickness of a stick as a percentage of the spacing between sticks. Thus 100 indicates 1 : 1 spacing, that is the sticks are one thickness apart; 50 a 1 : 2 spacing, two thicknesses apart, etc.

Pine (size 1 in.&$\frac{1}{2}$in.) and beech (size $\frac{3}{8}$&$\frac{1}{4}$) conditioned to equilibrium in air at 68°F and 65% relative humidity, were used.

2.4. Experimental Procedure

Before a test was started the box was hung on the cantilever and a large, luminous gas flame played on the inside so that the whole surface was heated for a period of $\frac{1}{2}$ hour. This was necessary to remove absorbed moisture from the asbestos wood. After heating, the box was allowed to cool for one hour, and then the crib was built inside in about $\frac{1}{4}$ hour. While it was being built, two pieces of metaldehyde were laid at the centre of the base of the crib to provide a source of ignition. Immediately the crib was built it was ignited and continuous records were made of the loss of weight, the radiation from the fire in the box, and the radiation from the flame above the box.

3. Results

3.1. Analysis of results

Figure 6 shows two typical loss of weight curves. In all the tests the central portion was practically a straight line. This part was used to calculate the maximum rate of loss of weight. Figures 7 and 8 show some typical radiation curves from flames above and from the open side of the box.

RESULTS OF CRIB TESTS IN 1 FT CUBE BOX

TABLE 2

Test No.	Type of Crib Weight Size Packing Density P.D. and Crib Height H	Maximum rate of loss of weight gm sec^{-1}	Maximum rate of loss of weight per unit area mg $cm^{-2}sec^{-1}$	Maximum Radiation		Maximum Flame Height above box cm.
				from Opening Cal $cm^{-2}sec^{-1}$	from flame above box Cal $cm^{-2}sec^{-1}$	
	4100gm of 2.54 cm wood					
28	PD = 100,H 25.4 cm	4.43	0.46	1.10	0.27	90
	2300gm of 2.54 cm wood					
13 & 14	PD = 100,H 14.6 cm	3.25	0.56	1.00	0.13	53
18	PD = 50,H 19.0 cm	3.63	0.57	1.10	0.17	45
19	PD = 33⅓,H 28.0 cm	3.70	0.58	0.97	0.20	60
	1400 gm of 2.54 cm wood					
24	PD = 100,H. 8.9 cm	2.05	0.59	0.78	0.05	30
25	PD = 50,H 11.5 cm	2.12	0.55	0.95	0.07	30
26	PD = 33⅓,H 15.2 cm	2.35	0.58	0.78	0.08	30
27	PD = 25,H 14 cm	2.35	0.57	0.87	0.07	30
	2300gm of 1.27 cm wood					
7 & 12	PD = 100,H 15.2 cm	3.47	0.29	0.90	0.19	60
20 & 13	PD = 50,H 23.0 cm	4.92	0.35	0.76	0.28	75
21	PD = 33⅓,H 30.5 cm	4.08	0.29	0.73	0.32	90
	1400gm of 1.27 cm wood					
29	PD = 100,H 9.5 cm	3.58	0.50	0.62	0.13	60
30	PD = 50,H 12.7 cm	4.93	0.66	0.60	0.18	75
31	PD = 33⅓,H 19.1 cm	5.30	0.61	0.69	0.21	90
32	PD = 25,H 19.1 cm	5.30	0.75	0.60	0.20	75
	700gm of 1.27 cm wood					
37	PD = 100,H 5.1 cm	1.90	0.55	0.45	0.04	23
33	PD = 50,H 7.6 cm	2.35	0.55	0.51	0.04	30
34	PD = 33⅓,H 10.2 cm	3.25	0.73	0.54	0.08	45
35	PD = 25,H 12.7 cm	3.33	0.72	0.60	0.09	45
36	PD = 20,H 12.7 cm	3.48	0.75	0.60	0.09	30
	2300gm of 0.95 cm wood					
11	PD = 100,H 19 cm	2.95	0.44	0.80	0.19	60
	1400gm of 0.95 cm wood					
39 & 41	PD = 33⅓,H 18.4 cm	4.17	0.31	0.51	0.20	75
	2300gm of 0.64 cm wood					
10	PD = 100,H 17 cm	3.40	0.11	0.80	0.16	60
	1400gm of .64 cm wood					
40 & 42	PD = 33⅓ H, 21.6 cm	4.47	0.23	0.47	0.23	90
	2300gm of 2.54 cm wood					
38	PD = 100,H 17.8 cm Back and front of box half open	3.78	0.56	0.24	0.24	75
	2300gm of 2.54 cm wood					
16	PD = 100,H 14 cm On open board	2.73	0.50			75*
	2300gm of 1.27 cm wood					
17	PD = 100,H 14 cm On open board	2.88	0.24			100*

* Height of flame from top of crib

The maximum radiation intensities from the flame above the box and from the burning crib inside the box, are given together with the height of flame in Table 2.

The results given in Table 2 have been subjected to a multiple regression analysis. For simplicity it was assumed that in the regression equations the rate of burning, the radiation levels, and the flame height were linear with respect to packing density, stick size and weight of crib.

In calculating the rate of loss of weight per unit initial area, the area was calculated from

$$A = 2\,t\,l \left\{ \frac{1 + \frac{200}{p}}{1 + \frac{100}{p}} \right\} \times N \qquad \text{.........(1)}$$

where

A = total exposed area of wood
t = thickness of stick
l = length of stick
p = packing density $= 100 \times \dfrac{\text{stick thickness}}{\text{distance between sticks}}$
N = number of sticks

Allowance is made in this formula for the unexposed area due to overlapping of sticks.

The signs with the significance levels in Table 3 show the direction of the effect i.e. they are the same signs as in equations (2) - (6). A somewhat surprising result was that the multiple correlation coefficient was larger for the radiation measurements than for the weight loss, indicating that the assumption of linearity is more nearly correct for radiation than for the other factors.

TABLE 3

LEVELS OF SIGNIFICANCE, STANDARD DEVIATIONS AND MULTIPLE CORRELATION COEFFICIENTS FOR STATISTICAL ANALYSIS

Independent Factor / Dependent Factor	Weight of Crib	Thickness of Wood	Packing Density	Multiple Correlation coefficient	Standard deviation σ In original units	$\frac{\sigma}{\text{mean}}$
Rate of loss of weight	1% (+ve)			0.59	1.1 gm/sec	0.40
Radiation from above box	0.1% (+ve)	1% (-ve)	1% (-ve)	0.93	0.038 cal $cm^{-2} sec^{-1}$	0.26
Radiation from front of box	0.1% (+ve)	1% (+ve)		0.92	0.079 cal $cm^{-2} sec^{-1}$	0.10
Height of Flame	0.1% (+ve)	1% (-ve)	5% (-ve)	0.81	14 cm.	0.25
Rate of wt. loss per unit area	0.1% (-ve)	1% (+ve)	5% (-ve)	0.82	0.12 mgm $cm^{-2} sec^{-1}$	0.24

From the analysis the following regression equations were obtained:-

$$u = 1.0 \times 10^{-3} W + 1.4 \qquad (2)$$
$$r_f = 0.1 \times 10^{-3} W - 0.059t - 1.2 \times 10^{-3}P + 0.14 \qquad (3)$$
$$r_B = 0.14 \times 10^{-3}W + 0.14t + 0.29 \qquad (4)$$
$$f = 2.4 \times 10^{-2} W - 17t - (0.20P) + 56 \qquad (5)$$
$$m'' = -0.14 \times 10^{-3}W + 0.19t - 0.16 \times 10^{-2}P + 0.54 \qquad (6)$$

where

r_B = maximum radiation from box cal. $cm^{-2}sec^{-1}$

u = maximum rate of weight loss : gm/sec

W = initial weight of crib : gm.

t = thickness of stick : cm.

