Fire Research Note

No. 743

THE CONTRIBUTION OF FLAMES UNDER CEILINGS
TO FIRE SPREAD IN COMPARTMENTS

Part II Combustible ceiling linings

by

P. L. HINKLEY and H. WRAIGHT

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ABSTRACT

In order to devise rational tests and performance requirements for combustible linings in various positions in buildings it is necessary to have some quantitative design criteria either from direct experience or from research. There are still many difficulties in presenting a clear description of the processes of fire growth and the contribution of the many factors involved. In parallel with an international study covering the factors in fire growth, certain fundamental features are being studied in detail, and this report is one of a series investigating the characteristics of flames beneath various kinds of ceiling.

At some stage in the growth of a fire in an enclosed space the flames from materials on the floor are deflected by the ceiling and extend horizontally. It was shown in part 1 that, even when the ceiling is incombustible, the horizontal flames dramatically increase the radiation to unburnt fuel away from the fire and this alone leads to fire spread irrespective of other influences.

This report shows that a combustible lining will cause an increase in the length of the horizontal flames and a more rapid increase in the intensity of downward radiation than an incombustible one. The types of lining investigated were all cellulose-based building boards and with most of these (including untreated fibre insulating board) the lengths of horizontal flames depended on the size of the fire on the floor; when this was restricted fire would spread indefinitely beneath only one of the boards tested, a stove-enamelled hardboard. Apart from this material, differences between linings lay in the rate of increase of downward radiation much more than in the intensity finally attained.

The measurements of downward radiation were used to estimate the spread of fire over a narrow strip of combustible material on the floor, the assumption was made that the flames from a narrow strip would be small so that they would not affect the ceiling fire and it was found that the initial rate of spread varied with performance of the material on the Fire Propagation Test. The final

rate of spread with the exception of stove-enamelled hardboard did not depend on the type of lining.

The importance of the initial rate of spread would be greatly increased where 'feedback' from a larger floor fire to the ceiling fire could occur because the spread would in effect them be an accumulation of successive initial rates of spread and would accelerate until other factors such as a shortage of oxygen intervened. It appears that under these circumstances the performance of a cellulose based board in the Fire Propagation Test is a good measure of its hazard when used as a ceiling lining.

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SUMMARY

Part 1 of this report described flames originating from a fire on a floor of a corridor and deflected horizontally by an incombustible ceiling. The present report described further experiments with a combustible ceiling lining of combustible cellulose-based building boards. A combustible ceiling results in longer flames, higher intensities of radiation to the floor and a faster rate of increase of radiation than an incombustible one with similar thermal constants. However, with most linings flames will not spread indefinitely from a limited floor fire; in this respect the indefinite spread of stove enamelled hardboard was exceptional.

The rate of increase of radiation was related to the performance of the material in the Fire Propagation Test; the maximum intensity of radiation was not so related but did not differ greatly between materials except for stove-enamelled hardboard.

The rate of spread of fire along a narrow strip of wood on the floor beneath a burning ceiling lining has been calculated and the results related to the index of performance on the Fire Propagation Test.

KEY WORDS: Fire spread, Ceiling, Linings, Heat transfer, Burning rate, Flame.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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1. INTRODUCTION

The first part of this report described a study of flames which originated from a fire on the floor and were deflected horizontally by an incombustible ceiling. Such flames were found to be much longer than vertical ones from the same size of fire.

The radiation from the horizontal portions of the flames and the hot ceiling was found to be sufficient to dramatically increase the rate of spread of fire within a compartment. It is to be expected that, if the ceiling is lined with a combustible material, the horizontal flames will become even longer when the lining ignites and the downward radiation will increase, resulting in an even faster rate of spread of fire. This has been confirmed by some small scale experiments carried out by Atallah[1] in which the effect of a combustible lining was simulated by the injection of town gas downwards through a ceiling of porous refractory bricks.

The present report described an experimental investigation of the influence of various types of cellulosic building board ceiling linings on the horizontal flames and the downward radiation from them.

2. EXPERIMENTAL ARRANGEMENTS

The experimental apparatus used for these experiments (Fig.1) was described in Part I of this report[2] and represented the ceiling of a corridor with a fire on the floor at one end. The ceiling made of asbestos wood, was 7.3 metres long, 1.2 wide and mounted 1.8 metres above the concrete floor of the laboratory; a town gas burner simulating the floor fire was situated 66 cm beneath the rear end. Screens extending downward from the sides and rear of the ceiling channelled the hot gases beneath it.

A lining of building board extended from the rear end of the ceiling for a distance of 4.4 metres; the lining was nailed to 38 x 19 mm timber battens which were bolted to the ceiling in the pattern shown in Fig.2. The nails were at the distance apart recommended by the manufacturers of the boards.

Depending on the thickness of the board the bottom of the lining was 63-64 cm above the burner. Full sized, 8 ft x 4 ft, (2.4 m x 1.2 m) sheets were used because small sheets of lining materials were expected to become detached from the ceiling. The first sheet extended to 2.4 metres from the rear of the

3. EXPERIMENTAL MEASUREMENTS

3.1. Radiation

The intensity of radiation downwards was measured by six radiometers[3] level with the top of the burner along the centre line of the corridor in the positions shown in Fig.1. The intensity of radiation downwards 60 cm from the rear of corridor was measured by a total radiation pyrometer.

3.2. Heat Transfer to the Ceiling

The rate of heat transfer to the ceiling was measured at three points (0.3, 2.0 and 3.8 metres from the rear) by copper block calorimeters (Appendix 1). The calorimeters at 0.3 and 2.0 metres from the rear were removed after 3 minutes to avoid overheating them but the one 3.8 metres from the rear remained in position throughout each experiment.

3.3. Temperatures of stream of hot gases

The vertical temperature distributions within the layer of hot gases flowing beneath the ceiling were measured at 2.0 and 3.8 metres from the rear end by vertical columns of 22 SWG chromel-alumel thermocouples 2, 5, 10, 15, 20, 25, 30, 35, 40 and 45 cm beneath the ceiling lining.

3.4. Burning rate of ceiling lining

A section of the building board lining 30 cm square near the end of the lining furthest from the rear of the corridor was weighed during each experiment. This piece of board was attached to narrow strips of asbestos millboard which were fastened to a horizontal steel plate suspended from one arm of a balance through a 31 cm square hole in the ceiling. The use of a steel plate in place of asbestos reduced errors due to loss of moisture. To reduce leakage of hot gases through the gaps around the edges of the steel plate, an asbestos cover with small holes for the suspension wires was placed over the hole in the ceiling. The balance was fitted with an automatic weight unloading device (Appendix 2) which recorded the times for the loss of weight at 10 gram intervals.

3.5. Visual observations

A tape recorded commentary was made during each experiment, this included visual estimates of flame length against a scale painted on the inside of the side screens.

4. LINING MATERIALS

Experiments were carried out with eight types of cellulosic building board linings; the lower surfaces of some were painted (Table 1). The classifications of the boards on both the Spread of Flame test[4] and the Fire Propagation Test[5] were determined, generally using 'off cuts' from the boards used to line the corridor.

4. LINING MATERIALS (Continued)

For the Spread of Flame test only four samples instead of the six specified in the Standard were available. This led to a difficulty in calculating the 'effective flame spread' (x_e) which, when six specimens are tested, is obtained from the formula

$$x_e = \bar{x} + 1.04 \left\{ \sum_{n=1}^{n=6} (x_n - \bar{x})^2 \right\}^{\frac{1}{2}}$$

where $\bar{x}$ is the mean flame spread calculated from the individual results x_1, x_2 etc. To obtain an approximately equivalent 'effective flame spread' with four specimens the constant 1.04 was multiplied by $(6/4)^{\frac{1}{2}}$ and became 1.27*.

The test ratings of many of the boards, particularly the painted ones, were lower than those usually associated with materials of the same type[6]; this may have been due to the paints not having been applied by professional painters.

5. EXPERIMENTS PERFORMED

Two experiments were carried out with the ceiling lined with each of the boards listed in Table 1. the rate of flow of town gas to the burner in each of these experiments was 125 cm^3/s per cm width of burner. The rate of heat transfer to the ceiling over the burner to an incombustible ceiling at this rate of gas flow was about 10 W/cm^2 which was sufficient to ignite all the combustible boards tested.

Experiments with a ceiling lined with untreated fibre board were also carried out at town gas flow rates of 83 and 300 cm^3/s per cm width of burner. In these experiments the lining was bolted directly to the asbestos wood ceiling. Measurements of heat flow to the ceiling were made only at 3.8 metres from the rear of the corridor model.

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* This is a numerical correction for the reduced number of specimens. However the reduction in the number of specimens will result in a decreased level of significance and strictly the constant should be even greater to restore the original level of significance. This would lead to an even greater 'effective flame spread'.

Table 1

Details of Boards

	Type of building board	Surface Treatment	Thickness - cm	Density g/cm^3	Thermal conductivity (approximate) $W\ cm^{-1}\ degC^{-1}$	Dry weight of surface coating kg/m^2	Nominal spread of flame test classification	Fire propagation test performance index
A	Fibre insulating board	None	1.27	0.25	5.2×10^{-4}	-	4	75.3
B	Fibre insulating board	3 coats emulsion paint	1.27	0.25	5.2×10^{-4}	0.40 0.29	4	42.0
C	Fibre insulating board	2 coats chlorinated rubber paint	1.27	0.25	5.2×10^{-4}	0.37 0.27	4	53.5
D	Impregnated Fibre insulating board	Surface already treated by manufacturer	1.27	0.30	5.5×10^{-4}	- -	1*	18.7
E	Medium hardboard	1 coat plastic paint	1.27	0.56	15.7×10^{-4}	1.09 1.09	2	23.7
F	Standard hardboard	2 coats intumescent paint	0.32	1.00	14.0×10^{-4}	0.13 0.14	2	16.5
G	Impregnated medium hardboard	None	0.64	0.46	5.8×10^{-4}	-	4	29.7
H	Tempered hardboard	Stove-enamelled	0.32	1.00	14.0×10^{-4}	- -	3	40.6

*Tested earlier[6]

The specific heat of these boards was taken as being similar to that for cellulose,

i.e. $1.64\ Jg^{-1}\ deg\ C^{-1}$

Table 2

Visual observations of burning of ceiling lining

	Ceiling lining	Ignition time - s	Times in minutes: Ceiling board started to fall	Times in minutes: First sheet burnt away	Times in minutes: End of** experiments	Length of ceiling left after experiment -m	Maximum flame length -m	Time to reach 80% of maximum flame length - min
A	Untreated fibre insulating board	10 10	3 3	10 10	20 22	0 0	7.3 7.3+	1 1
B	Fibre insulating board with emulsion paint	20 15	4 3	13 16	21 22	1.2 1.3	5.0 5.5	1 1
C	Fibre insulating board with chlorinated rubber paint	- 30	3 3	12 10	23 25	0 0	5.5 5.5	1 2
D	Impregnated fibre insulating board	55 45	4 4	14 17	18 20	0.5 1.5	7.3 6.0	6 5
E	Medium hardboard with plastic paint	65 40	8 8	25 21	36 32	0.0 1.5	7.3 6.0	4 3
F	Standard hardboard with intumescent paint	80 140	4 6	8 10	14 15	0 0	7.3 7.3	4 5
G	Impregnated medium hardboard	17 15	3 4	7 8	11 13	0 0	7.3 4.5	5 2
H	Stove-enamelled tempered hardboard	30 35	2 2	4 -	5 6	0 0	7.3+* 7.3+*	1 1

*Flames about 3 metres high out of end of corridor

**Either board had burnt away or flaming had died down

6. EXPERIMENTAL RESULTS AND DISCUSSION

6.1. Visual observations of burning of ceiling linings

The times taken for the ceiling lining to ignite are given in Table 2; they varied from 10 seconds for untreated fibre insulating board to about 2 minutes for hardboard treated with intumescent paint.