P = packing density = $100 \times \frac{\text{stick thickness}}{\text{distance between sticks}}$

r_f = maximum radiation from flames : cal $cm^{-2}sec^{-1}$

m'' = maximum rate of loss of weight per unit area mgm $cm^{-2}sec^{-1}$

f = maximum flame height : cm.

The levels of significance of each term in the above equations, the standard deviation and the multiple correlation coefficient are given in Table 3.

However, it will be seen from the data in columns 2 and 4 of Table 2 that the burning rate per unit area for 1 in. wood is independent of packing density and total fire load. Strictly speaking, a statistical analysis should exclude 1 in. wood or include non-linear terms. This was not considered worth while at the present stage of the work. If we neglect the results for the largest crib which nearly filled the room and was clearly affected by this, we obtain for the maximum rate of burning per nominal unit area, the value 0.57 ± 0.01 mgm.cm^{-2} sec^{-1}.

3.2. The duration of the fires

In Figure 9, the nominal time for which flames emerge from the windows has been plotted against the nominal duration, these times being defined as follows:-

(1) The flaming time is the time for which the flame radiation is above 5 per cent of its peak value.

(2) Nominal duration - the time it would take to convert all the wood to charcoal, calculated from the total weight and the maximum rate of burning. Since the rate of burning is approximately constant during the time for the weight to fall from 90 to 20 per cent of the initial weight, the nominal duration is 1.43 times this interval.

Figure 9 indicates that these two times are directly related and in practice both definitions are equivalent as definitions of effective duration. The time of growth is deliberately reduced in these tests to ensure that part of the crib is not fully burnt before all of it is alight. There is also some contribution to the total duration from the glowing combustion stage. The duration of these fires was for all cases less than $\frac{1}{4}$ hour. This is a consequence of the relatively high ventilation.

3.3. Radiation results

The intensities of radiation from the flames r_f and the box r_B may be converted into radiation temperatures assuming them to behave as black bodies, i.e.

$$T = \left\{ \frac{r_B}{\phi \sigma} \right\}^{\frac{1}{4}}$$

where ϕ = configuration factor with respect to opening in box

σ = Stefan Boltzmann constant 1.37×10^{-12} cal $cm^{-2} sec^{-1}$ $^{o}C^{-4}$

T = absolute temperature

In the calculation of the radiation temperatures of the flames above the box, the configuration factor ϕ was assumed to be 1. The radiation temperature appears to be about 200°C: this value is low because there is insufficient thickness of flame to give black body conditions. The value of the effective total emissivity is therefore of order 0.035 assuming 900°C for the black body temperature of the flame

Because the thickness of flame is likely to increase with the flame height it is to be expected that the radiation from the flame above the box should be related to flame height. This is shown in Figure 10. The relation may be also seen from the equations (3) and (5). The ratios of the coefficients of the three terms are 240, 300, and 170, which, allowing for the tolerances on each regression coefficient, are of the same order. The black body temperatures for the box have been calculated from the radiation values given in Fig. (8) and they lie in the range 650° - 800°C.

3.4. Flame-height

The values of flame height have been plotted against the gross rate of burning in Figure 11. Although it is clear from equations (2) and (5) that their relation depends on t and P, it is interesting to observe that within the range of these experiments and the accuracy to which flame height was measured, a simple linear relation appears to hold good. The value of the negative intercept on the flame height axis is about 20 cm., which is in agreement with the view that real origin of the flame is within the lower half of the box. There are theoretical reasons for supposing that this relation is not strictly linear and these will be discussed in a later report.

3.5. Comparison with an open fire and miscellaneous tests

Three tests Nos. 38, 16 and 17, Table 2, were made to obtain some indication of the relative significance of ventilation in these experiments. In test No. 38 the top half of the front of the box was closed and the top half of the back of the box opened. It was hoped by this means to provide greater mixing in the box and increase the circulation of air through it. In tests No. 16 and 17 the cribs were built and burnt on flat asbestos boards so that there was no restriction on the air going into the sides of the crib such as may occur in the tests using the box. A comparison of the results of these tests with those for enclosed cribs shows that the rates of burning for enclosed cribs are higher by about 20% than for corresponding cribs in the open.

Discussion

The open cribs burn more slowly than the enclosed cribs and this shows that the enclosed crib fires are heat and not ventilation controlled. This does not, however, explain all the results, for example, equation (4) shows that increasing the size of the crib increases the total burning rate and the radiation from the opening; it presumably also increases the level in the enclosure but the rate of burning per unit area m" decreases as is shown by equation (6). This may be because, for closely packed large cribs, increasing the size of the crib leads to little, if any, increase in the actual surface of wood exposed to heating the lower parts of the crib being shielded from the flames. Also, increasing the size of the crib reduces the amount of oxygen reaching unit area of wood surface. Burning will probably tend to occur more above the crib and less within the crib. This, too, would lower the heat transfer to the wood surface and tend to reduce m". This does not happen with cribs of 1 in. wood. For these the vertical spaces are greater and the horizontal spaces, although varying with packing density, are greater absolutely for a given packing density than they are for cribs of thinner sticks. These spaces are, presumably, large enough for burning within the crib, not to be restricted by low ventilation or by low internal heating and the value of m" is therefore constant.

The effect of increasing the stick thickness for a given total weight of wood is to decrease the surface area; and if the packing density is kept constant, to increase also the linear dimensions of the air spaces within the crib. This, also, increases the burning rate within the crib itself and raises the heat transfer rate to the wood surface. This might explain why the value of m" (the maximum rate of loss of weight per unit area) and the radiation from the opening r_B are increased as shown by equations (4) and (6). This effect appears to be large enough for the gross burning rate not to be affected significantly by changes in thickness. However, it is interesting to note that the amount of flaming does decrease (equations (3) and (5)).

These arguments suggest that increasing the wood thickness changes the position of the combustion zone so that more combustion occurs within the crib. This is supported by the increase of radiation from the box and decrease in flame height and radiation that were found to follow an increase in wood thickness (equations (3), (4) and (5)).

The effect of increasing the packing density is to reduce the spaces within the crib. All those quantities which reflect the rate of burning are therefore lowered unless the air spaces are large enough in the first place. This packing density in the range examined here has no effect on the behaviour of cribs of 1 in. wood. A more detailed and quantitative assessment of these relationships will be made in a later report.

Although in general the flame height, the radiation from the opening and the flames, and the rate of burning per unit area are influenced by changes in the design of crib, the rate of burning for 1 in. wood is an exception. It is effectively constant with a value of 0.57 $mg.cm^{-2}sec^{-1}$ except for a crib which nearly filled the box.

For these fires where the duration of the fire is unaffected by the fireload, the best value of the rate of burning for the 1 in. wood is 0.57 $mg.cm^{-2}sec^{-1}$. The effective duration of flaming was about 10 minutes so that the result corresponds to about half the wood being involved in flaming combustion and half remaining as charcoal. It is important to note that the flame height is related mainly to the rate of burning. Although it is affected to some degree by the crib design, it provides a method of relating the hazard to a room above the fire with the rate of burning of the fire and a method for an observer to estimate the rate of burning of fires in a building.

5. Conclusions

Some empirical relations have been obtained for relating the rate of burning, the radiation from the enclosure and the flames, and the flame height to the properties of the crib in an enclosure 1 ft cube.

Flame height is related mainly to the rate of burning and though crib properties affect this dependence they appear in these experiments to be of secondary importance.

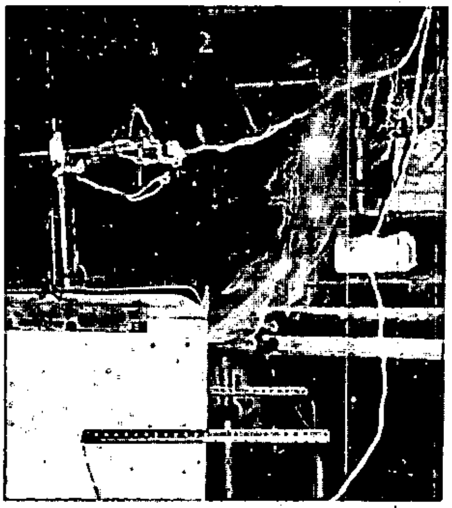
The rate of burning per unit nominal area of wood appears to be constant for 1 in. sticks being independent of the total amount of wood and the spacing except for the largest amount of wood where the height of the crib was too large to be considered small compared with the room height.

References

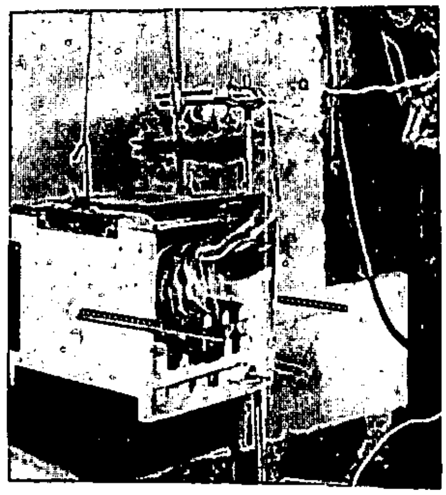
1. Webster, C. T. and Gregsten, M. J. A disc type radiometer. Instruments in Industry, Vol. 3. No. 23.

Before starting the test, showing cantilever above

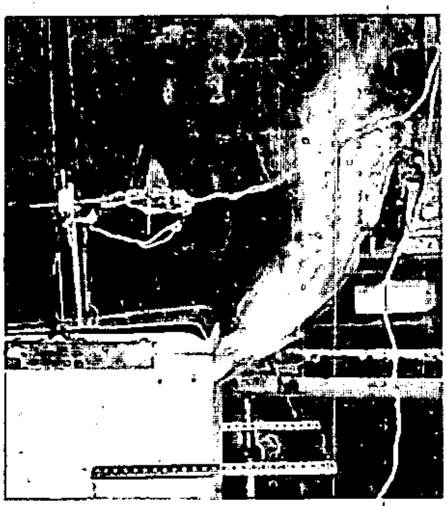
PLATE.I. TEST No.13



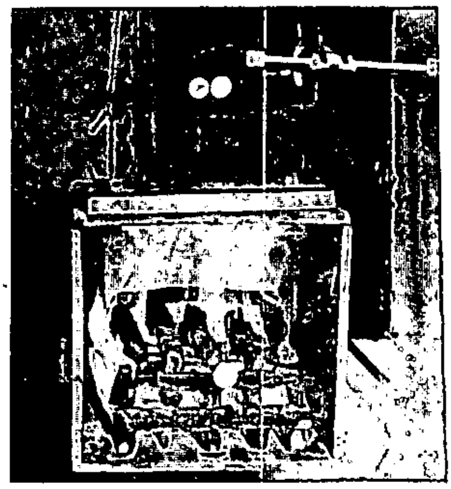
$7\frac{1}{2}$ minutes after ignition of crib.
Flames emerging



At $8\frac{1}{2}$ minutes
about 30% weight lost



At 12 minutes
Maximum flaming about 2 ft high
about 60% weight lost



At 16 minutes
Flames dying down. Radiation from glowing wood near its peak about 0·5 cal $cm^{-2} s^{-1}$

At 20 minutes
Flaming ceased Glowing charcoal remains.
Over 90% weight lost

PLATE. 2.