After ignition, the flame length increased to a maximum which was greater than the length of the ceiling lining, both the maximum flame length and the time to reach it depended on the type of lining (Table 2). Generally they were only small differences in maximum flame lengths except for stove-enamelled hardboard (H) which produced large volumes of flame extending to a height of about 3 metres out of the end of the corridor with some flames emerging beneath the side screens. The time taken for the flames to reach their maximum length varied from about 1 to 5 minutes, and was greatest for materials with good ratings in the Fire Propagation Test.

Generally the flame length remained near the maximum for 3 or 4 minutes and then decreased to a minimum which was less than the length of the ceiling lining. The flame tips then tended to advance a second time as the ceiling lining burnt away. However with hardboard treated with intumescent paint (F) and stove-enamelled hardboard (H), once the flames had extended beyond the end of the ceiling lining they did not retreat until the lining was nearly burnt away.

After a few minutes (Table 2) pieces of the ceiling lining started to fall to the floor where they generally continued burning. With all the materials except the stove-enamelled hardboard, pieces of board of the order of 50 cm square curled downwards and hung by one edge for some time before falling off; this was generally accompanied by an increase in flaming due apparently to the material burning on its upper surface and to increase mixing within the layer of hot gases caused by the obstruction in the gas stream.

The times at which the first sheet of the lining material had burnt away are given in Table 2; at this stage the wooden studding was contributing significantly to the fire. There was generally a pause of the order of a minute before the second sheet started to fall. The experiment was terminated either when all the second sheet had burnt away or the flaming had died down. A considerable length of the lining material sometimes remained in position at this stage (Table 2) although badly charred.

6.2. Vertical temperature distribution in hot gas layer

Typical vertical temperature profiles (at the time when the flame length was a maximum) 2 metres from the rear of the corridor are shown in Figs 3a and 3b. These temperatures are only approximately comparable

6.2. Vertical temperature distribution in hot gas layer (contd)

with those in Part 1 of this report because the 22 SWG thermocouples were much more subject to radiation errors than the 40 SWG ones used previously

The maximum temperature incfeased from 600°C to about 750–800°C when a combustible lining was substituted for an asbestos wood one. Generally the maximum temperature occurred about 10 cm below the ceiling and the shapes of the temperature profiles were characteristic of those obtained in previous experiments when the layer of hot gases contained sufficient air for complete combustion of the fuel gases.

This did not apply for stove enamelled hardboard, the shape of the temperature profile obtained with this material showed that the layer was fuel-rich.

Generally the depth of the layer of hot gases was little changed by lining the ceiling with a combustible material, this confirmed that the mass of fuel gases emitted by the burning ceiling was small compared with the mass of hot gases resulting from the floor fire and the entrainment of air by the vertical flames.

6.3. Radiation downwards

Fig 4 shows the variation with time of the intensity of radiation downwards from the bottom of the layer of hot gases 2.5 metres from the rear of the corridor when this was lined with the various types of board; each line represents the mean of two experiments. The intensity increased more rapidly with a combustible ceiling lining than with an asbestos wood one and the maximum intensity was generally much longer. The differences are greater than can be explained by differences in the thermal properties of the materials; a perfectly insulating ceiling would result in a maximum intensity of about 1·0 W/cm^2 at 2.5 metres from the rear of the corridor at the gas flow of 125 cm^3/s per cm width used on the present experiments.

The intensity then remained at a high level until most of the first sheet of lining had burnt away. There were considerable fluctuations in intensity; large increases were generally associated with large pieces of the lining becoming partly detached from the ceiling and hanging by one edge. This occurred at roughly the same times in the two experiments with any one material.

The variation of the intensity of radiation with distance along the corridor at 3 minutes after the commencement of the experiments with the various lining materials is shown in Fig.5. The intensity at the flame tips was of the order of 1.0 W/cm^2 but could fluctuate between 0.5 and 1.5 W/cm^2 according to whether the flames were advancing under a cold ceiling or receding

6.3. Radiation downwards (contd)

The distance from the rear of the corridor over which the intensity exceeded 1.0 W/cm^2 at the time of the first maximum is given in Table 3; also shown is the rate of flow of town gas needed to produce the same flame length with an asbestos wood ceiling at equilibrium, the data being taken from Part I of the report. There was remarkably little difference between the types of materials tested except for stove enamelled hardboard; with this material the intensity of radiation remained approximately constant along the length of the corridor at about 4 W/cm^2 during the period of intense flaming. With the other materials the increase in the flame length due to the ceiling lining was roughly the same as that which would have been produced beneath the unlined asbestos ceiling by doubling the rate of burning of the primary fire. When the flow of hot gases was not disturbed by detached pieces of lining the intensity decreased, to a first approximation, exponentially with distance along the corridor except with stove-enamelled hardboard (Fig.6).

Table 3

	Ceiling lining	Distance on 'floor' over which intensity of radiation exceeded 1.0 W/cm^2 m	Rate of flow of town gas with asbestos ceiling for similar radiation at equilibrium cm^3/s per cm width
A	Untreated fibre insulating board	4.7	260
B	Fibre insulating board with emulsion paint	4.2	240
C	Fibre insulating board with chlorinated rubber paint	4.1	230
D	Impregnated fibre insulating board	4.4	250
E	Medium hardboard with plastic paint	4.7	260
F	Standard hardboard with intumescent paint	5.0	280
G	Impregnated medium hardboard	4.3	240
H	Stove-enamelled tempered hardboard	$\gg$ 7.3	$\gg$ 300

$$I_x / I_{2.5} = e^{-K(x - 2.5)} \quad (1)$$

where x was distance from the rear of the corridor in metres

I_x was the intensity at x metres from the rear

and $I_{2.5}$ was the intensity at 2.5 metres from the rear

K was constant having a value of about 0.45 m^{-1} for the linings tested.

This value of K could be obtained with an unlined ceiling by increasing the town gas flow rate by a factor of about 3.5 to 450 cm^3/s. This must be compared with the factor of 2 by which it would be necessary to increase the town gas flow rate to obtain the same flame length with an unlined ceiling as was obtained with most types of lined ceilings (p.8)

It is evident that the effects of lining the ceiling with a combustible board cannot be considered simply as equivalent to an increase in size of the primary fire.

In the experiments with the ceiling lined with fibre insulating board and a town gas flow rate of 83 cm^3/s per cm width, the rate of increase of intensity of radiation was about half that when the town gas flow rate was 125 cm^3/s per cm width and the level of steady radiation was also about half; its distribution along the corridor was still given by equation (1) with $K \cong 0.4$. The flames were about one metre shorter, this difference was similar to that observed with an incombustible ceiling.

The effect of lining the ceiling with fibre insulating board (compared with an asbestos board) was greater at the lower rate of flow of town gas than at the higher one.

When the ceiling was lined with fibre insulating board and the town gas flow rate increased to 300 cm^3/s, the steady distribution of radiation downwards was no longer exponential and the intensity near the burner was lower than with an unlined ceiling (Fig 7). The experiments with the asbestos ceiling had shown that at this rate of town gas flow the layer contained barely sufficient oxygen for complete combustion of the town gas; it follows that the additional fuel gases provided by the burning ceiling lining resulted in the layer becoming fuel-rich which resulted in the reduced rates of heat transfer near the burner.

The effect of a ceiling, both unlined and lined with fibre insulating board, on the distance over which the downward intensity of radiation exceeds 1.0 W/cm^2 is shown in Table 4.

Table 4

Gas flow rate cm^3/s per cm width of corridor	Distance in metres over which intensity at floor level exceeded 1.0 W/cm^2		
	No ceiling*	Incombustible ceiling	Fibre insulating board ceiling
83	0.9	1.3	4.5
125	1.5	2.5	5.2

*Calculated from configuration factor of vertical flames assuming intensity of radiation at their surface of 10.0 W/cm^2

The distance over which the intensity exceeded 1.0 W/cm^2 at the higher gas flow was doubled by substituting a combustible for an incombustible ceiling, whereas it was trebled at the lower gas flow, i.e. the contribution of a combustible ceiling lining to fire spread on the floor is relatively greater if the ceiling ignites when the primary fire on the floor is only small.

6.4. Heat transfer to ceiling

The heat transfer to each of the copper blocks in the ceiling had generally attained a roughly steady value (Table 5) before the two nearest the rear were removed (about $3\frac{1}{2}$ minutes after ignition of the town gas burner). When the ceiling was lined with hardboard treated with intumescent paint the rates of heat transfer were still rising and the values immediately before removal of the blocks are given.

The heat transfer to the ceiling over the burner (0.3 metres from the rear) at a given time was generally less than that to an asbestos ceiling at the same time after the commencement of the experiment and was always less than the equilibrium transfer (Fig 8). This may have been due to the presence beneath the ceiling of a layer of hot gases (resulting from the decomposition of the lining) which was cooler than the flames.

The heat transfer to the ceiling at 2.0 metres from the rear was about the same as the downward radiation at that point i.e. about 2.0-2.5 W/cm^2 except for stove-enamelled hardboard when it was about 4.0 W/cm^2.

The heat transfer at 3.8 metres from the rear was about the same as at 2.0 metres and was much greater than the downward intensity of radiation. The convective transfer was therefore probably greater at 3.8 metres than at 2.0 metres from the rear. It is possible that the rate of heat transfer was partly controlled by the "negative feedback"

6. EXPERIMENTAL RESULTS AND DISCUSSION (Contd)

6.4. Heat transfer to ceiling (Contd)

effect arising from a layer of relatively cool decomposition products beneath the ceiling. Any decrease in heat transfer would lead to a decrease in decomposition rate and hence an increase in heat transfer.

Table 5

Copper block calorimeter results

	Ceiling lining	Heat transfer to ceiling 3-5 minutes after ignition - W/cm^2		
		Distance from rear of corridor		
		0.3 m	2.0 m	3.8 m*
A	Untreated fibre insulating board	6.5	2.3	3.0
B	Fibre insulating board with emulsion paint	5.3	2.0	2.5
C	Fibre insulating board with chlorinated rubber paint	5.6	2.1	2.5
D	Impregnated fibre insulating board	5.0	1.9	2.0
E	Medium hardboard with plastic paint	5.5	2.5	2.0
F	Standard hardboard with intumescent paint	8.0	2.5	2.6
G	Impregnated medium hardboard	5.5	1.9	1.7
H	Stove-enamelled tempered hardboard	7.0	3.0	3.7
	Unlined asbestos (at equilibrium)	9.6**	-	-

*Values are the mean from two experiments

**Value obtained using water flow calorimeter[2]

6.5. Burning rate of ceiling lining

A typical record of the loss of weight of the weighed portion of the ceiling lining (4 metres from the rear of the corridor) is shown in Fig.9; after a few minutes the burning rate became approximately steady for most of the remaining period of an experiment. The steady burning rates and the corresponding mean heat transfer rates are given in Table 6. The burning rates of fibre insulating board are lower than those of hardboard and are further decreased by surface and impregnation treatments. Stove-enamelled hardboard had a burning rate which was much greater than that of any other material tested.

The burning rate of fibre insulating board (both treated and untreated) is shown as a function of heat transfer rate in Fig.10. The burning rate of vertical specimens in front of a radiant panel[7] are also shown on the same figure. The burning rate increased with heat transfer and there was little difference between treated and untreated fibre insulating board ceiling linings. The burning rates of the ceiling linings, which were 1.27 cm thick, were approximately comparable with the 2.5 cm thick vertical specimens and considerably lower than the values for the 1.27 cm thick ones. Possibly the burning rate of the ceiling lining was reduced by the presence of the steel plate above it.

The burning rates of the denser materials were higher than that of fibre insulating board at similar rates of heat transfer. The net heat output, assuming complete combustion of the emitted volatiles and that they had the same calorific value as those from wood, was given approximately by 1.5×10^4 M" W/cm^2, where M" was the burning rate per cm^2 of ceiling. The heat losses by conduction into the ceiling and side screens, and by radiation downwards from the hot gas layer, and also the heating of the air entrained by this layer were all calculated by methods similar to those used in Part 1 of this report[2], and in Table 7 are compared with the net heat output. Because of the relatively short time-constant of the ceiling boards used, about 1-2 minutes, they could be regarded as being in a state of thermal equilibrium during most of the duration of the experiment, including the period of steady burning rate.

6. EXPERIMENTAL RESULTS AND DISCUSSION (Contd)

6.5. Burning rate of ceiling lining (Contd)

Table 6

Burning rate and heat transfer

	Ceiling lining	Period of steady burning min from	to	Steady burning rate $g\ m^{-2}s^{-1}$	Mean heat transfer during steady burning W/cm^2	Heat per unit mass burned J
A	Fibre insulating board	3	15	2.9	2.6	9,000
B	Fibre insulating board with emulsion paint	1	14	2.2	2.3	10,500
		1	16	2.1	1.7	8,100
C	Fibre insulating board with chlorinated rubber paint	4	18	2.2	2.0	9,100
		1	13	2.6	2.1	8,100
D	Impregnated fibre insulating board	7	18	2.1	2.1	10,000
		6	20	2.0	1.7	8,500
E	Medium hardboard with plastic paint	4	16	3.9	1.9	4,900
		5	13	3.6	2.0	5,500
F	Standard hardboard with intumescent paint	6	9	5.1	2.9	5,700
		8	18	3.5	2.3	6,600
G	Impregnated medium hardboard	5	10	3.6	1.8	5,000
H	Stove-enamelled tempered hardboard	2½	4	13.1	4.6	3,500
		2	5	13.9	4.0	2,900

6.5. Burning rate of ceiling lining (Contd)

Table 7

Partial Heat Balance

All values in W/cm^2

	1	2	3	4	5	6
	Ceiling lining	Net heat output (assuming complete combustion)	Heat transfer through ceiling and walls	Radiation downward	Increase in sensible heat due to heating of entrained air	Sum of columns 3-5
A	Untreated fibre insulating board	4.3	1.8	1.1	1.8	4.7
B	Fibre insulating board with emulsion paint	3.2	1.1	1.0	1.9	4.0
C	Fibre insulating board with chlorinated rubber paint	3.6	1.1	1.1	1.6	3.8
D	Impregnated fibre insulating board	3.1	1.0	0.8	1.3	3.1
E	Medium hardboard with plastic paint	5.6	1.1	1.2	1.8	4.1
F	Standard hardboard with intumescent paint	6.5	1.2	1.5	1.2	3.9
G	Impregnated medium hardboard	5.3	1.0	1.0	1.3	3.3
H	Stove-enamelled tempered hardboard	20.2	1.8	3.2	2.1	7.1

For fibre insulating board, both treated and untreated, the net heat output and total heat loss were approximately the same, but for the other types of board the net heat output of the volatiles, if they were completely burned, was higher than the total heat loss, by a factor of three in the case of stove-enamelled hardboard. With these materials

6. EXPERIMENTAL RESULTS AND DISCUSSION (Contd)

6.5. Burning rate of ceiling lining (Contd)

combustion must have been incomplete otherwise the temperature and downward radiation would have increased from the rear of the model towards the front whereas the measurements showed a decrease except for stove-enamelled hardboard when the downward radiation varied only slightly with distance.

The rate of combustion was generally not limited by the air content of the layer of hot gases. The upward velocity of entrainment of air into the layer was unlikely to have been very different from that measured with an incombustible ceiling (i.e. about 2 cm/s) and this was sufficient for the combustion of volatiles emitted at a rate of 5 g $m^{-2}s^{-1}$ which was higher than that measured for any material except stove-enamelled hardboard. The incomplete combustion could have been due to a lack of mixing within the layer resulting in an accumulation of decomposition products and combustion products beneath the ceiling.

The rate of combustion of the volatiles from stove-enamelled hardboard was probably controlled by the rate of entrainment of air at the base of the layer. A rate of 2 cm/s would give a heat output of 7.5 W/cm^2 which agrees with the estimated heat loss of 7.1 W/cm^2.

6.6. Anomalous behaviour of stove-enamelled hardboard

The anomalous behaviour of stove-enamelled hardboard may have been due to an increase in mixing within the layer. This could have been caused by the gases from the hardboard being emitted as jets through pin holes which appeared in the relatively intact stove-enamelled coating. Plate 1 shows a piece of stove-enamelled hardboard supported horizontally (stove-enamelled side down) in front of a small (30 cm square) radiant panel; the jets of flame spurting downwards can be easily seen. This is contrasted with untreated fibre insulating board in Plate 2; in this instance there are merely small tenuous flames close to the surface of the fibreboard. Another type of stove-enamelled hardboard did not produce jets of flame when tested in front of the radiant panel, the flames from it resembled those from fibre insulating board.

Hardboard coated with intumescent paint produced a few jets of flame, however, these did not cause large flames similar to those observed with stove-enamelled hardboard.

Increased mixing within the layer may also have been partly responsible for the increase in downward intensity observed when pieces of ceiling lining hung downwards thus partly obstructing the flow of hot gases.

6.7. Effect of downward radiation on fire spread along floor

The times taken for fire to spread along a wooden strip on the floor to various distances from the primary fire (Fig.11) with different types of ceiling lining were calculated from the experimental data on downward radiation using a simple electrical analogue. The following assumptions were made:-

1) The floor was assumed to behave as a semi-infinite solid having a density of 0.5 g/cm^3, thermal conductivity of 0.0012 W cm^{-1} $degC^{-1}$ and a specific heat of 1.4 J cm^{-2} sec^{-1}.
2) Cooling was Newtonian with a constant of 0.0025 W cm^{-2} $degC^{-1}$.

Table 8

Analogue equivalents

Quantity	Heat problem	Analogue equivalent
Potential	1 deg C	10^{-2}V
Time	1 s	10^{-2}s
Energy flux	1 W/cm^2	2.39 μA
Resistance	1 deg C cm^2 W^{-1}	4.18×10^3 Ω
Capacitance	1 J cm^{-2} deg C^{-1}	2.39×10^{-6} μF

3) The floor ignited when its upper surface attained a temperature of 260 deg C above ambient.
4) The burning floor had no effect on the intensity of radiation downwards from the burning ceiling.
5) The shape of the radiation - time curve was independent of position; and the intensity of radiation at any point was derived by multiplying the intensity at 2.5 metres by a constant factor which was derived from the experimental measurements (Fig 6).

The analogue equivalents are given in Table 8 and the circuit is shown in Fig.12. The variation in the intensity of radiation with time was simulated by a cam driven potentiometer, and readings of output voltage simulating the temperature of the surface of the wood were taken at the rate of ten per second using a digital voltmeter connected to a high speed

6. EXPERIMENTAL RESULTS AND DISCUSSION (Contd)

6.7. Effect of downward radiation on fire spread along floor punch.

The calculated spread of fire along a wooden floor due to radiation downwards from various types of ceiling lining is shown in Fig.13; the curve for the perfectly insulating ceiling was calculated on the assumption that the downward radiation immediately assumes its maximum value.

The rate of spread of fire in the early stages depends on the rate of rise of intensity of radiation. This is because the initial rise in temperature of the floor due to an increase in intensity of radiation occurs more rapidly than the increase of radiation itself. The ultimate distance of spread was a function of the maximum intensity of radiation, except for stove-enamelled hardboard.

The rate of rise of intensity of radiation and the rate of spread of fire can be correlated with the index of performance on the fire propagation test.[8]

7. CONCLUSIONS

(1) The lengths of flames from a fire on the floor flowing horizontally beneath a non-combustible ceiling are increased by lining the ceiling with a combustible board. With the size of floor fire used in these experiments the mean flame length when the board was burning was about twice that with an unlined ceiling, although there were considerable fluctuations in flame length. Stove-enamelled hardboard behaved anomalously and gave much longer flames.

(2) Although the maximum flame length was greater than the length of the ceiling lining with most materials in at least part of the experiment there is no evidence (except for stove-enamelled hardboard) that the flames would have been much longer beneath a very long ceiling lining. The flame length appeared to be controlled by the size of the floor fire.

(3) The intensity of radiation was about 1.0 W/cm^2 at the flame tips and it increased exponentially towards the rear of the corridor.

$$I_x = e^{-K(x-l)} \quad W/cm^2$$

where l was flame length in metres from rear of corridor and K was about 0.45 m^{-1} (except for stove-enamelled hardboard).

The rate of rise of the intensity of downward radiation after ignition of the primary fire depended on the type of lining material and its treatment and was slowest for materials classed as 'good' on the results of the Fire Propagation Test. The maximum intensity attained varied much less than the rate of rise and was not correlated with the test results.

Materials which ignite when the primary fire is small have relatively a greater effect on fire spread as compared with those which do not ignite until the primary fire is larger.

(4) The spread of fire over a strip of combustible material on the floor from a localized source has been estimated from the downward radiation on the assumption that there is no 'feedback' from the floor fire to the ceiling. The initial rate of spread over the floor can be correlated with the Fire Propagation Test Performance Index of the material (Fig 14). The final distance of spread cannot be so correlated but it did not vary greatly from one material to another except for stove-enamelled hardboard where unlimited spread would apparently occur. Where 'feedback' from the floor fire to the ceiling can occur an accelerating rate of spread of fire would result until other factors, such as a shortage of air, intervened. In these circumstances the initial rate of spread would assume even greater importance, since the accelerating spread would in effect be an accumulation of successive initial rates of spread, rather in the same way as spread itself is a succession of ignitions.

(5) It appears that the heat output from a burning ceiling may be controlled by local mixing within the layer of hot gases and that when this is increased (e.g. by downward jets of flame) the heat output correspondingly increases . This may be the explanation for the anomalous behaviour of stove-enamelled hardboard.

8. ACKNOWLEDGMENT

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APPENDIX 1

COPPER BLOCK CALORIMETERS

The copper block calorimeter was in principle similar to the copper block absolute radiometer described by Simms[9]. It consisted essentially of a block of copper 4.4 cm square and 1.27 cm thick with its square faces horizontal and the lower surface set flush with the surface of the ceiling (Fig.1). Both the upper and lower surfaces were blackened. The edges were separated by a 0.76 mm air gap from a guard ring of 1.27 cm square section copper. The temperatures of both block and guard ring were measured by 40 SWG chromel-alumel thermocouples which were connected to the data-logging system. Generally the temperature of the guard ring was higher than that of the block.

The gross rate of heat transfer to the block in J/s was given by

$$Q = L^2 d \rho c \frac{dT_B}{dt} + Q_R + Q_C - Q_G - Q_{rg}$$

where L = length of side of block = 4.4 cm

d = thickness of block = 1.27 cm

ρ = density of block = 8.9 g/cm^3

c = specific heat of block = 0.385 J g^{-1} deg C^{-1}

T_B = absolute temperature of block in $^\circ$K

Q_R = heat lost by radiation from all faces of the block

Q_C = heat lost by convection from upper face of block

Q_G = heat gained by conduction across air gap

and Q_{rg} = heat gained by radiation across air gap

$$Q_R = 2L^2 \epsilon \sigma T_B^4 + 4Ld\epsilon\sigma T_B^4 = 2L\epsilon\sigma T_B^4(L + 2d)$$

where ϵ = emissivity of surface of block, here taken as 0.9

and σ = Stefan's constant = 5.7×10^{-12} J cm^{-2}s^{-1}deg K^{-4}

$$Q_C = L^2 H(T_B - T_o)^{1.25}$$

where H = coefficient of heat loss by natural convection, here taken as 2.5×10^{-4} J cm^{-2}s^{-1} deg K$^{-1.25}$

and T_o = absolute ambient temperature over block in $^\circ$K

$$Q_G = 4LdK(T_G - T_B)/x$$

where K = thermal conductivity of air, which for an air temperature of T is taken as $(60 + 0.6T) \times 10^{-6}$ J cm^{-2}s^{-1} deg K^{-1}

T_G = absolute temperature of guard ring in $^\circ$K and x = width of air gap = 0.76 mm

$$Q_{rg} = 4Ld\epsilon\sigma T_G^4$$

neglecting re-radiation between block and guard ring.