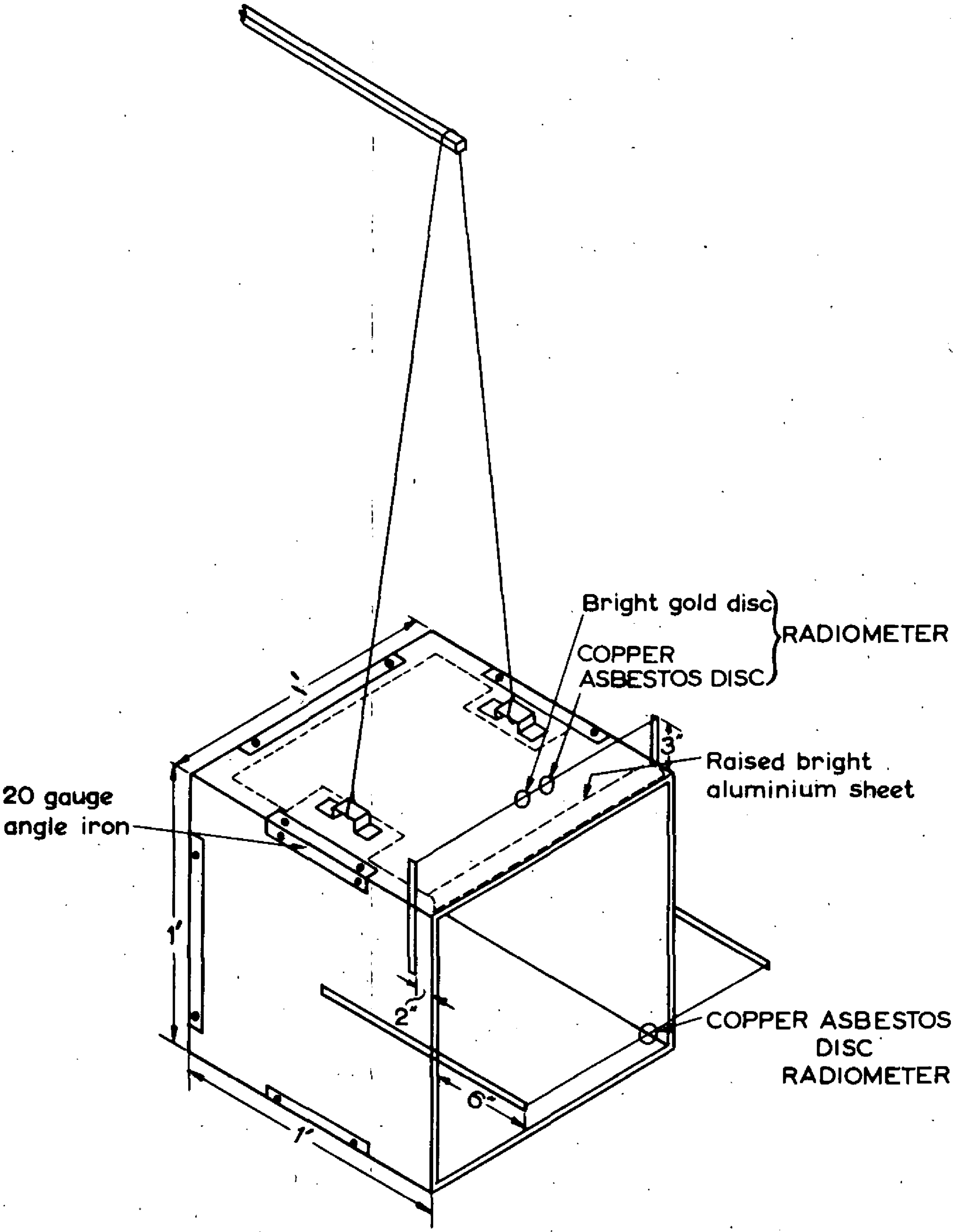


FIG. 1 DIAGRAM OF APPARATUS

1/3327 F.R. 398

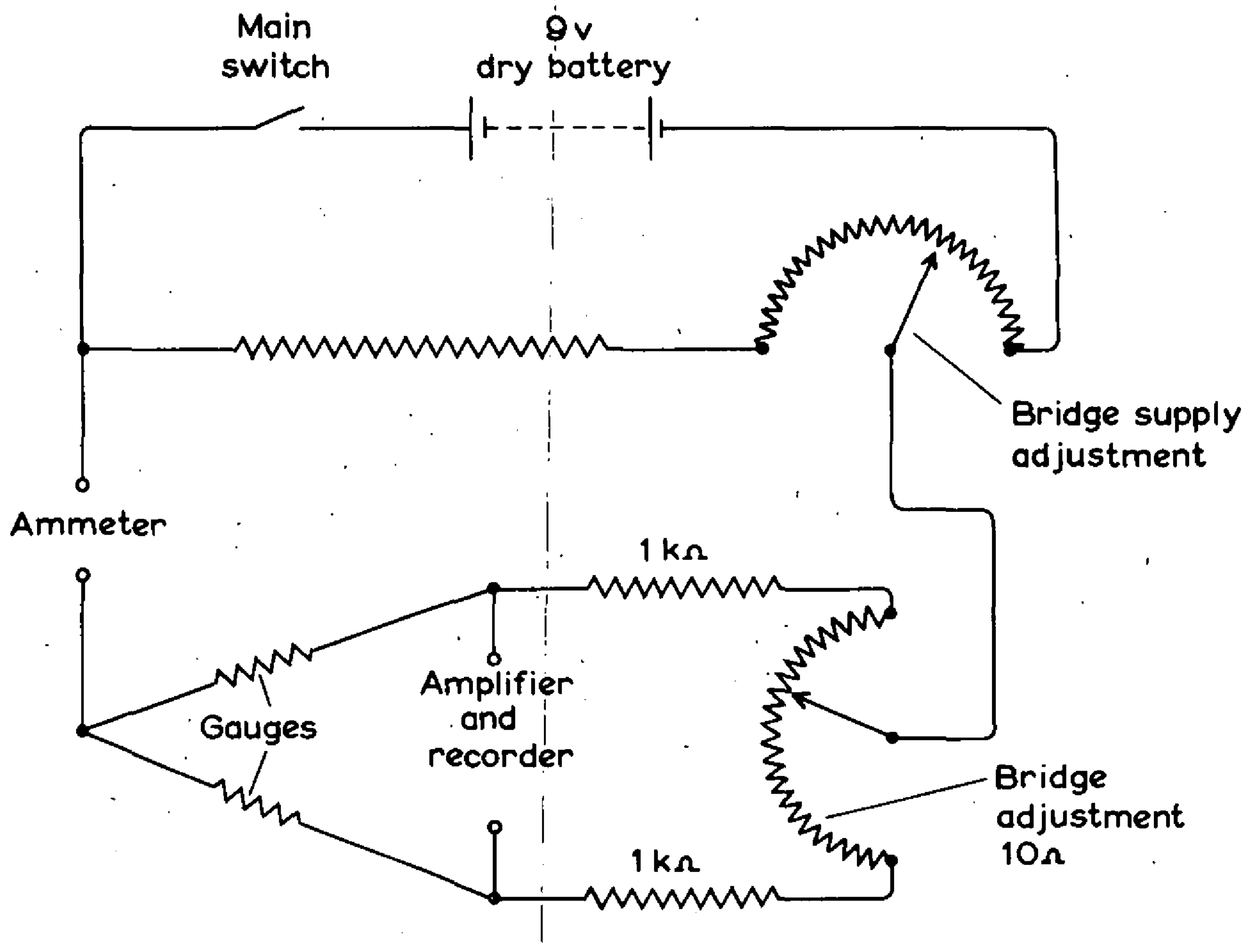


FIG. 2 STRAIN GAUGE CIRCUIT DIAGRAM

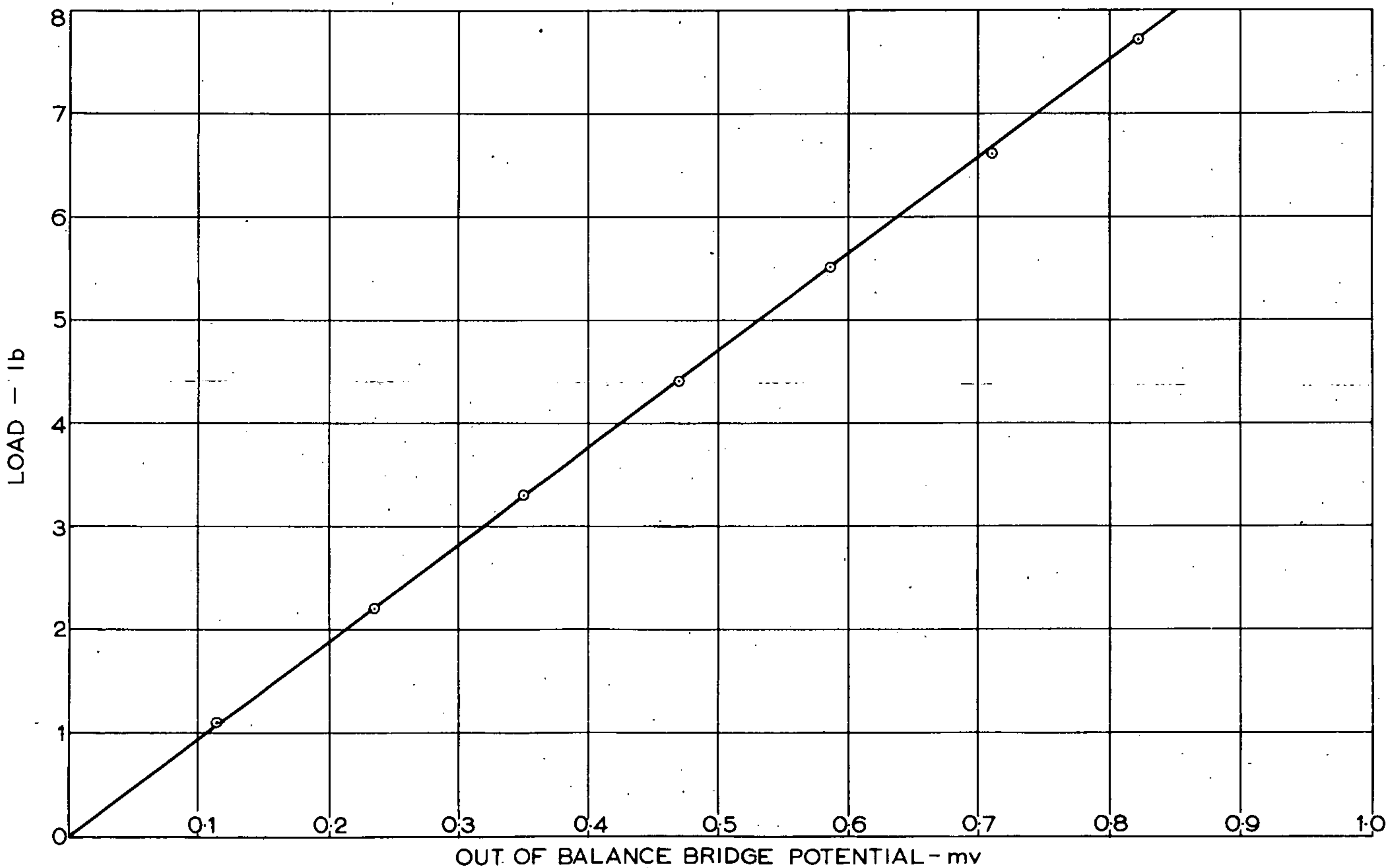