Inserting numerical values into these expressions and dividing throughout by L^2, the area of the lower face of the block, we obtain the following expression for the gross rate of heat transfer in W/cm^2.

$$Q = 4.35\frac{dT_B}{dt} + 1.62 \times 10^{-11}\ T_B^4 + 2.5 \times 10^{-4}\ (T_B - T_o)^{1.25}$$

$$+ (910 + 9.1\ T)\ 10^{-6}\ (T_B - T_G) - 5.92 \times 10^{-12}\ T_G^4$$

where T is taken to be $\frac{1}{2}(T_B+T_G)$ ^oK

The value for the rate of rise of temperature of the block, dT_B/dt, was obtained from the temperature readings (small differences between which were accurate to 0.25 deg C) using a central difference formula assuming the variation of T_B with time could be fitted to a polynomial formula. If consecutive values of block temperature, at time intervals of Δt were θ_1, θ_2, θ_3 and θ_4, then $dT_B/dt = (1/\Delta t)(\theta_1/24 - 27\theta_2/24 + 27\theta_3/24 - \theta_4/24)$

The value of block temperature (θ_B) at the time when dT_B/dt had the value given by the above formula was

$$\theta_B = -\theta_1/16 + 9\theta_2/16 + 9\theta_3/16 - \theta_4/16$$

The above calculations were easily performed using a computer to process the punched tape output of the data-logger.

APPENDIX 2

AUTOMATIC WEIGHT UNLOADING DEVICE

The weighing device (Fig.15) was a modified balance with the weighed portion of the ceiling suspended from the right-hand arm. A number of weights, all the same value, were attached at equal intervals along a lightweight cord, one end of which was secured to a winding drum driven by a geared electric motor. Initially, the weights rested in a pan suspended from the left-hand arm of the balance.

A mercury switch operated by the balance arm actuated a relay which started the motor and also provided an electrical signal which was used to provide an automatic record of the loss in weight. A microswitch operated by the moving weights stopped the motor.

The movement of the balance beam, due to a loss in weight of the right-hand side, started the motor and wound up the cord until one weight had been lifted off the pan; another weight then operated the switch to stop the motor, the balance beam meanwhile having moved back to its original position. A further loss in weight of the right-hand side restarted the process.

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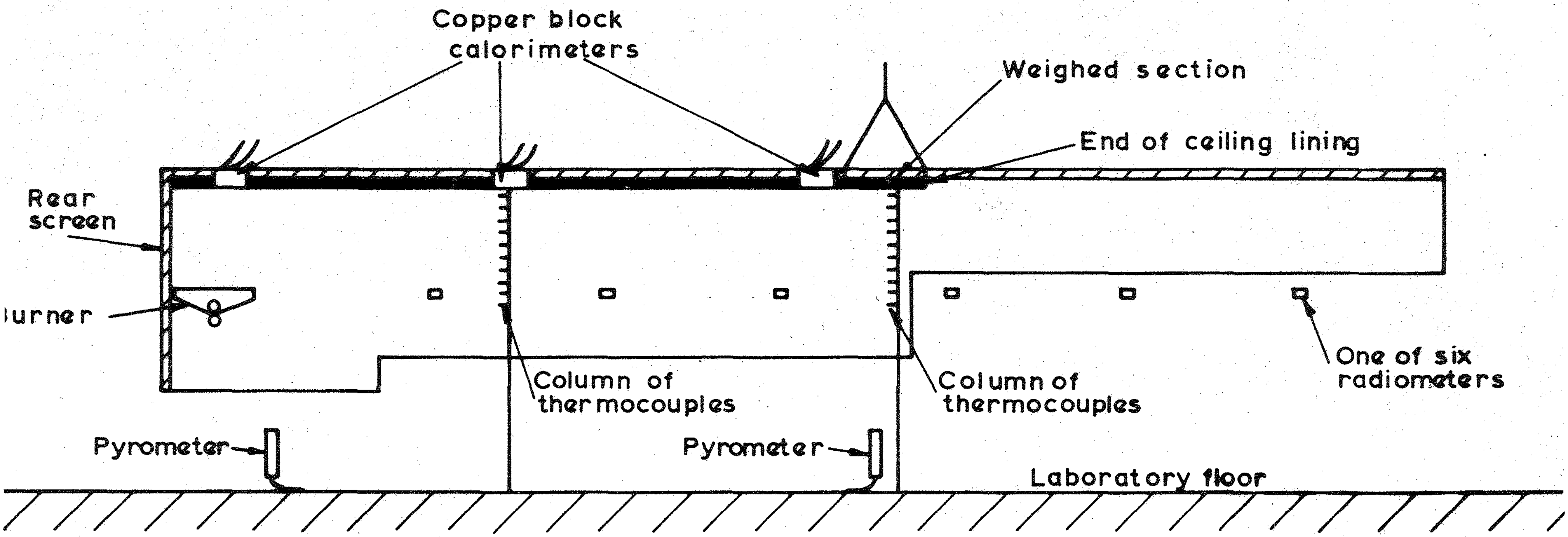
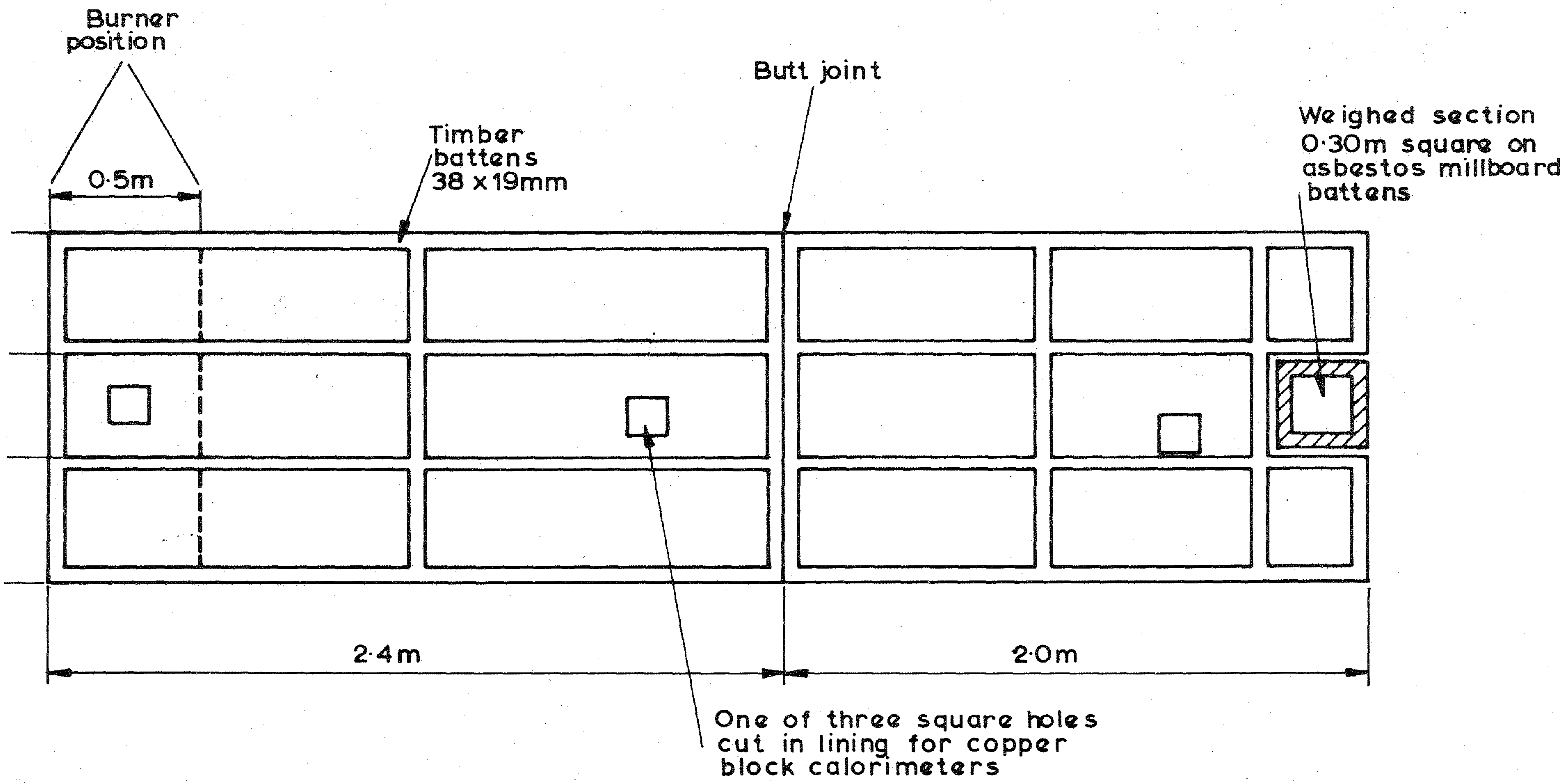
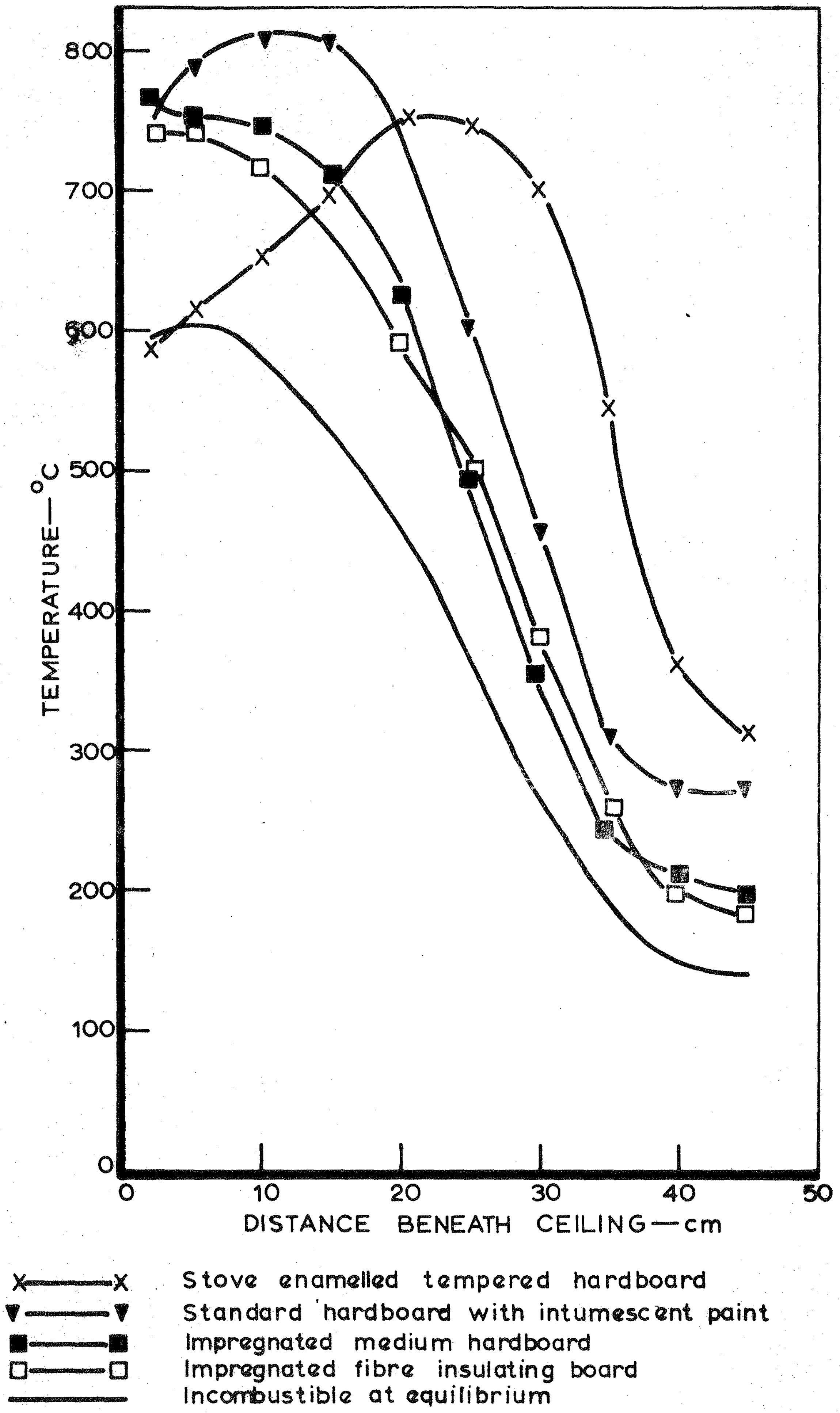