FIG. 3 CALIBRATION OF CANTILEVER WEIGHING SYSTEM

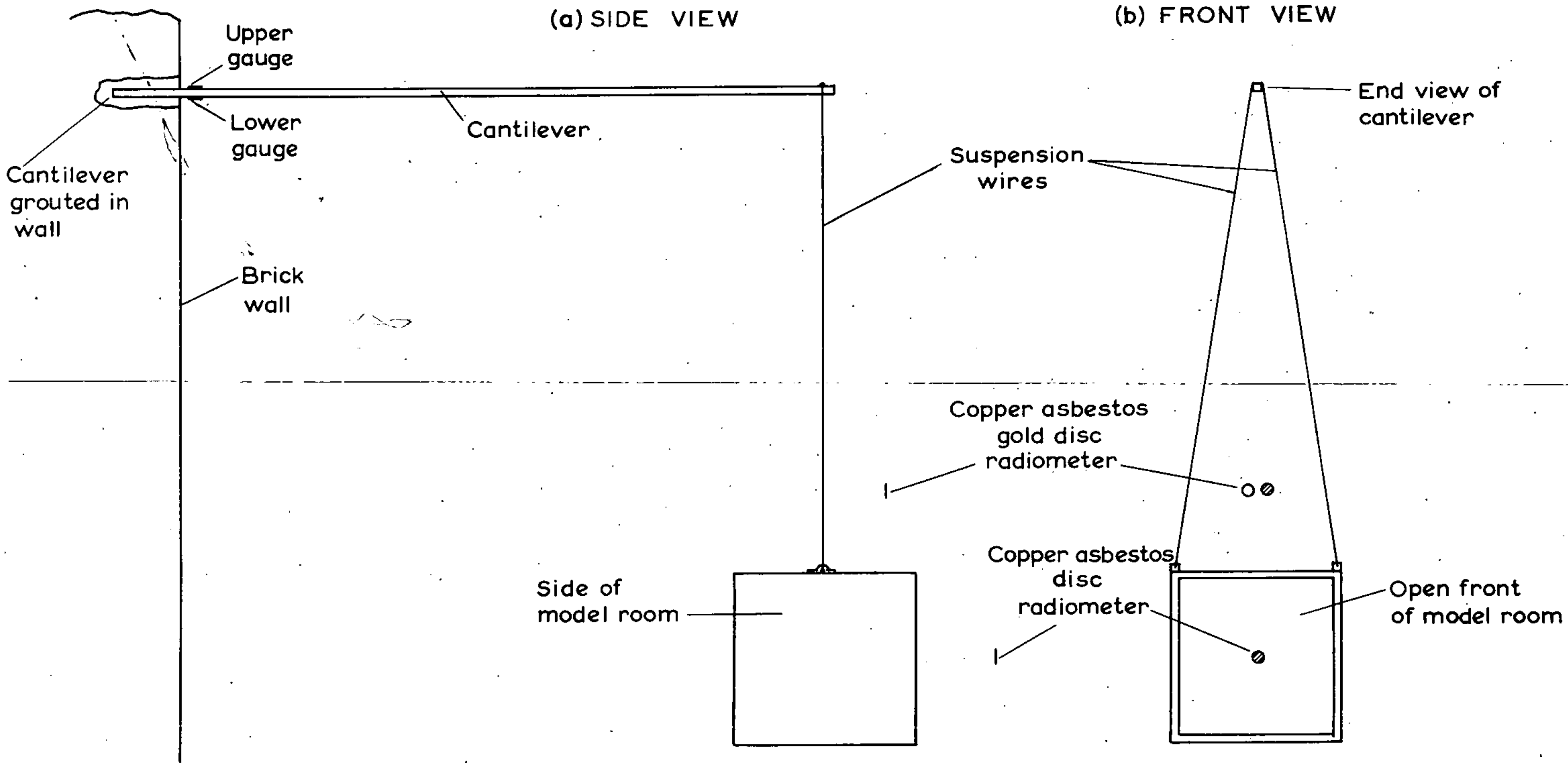


FIG. 4 EXPERIMENTAL ARRANGEMENT OF MODEL

1/3331. F.R.398

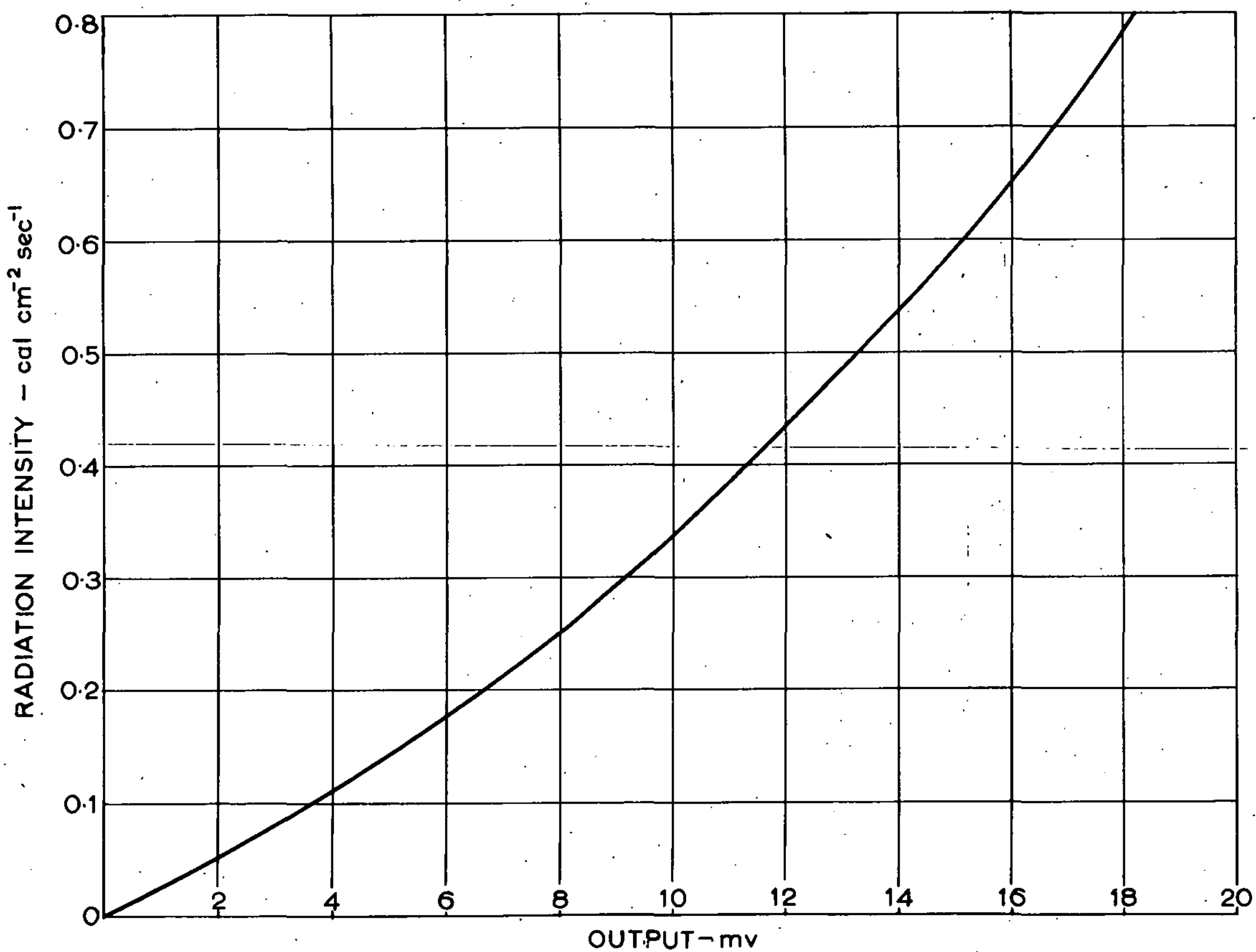


FIG. 5 CALIBRATION CURVE FOR COPPER ASBESTOS GOLD DISC

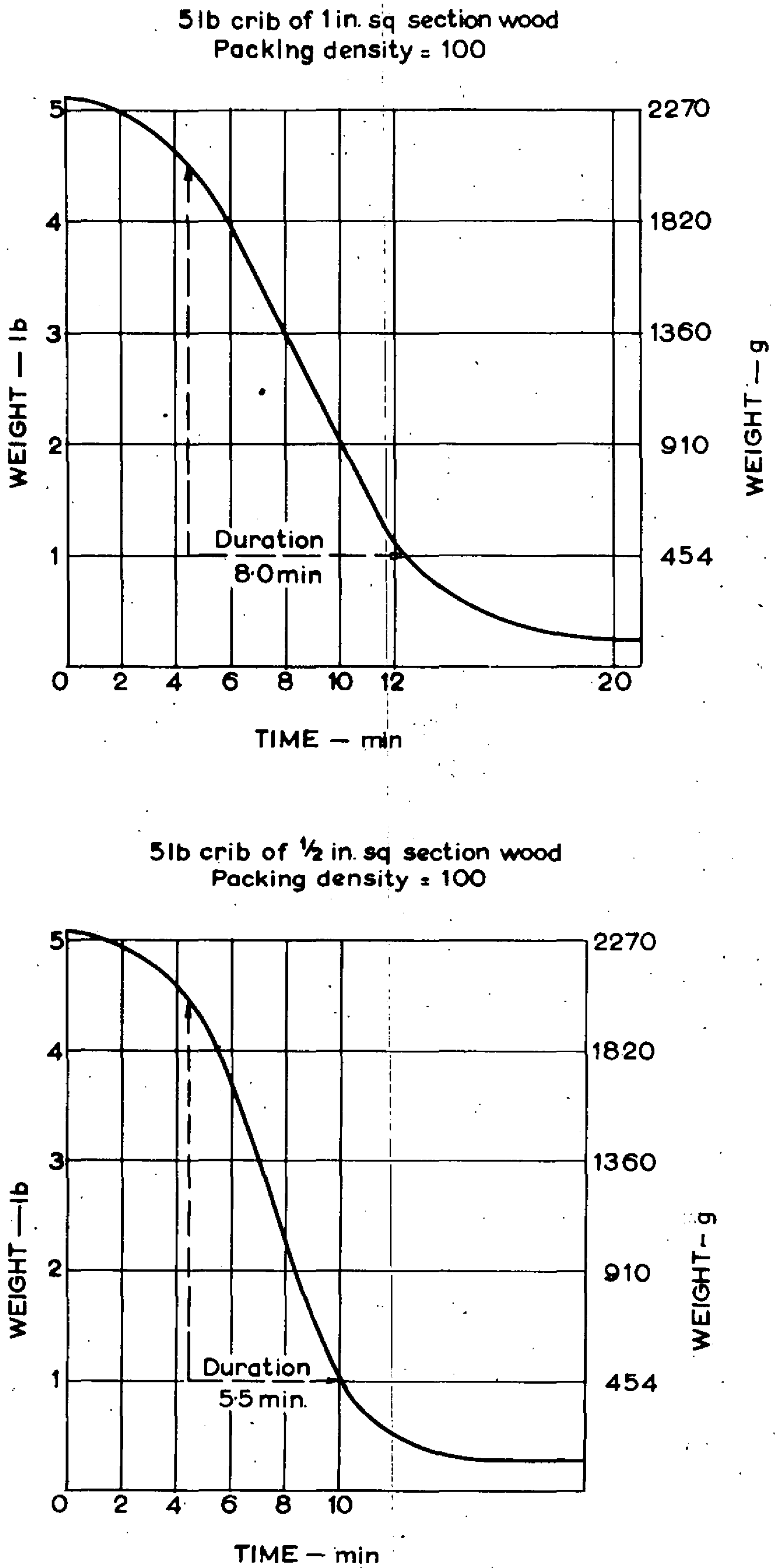


FIG. 6 LOSS OF WEIGHT OF CRIB

/3333 F.R.398

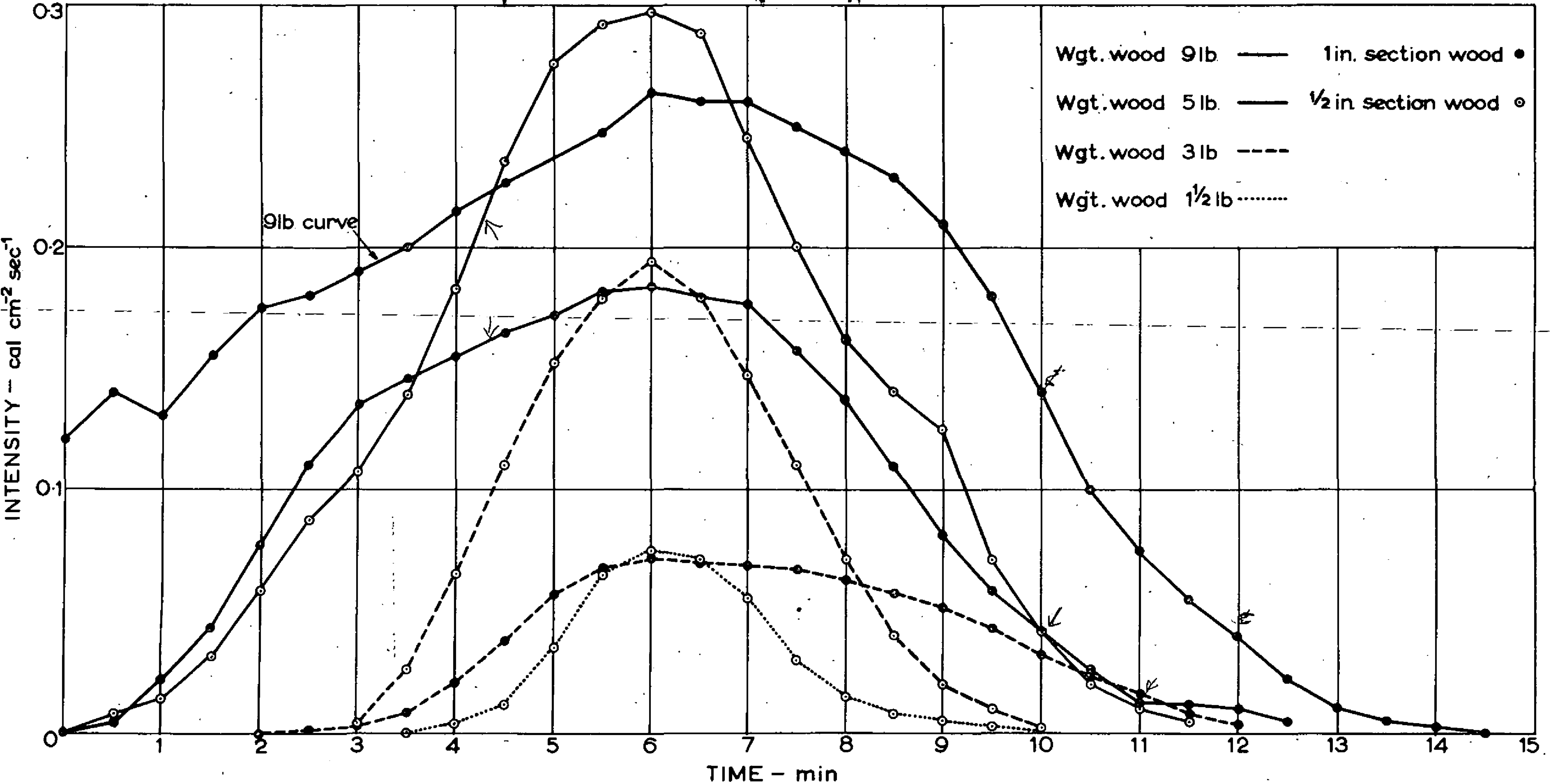