FIG. 1. DIAGRAM OF MODEL CORRIDOR AS USED FOR LINED CEILINGS (APPROX. 1/33 SCALE)

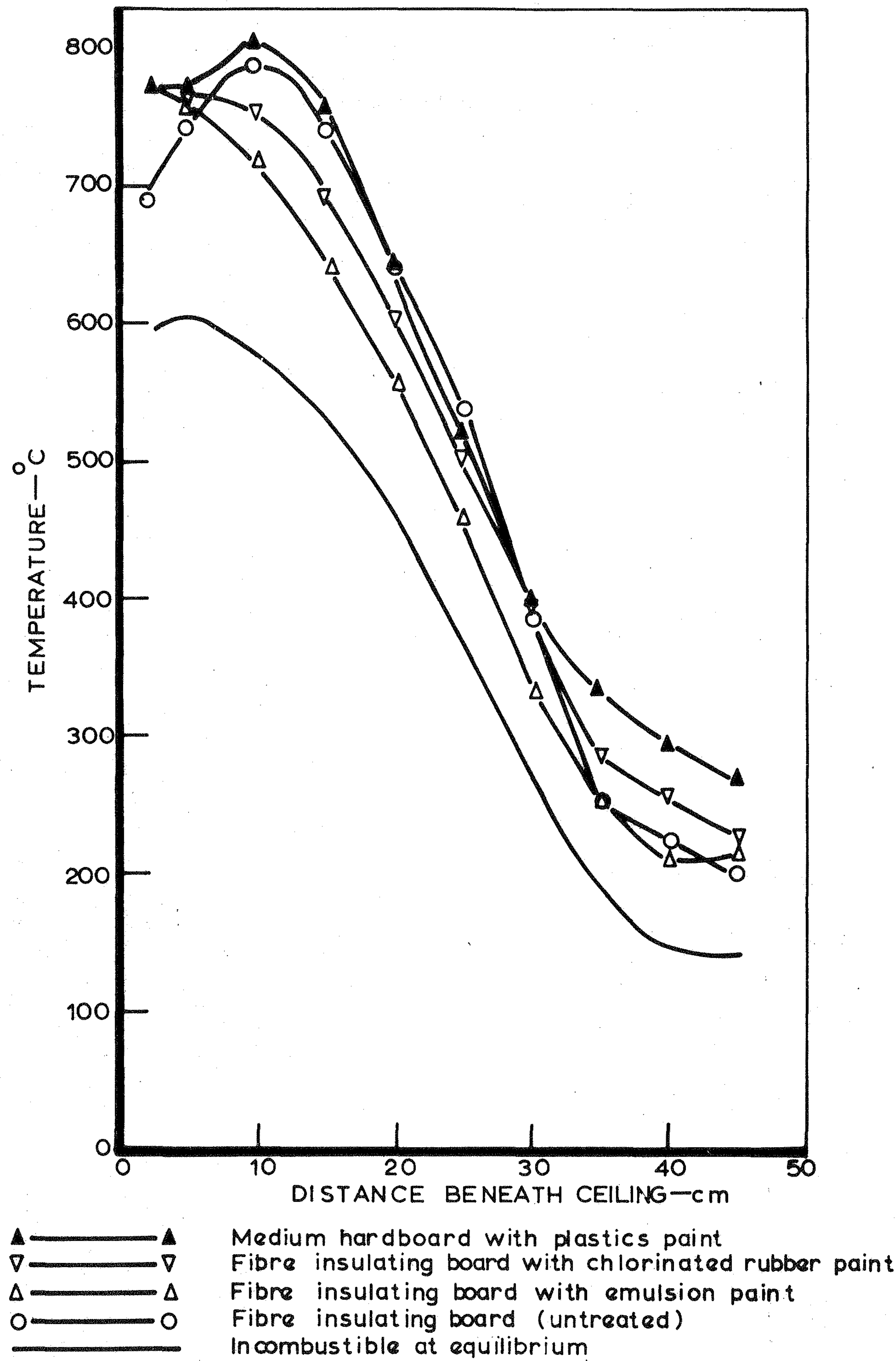


. 2. PLAN OF CEILING LINING VIEWED FROM ABOVE (APPROX. 1/20 SCALE)



800
700
600
500
400
300
200
100
0
TEMPERATURE — °C
0
10
20
30
40
50
DISTANCE BENEATH CEILING — cm
Stove enamelled tempered hardboard
Standard hardboard with intumescent paint
Impregnated medium hardboard
Impregnated fibre insulating board
Incombustible at equilibrium

FR 743


TEMPERATURE — °C
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
DISTANCE BENEATH CEILING — cm
Medium hardboard with plastics paint
Fibre insulating board with chlorinated rubber paint
Fibre insulating board with emulsion paint
Fibre insulating board (untreated)
Incombustible at equilibrium

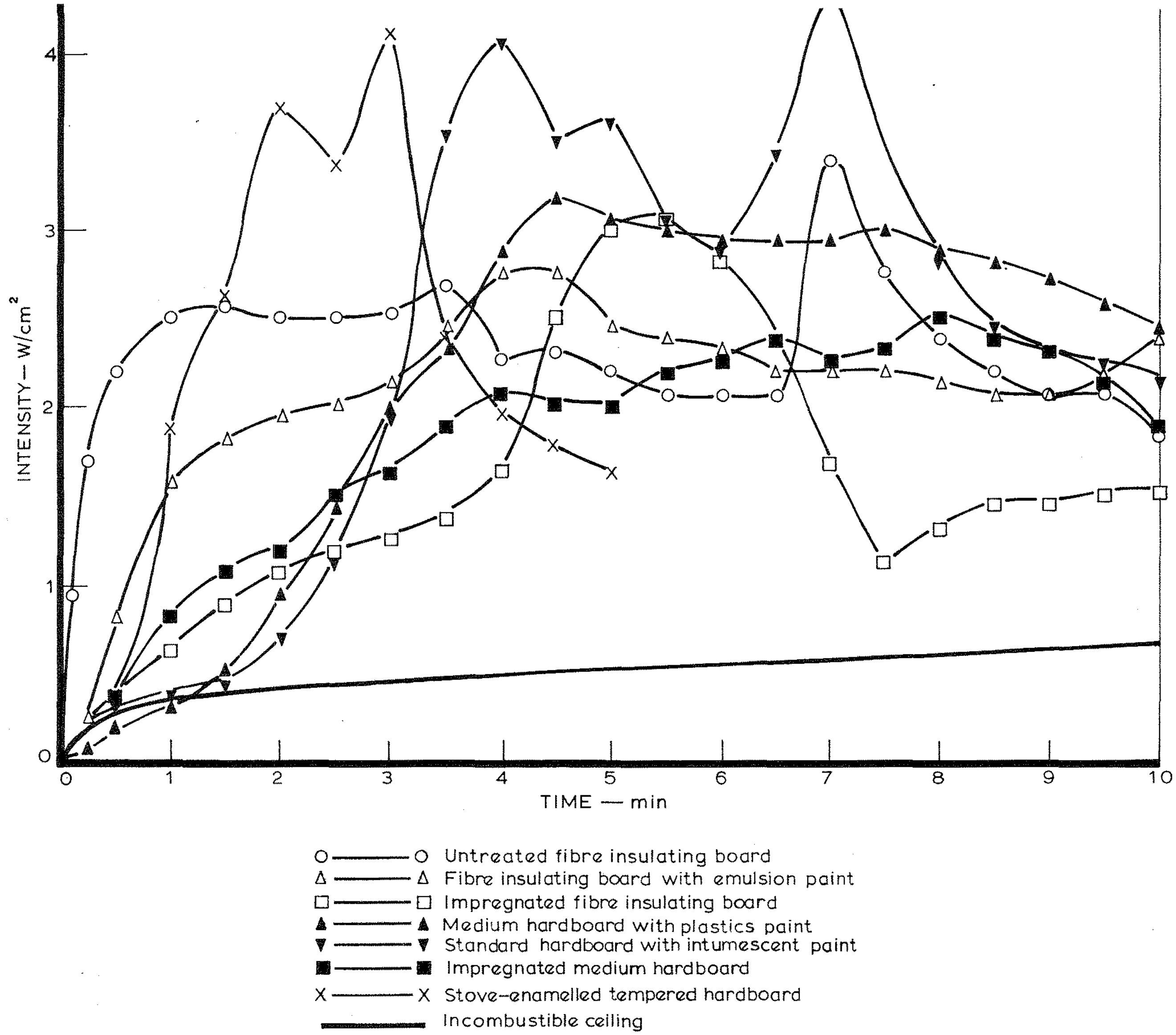
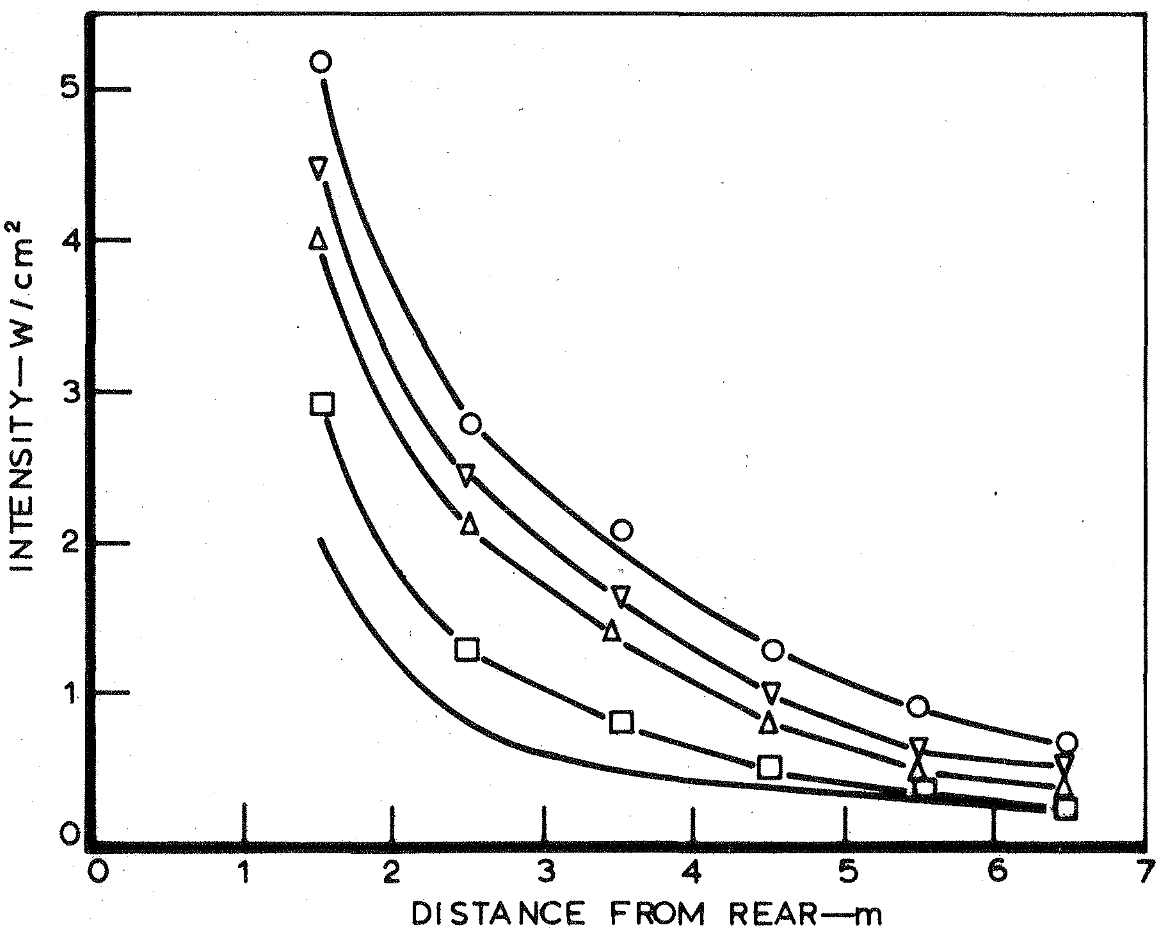


FIG.4. DOWNWARD RADIATION AT BASE OF HOT GAS LAYER (AT 2·5 METRES)



○——○ Untreated

△——△ With emulsion paint

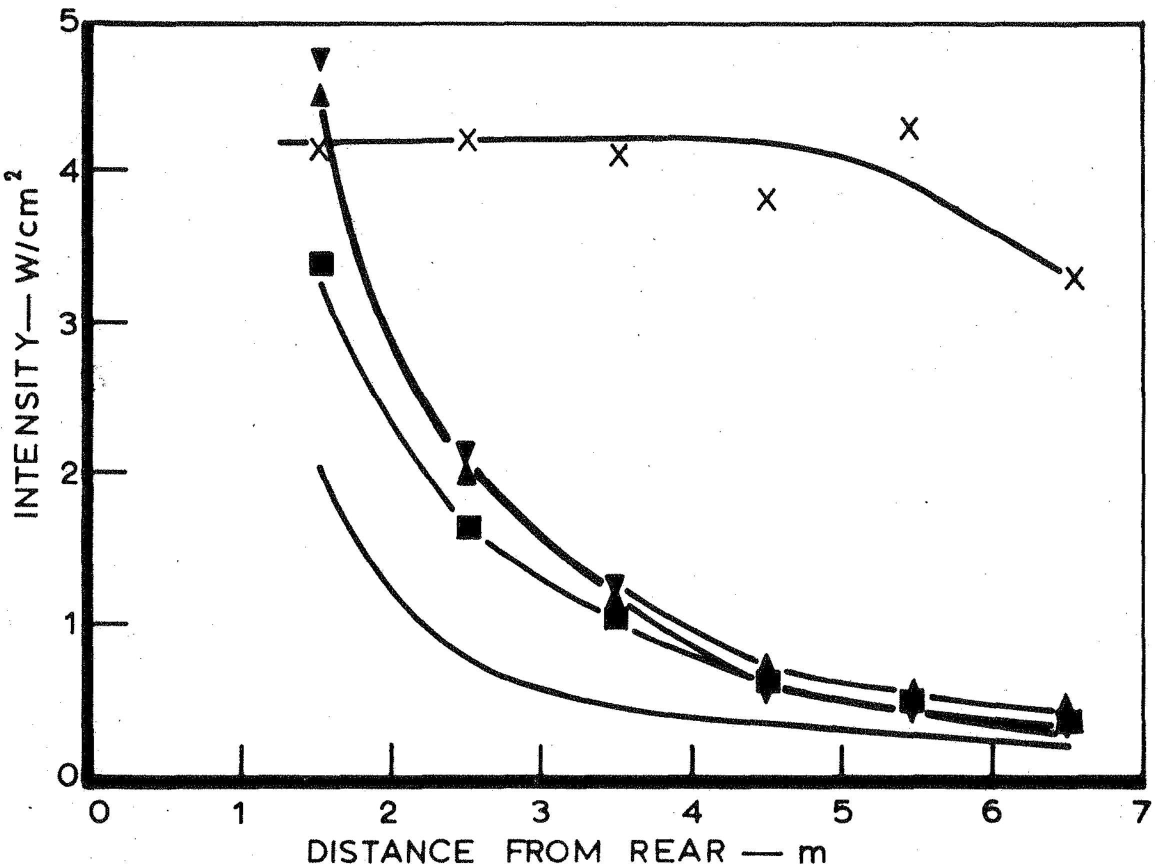
▽——▽ With chlorinated rubber paint

□——□ Impregnated

—— Incombustible ceiling at equilibrium

Fibre insulating board type ceilings

FIG. 5a. DOWNWARD RADIATION AT BASE OF HOT GAS LAYER (3 MINUTES FROM START OF TEST)



▲—▲ Medium hardboard with plastics paint

▼—▼ Standard hardboard with intumescent paint

■—■ Impregnated medium hardboard

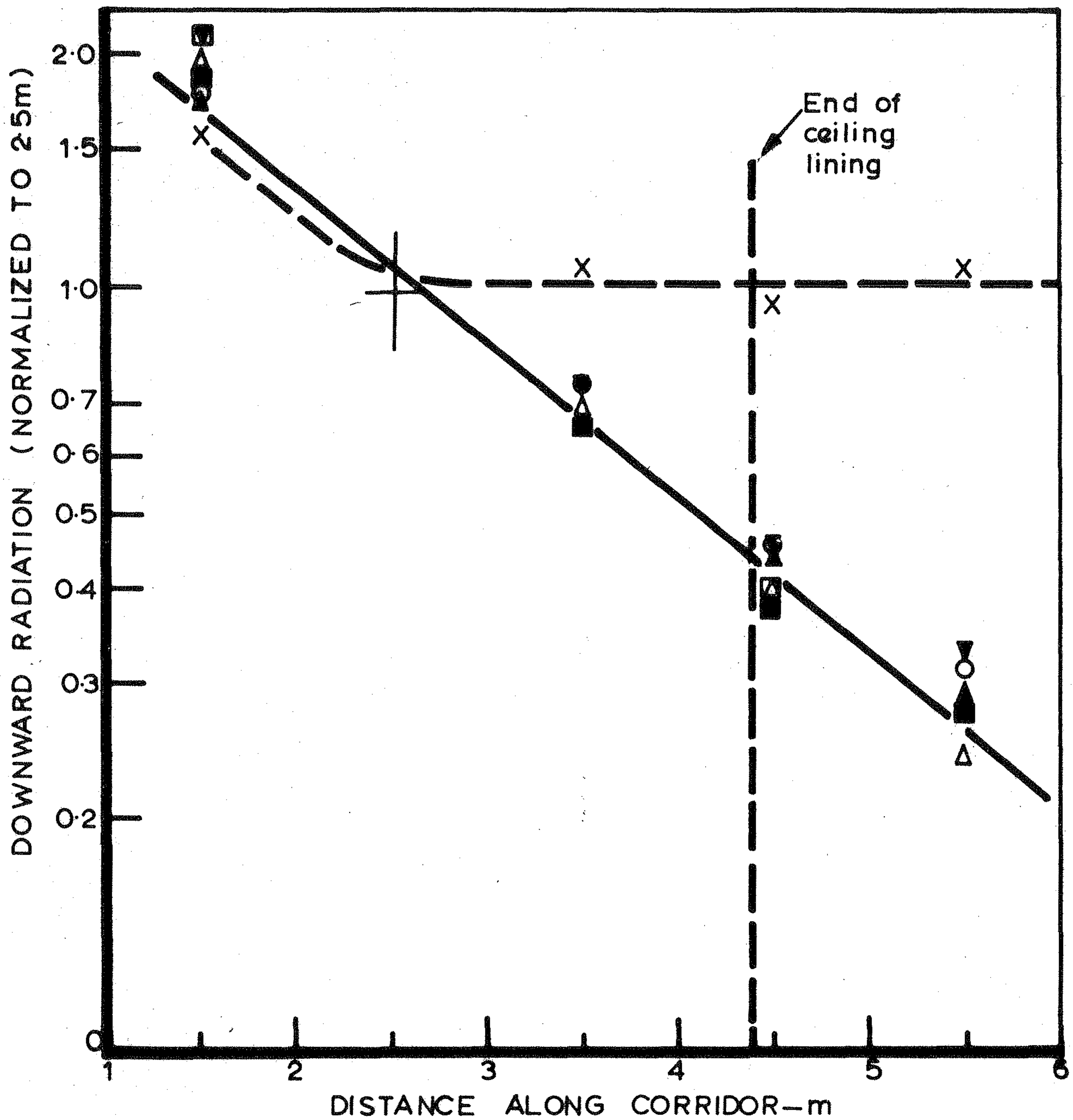
x—x Stove enamelled tempered hardboard

—— Incombustible ceiling at equilibrium

Hardboard type ceilings

F.R. 743.

FIG. 5b. DOWNWARD RADIATION AT BASE OF HOT GAS LAYER (3 MINUTES FROM START OF TEST)



○ Untreated fibre insulating board
△ Fibre insulating board with emulsion paint
□ Impregnated fibre insulating board
▲ Medium hardboard with plastics paint
▼ Standard hardboard with intumescent paint
■ Impregnated medium hardboard
X Stove enamelled tempered hardboard

FIG. 6. VARIATION OF DOWNWARD RADIATION

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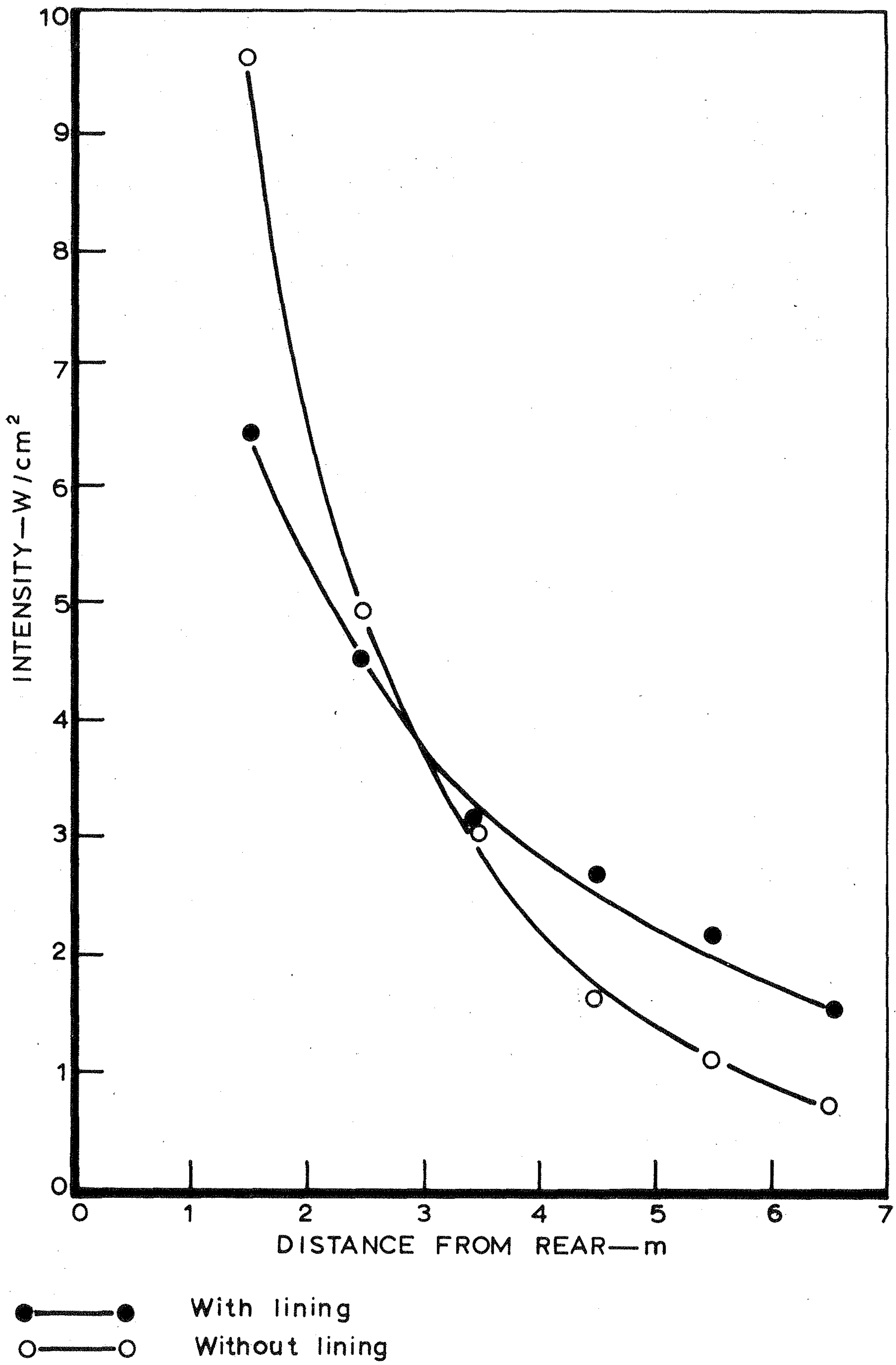

(Gas flow = 300 cm^3/s per cm width)

F.R. 743.