FIG. 7 RADIATION FROM FLAMES

13334 F.R.398

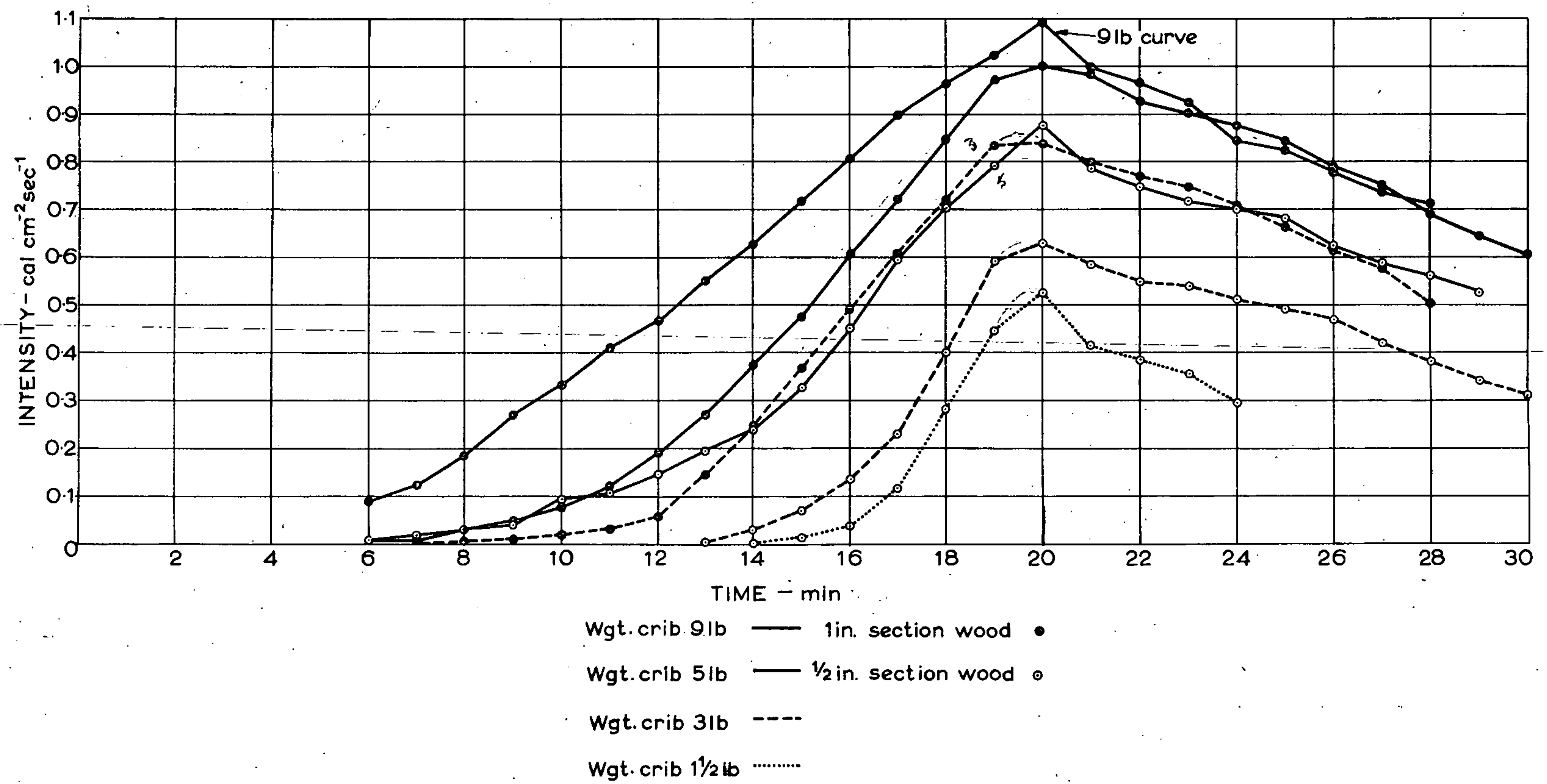


FIG. 8 RADIATION FROM OPENING

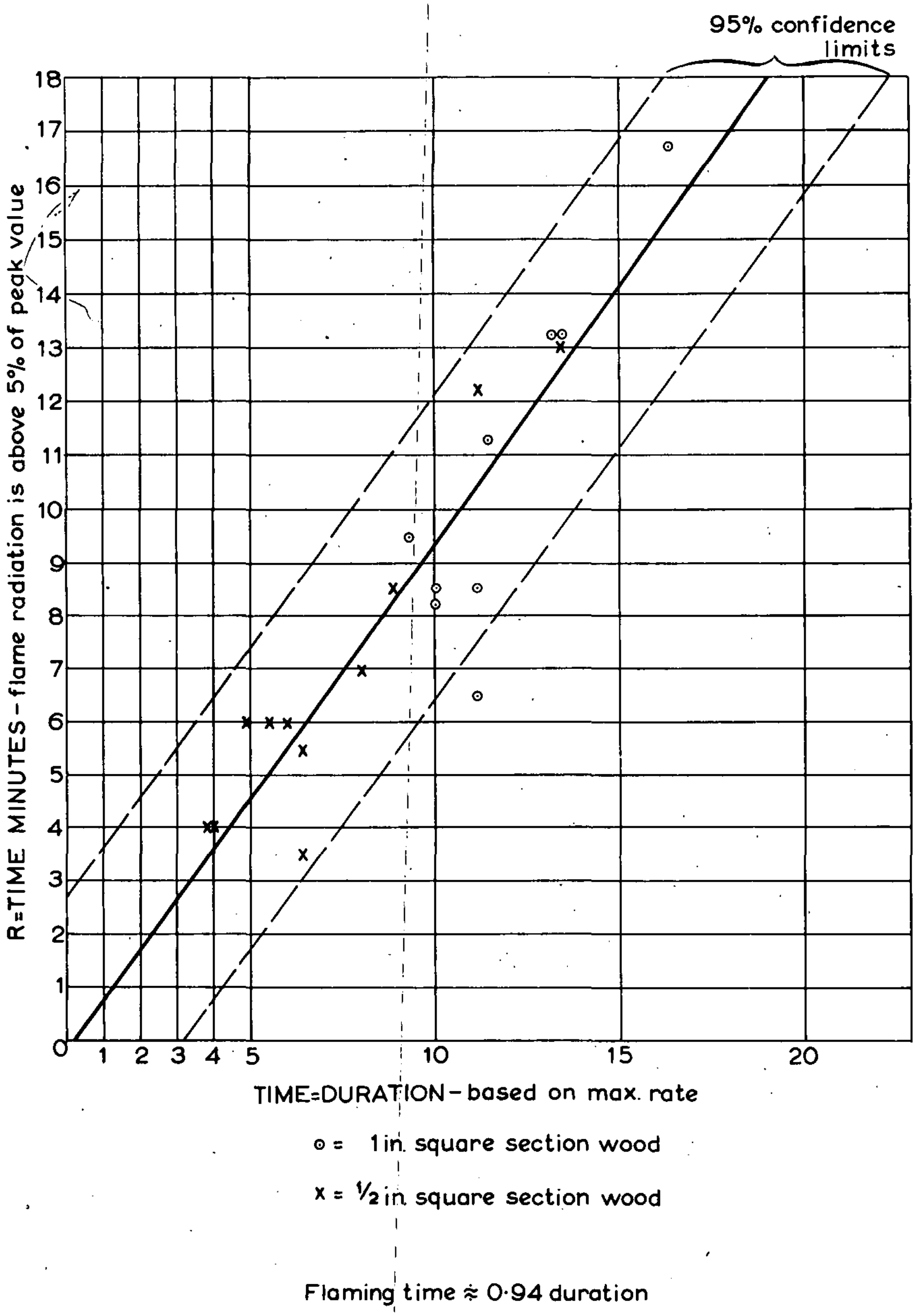


FIG. 9 DEFINITIONS OF DURATION