FIG 7 DOWNWARD RADIATION AT BASE OF HOT

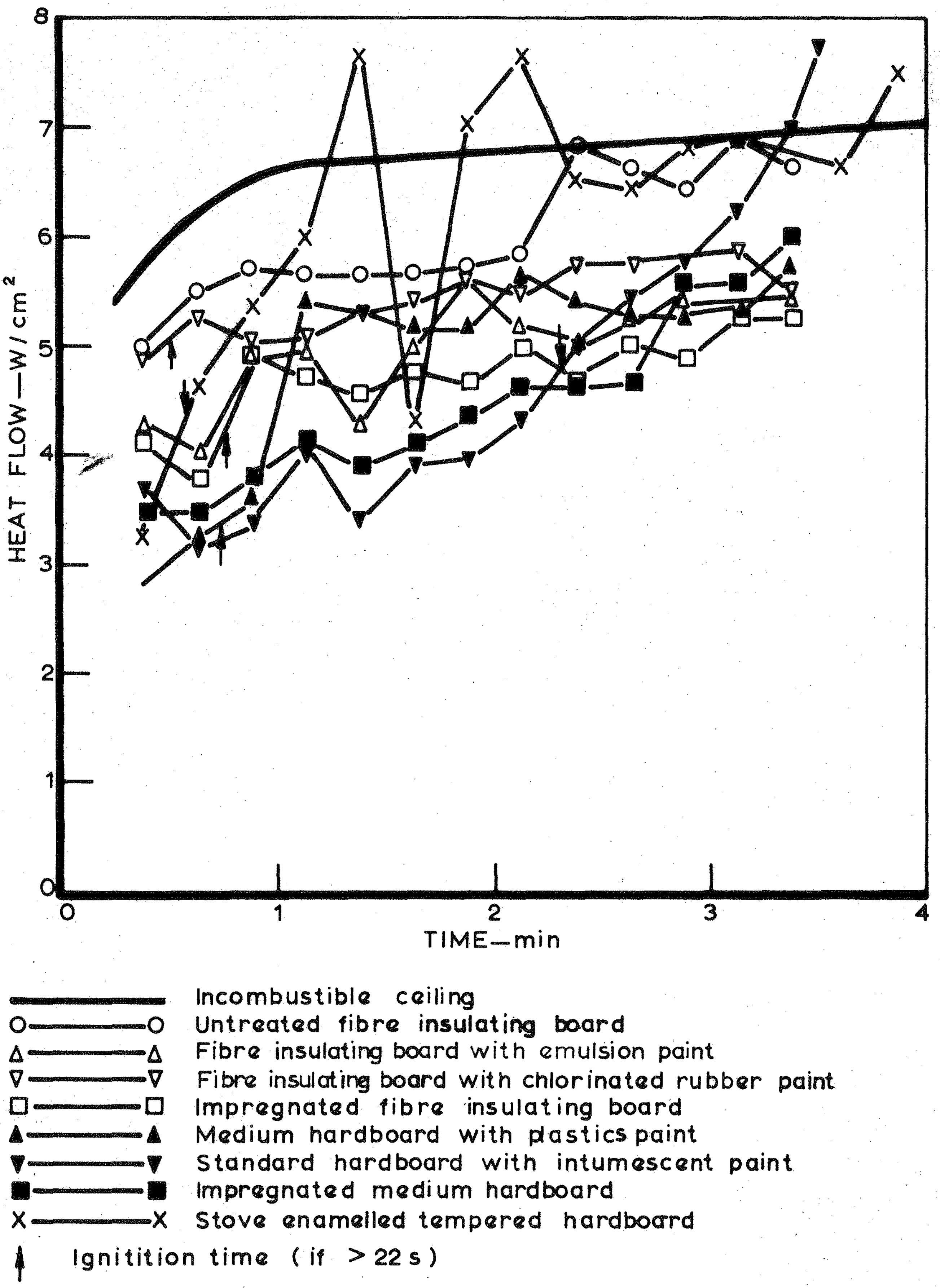

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FIG 8 HEAT FLOW INTO CEILING OVER BURNER

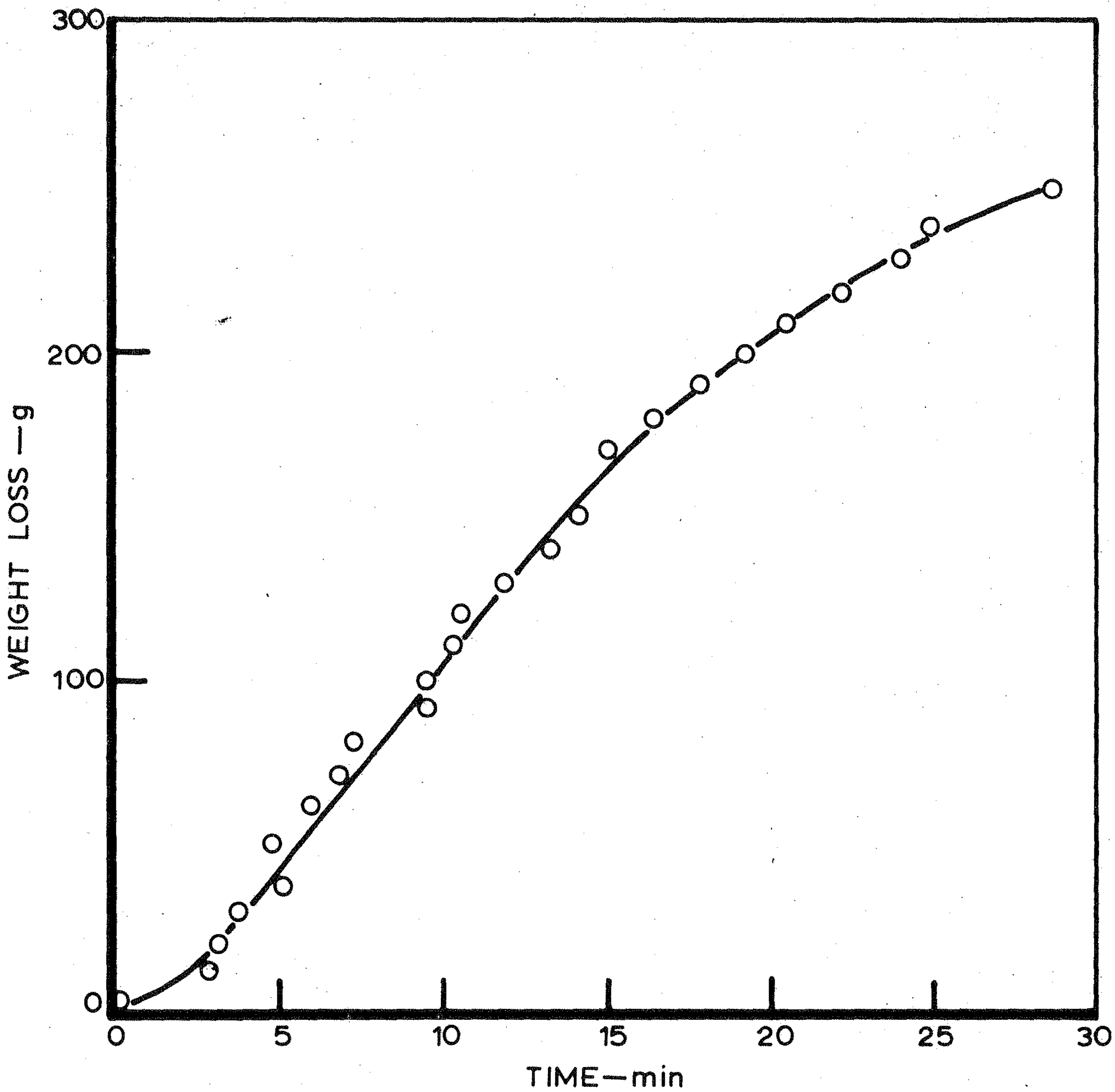
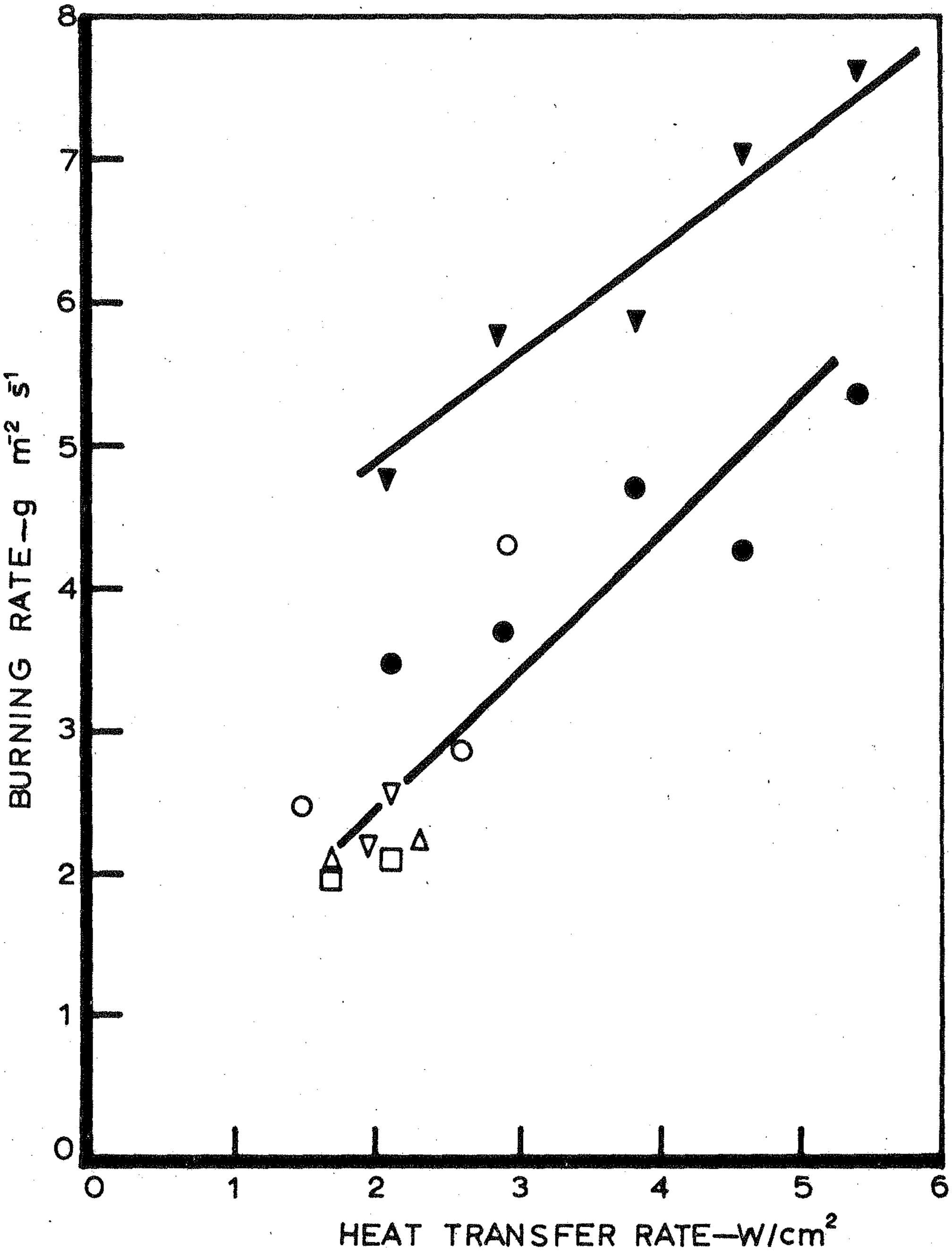


FIG. 9. LOSS OF WEIGHT OF FIBRE INSULATING BOARD WITH EMULSION PAINT DURING AN EXPERIMENT

F.R. 743.