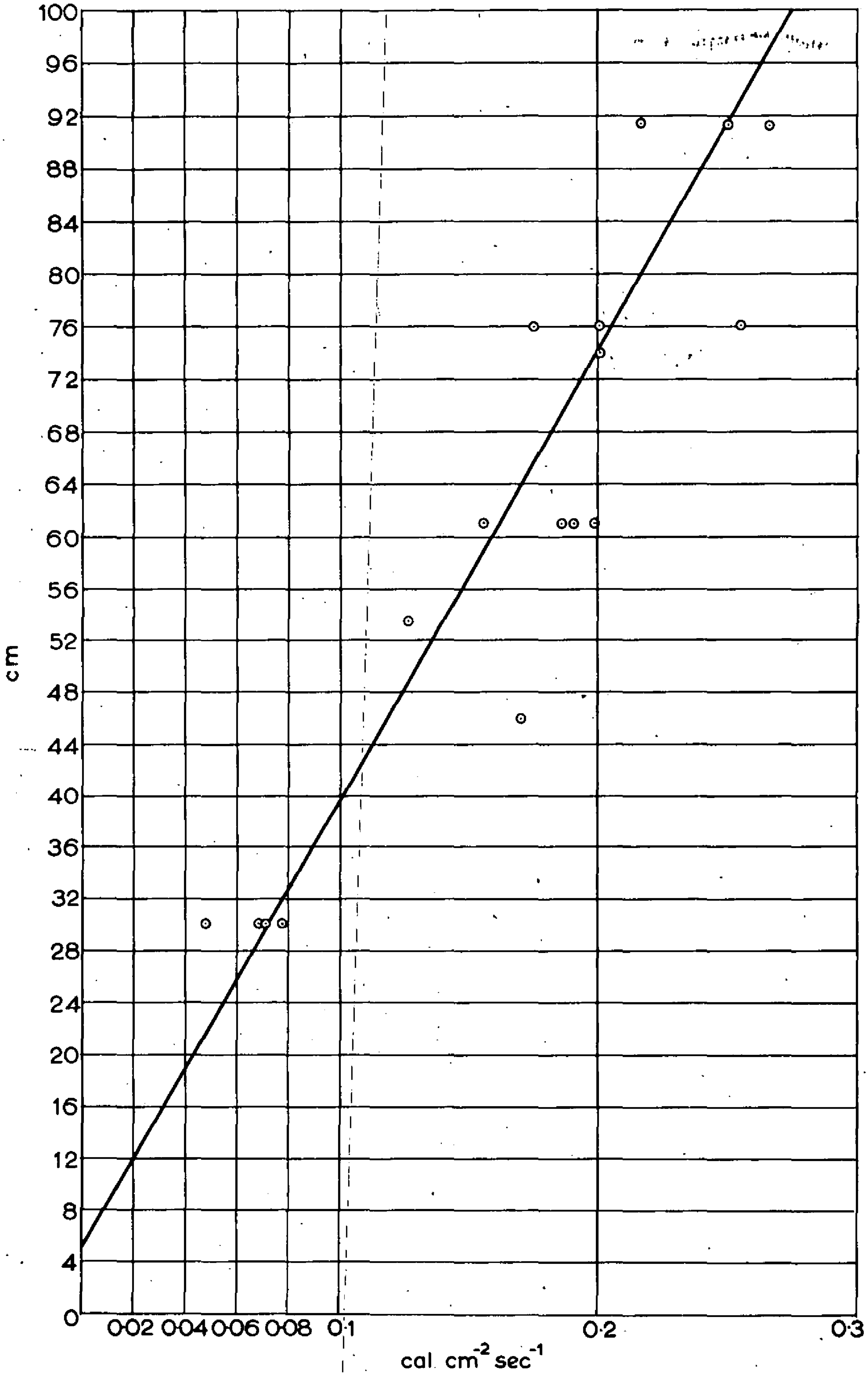


FIG. 10 PEAK FLAME HEIGHT AND RADIATION FROM FLAME ABOVE ROOM

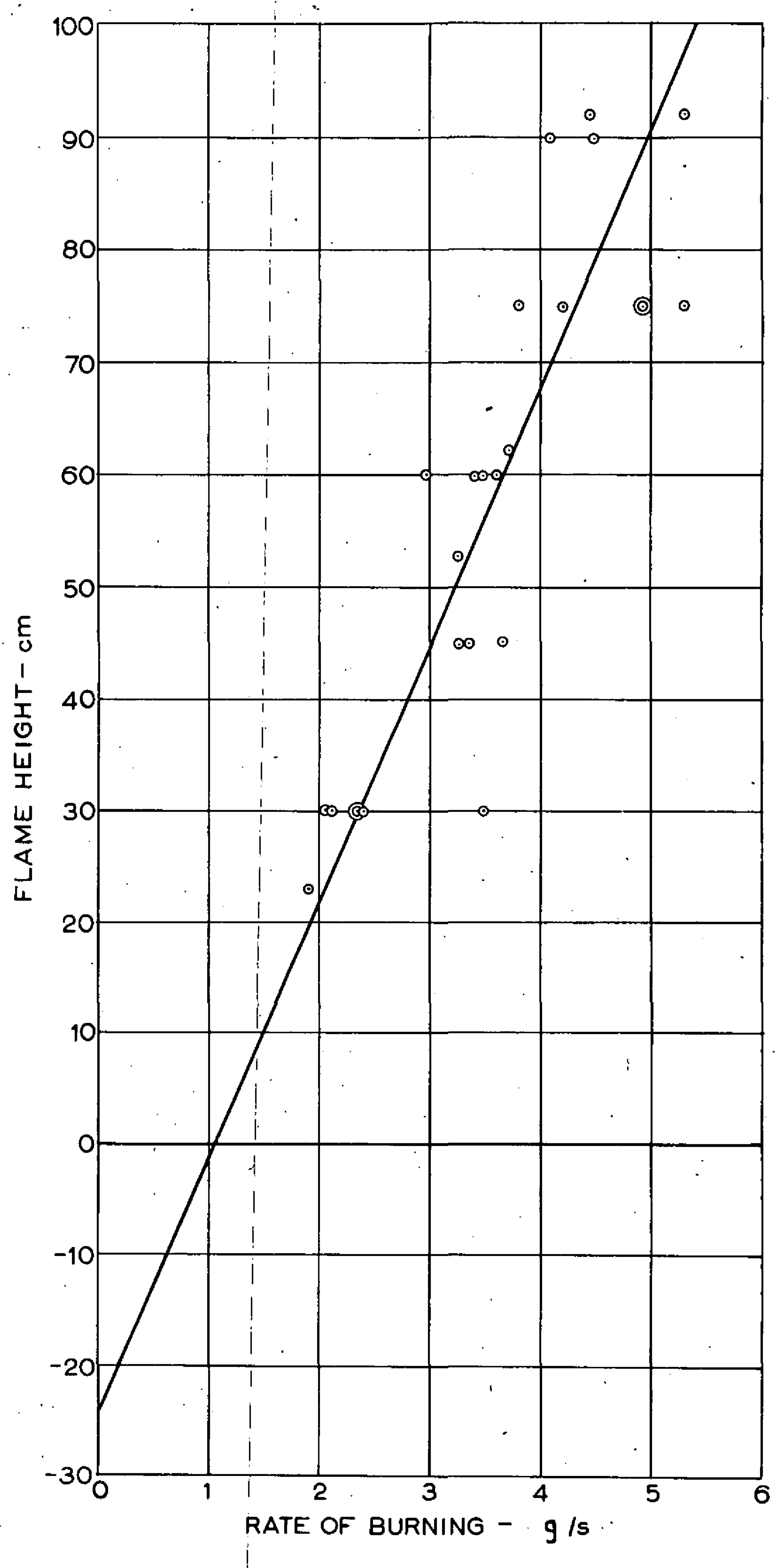


FIG. 11 FLAME HEIGHT AND RATE OF BURNING