Vertical specimens[7]	
Untreated 2·5 cm thick	●
Untreated 1·27 cm thick	▼
Ceiling linings	
Untreated	○
With emulsion paint	△
With chlorinated rubber paint	▽
Impregnated	□

F.R. 743.

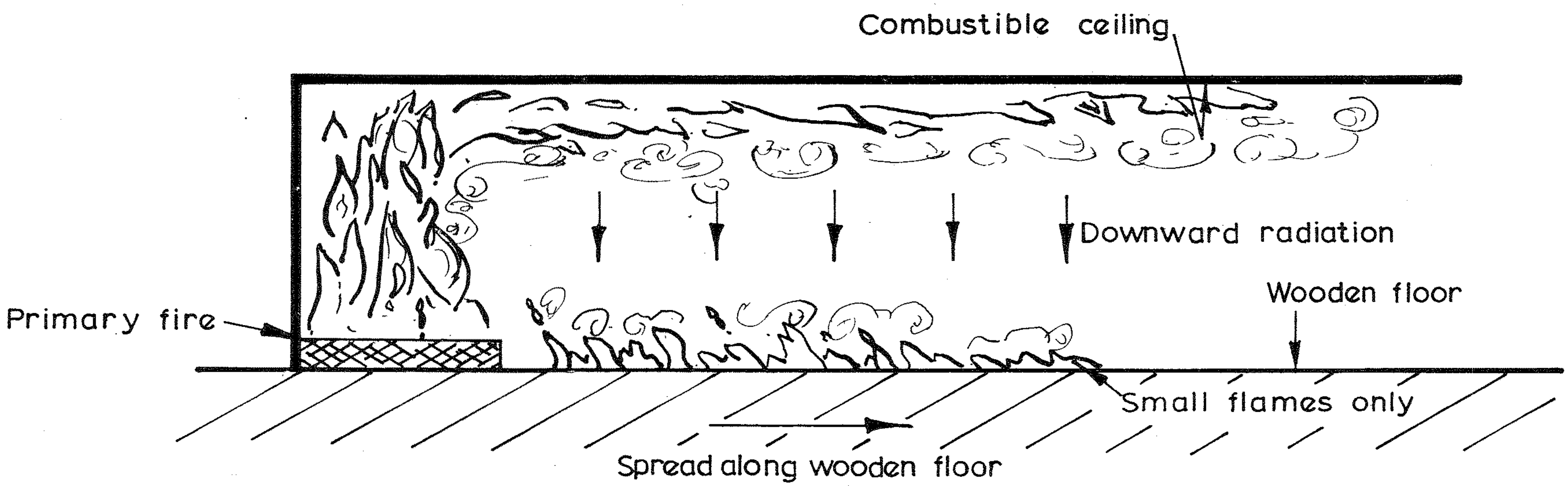


FIG.11. SPREAD ALONG A WOODEN FLOOR DUE TO DOWNWARD RADIATION FROM BURNING CEILING

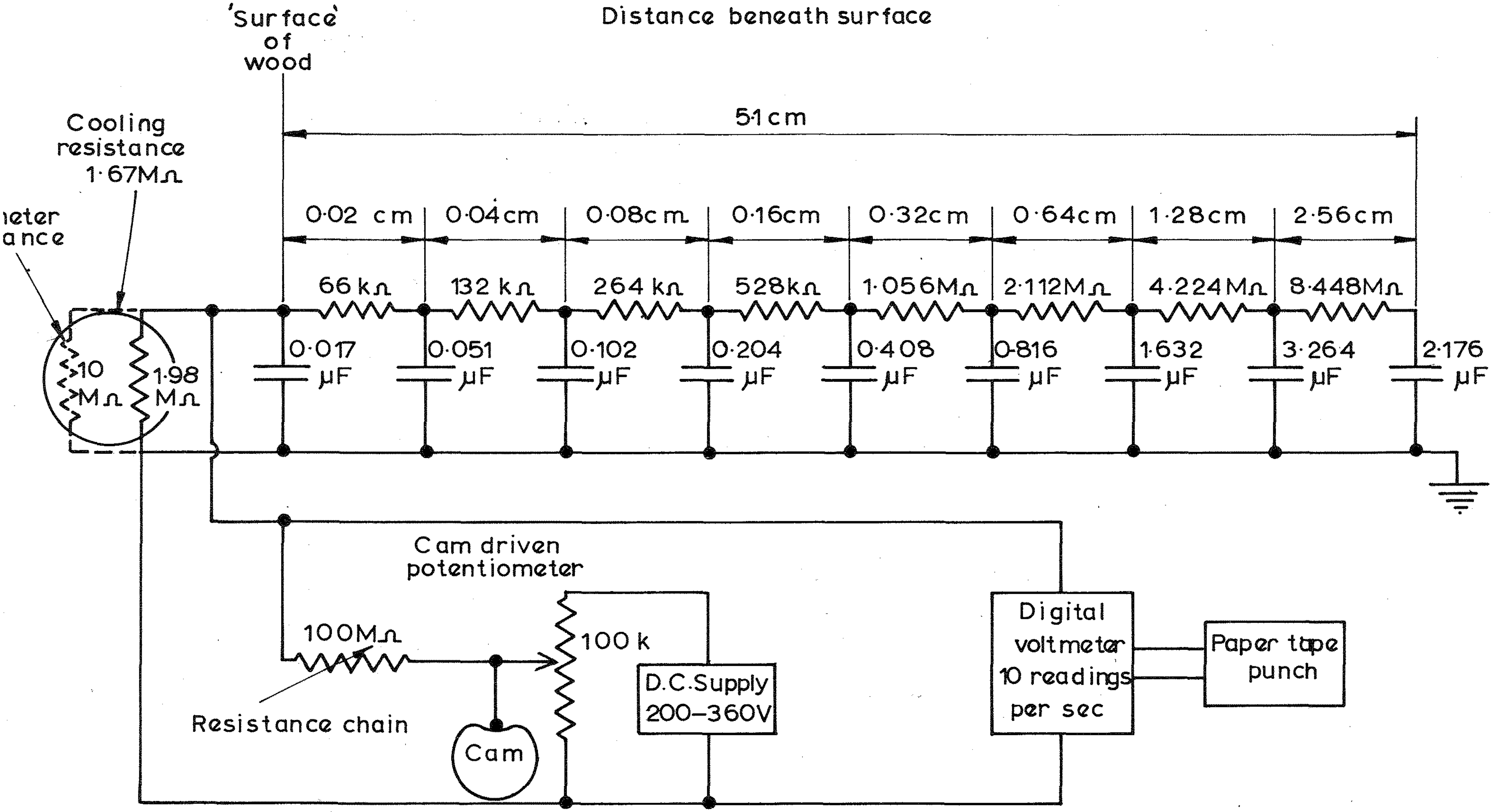


FIG. 12. DIAGRAM OF ANALOGUE

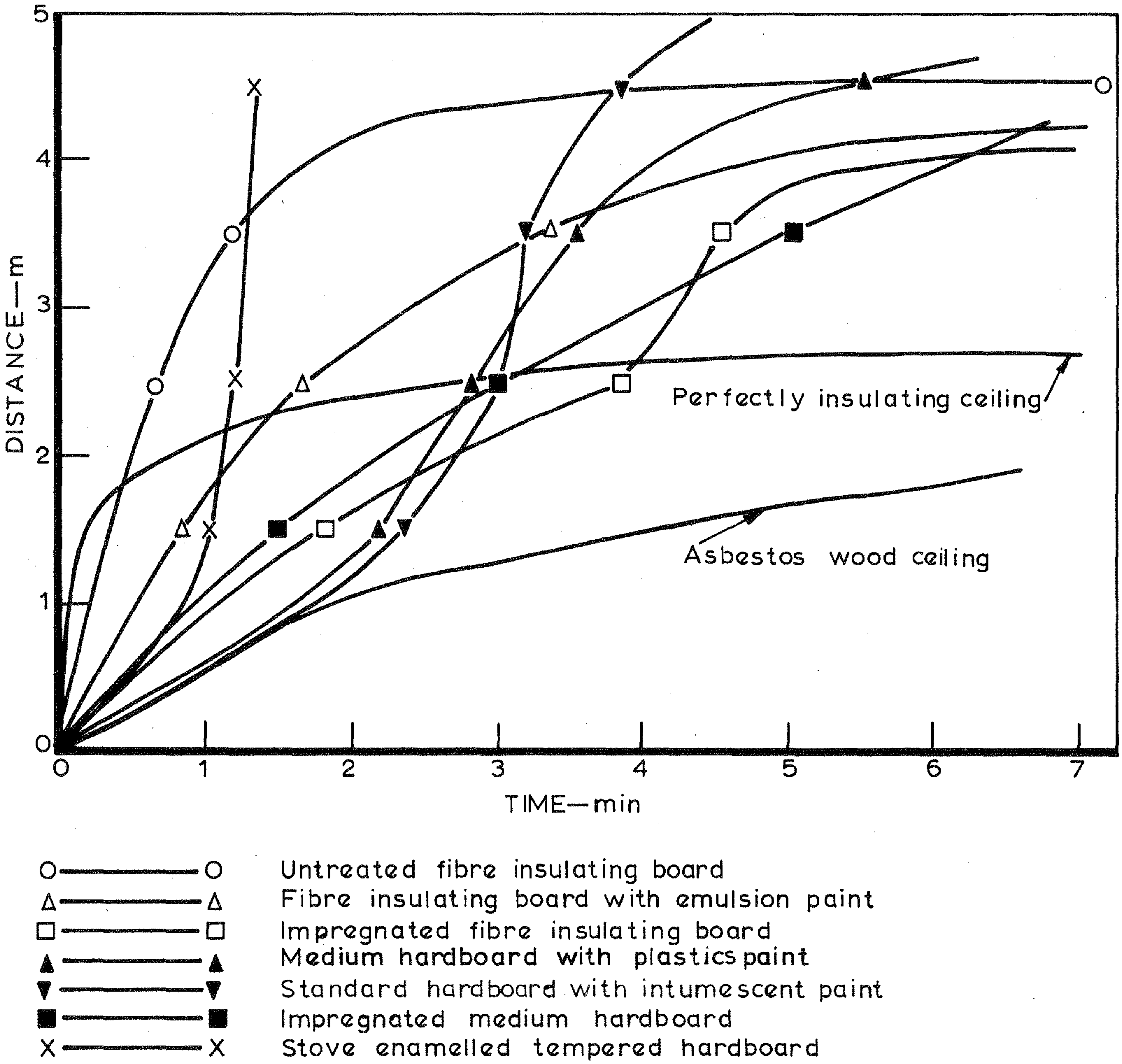


FIG. 13. CALCULATED SPREAD ON WOOD FLOOR UNDER LINED CEILING

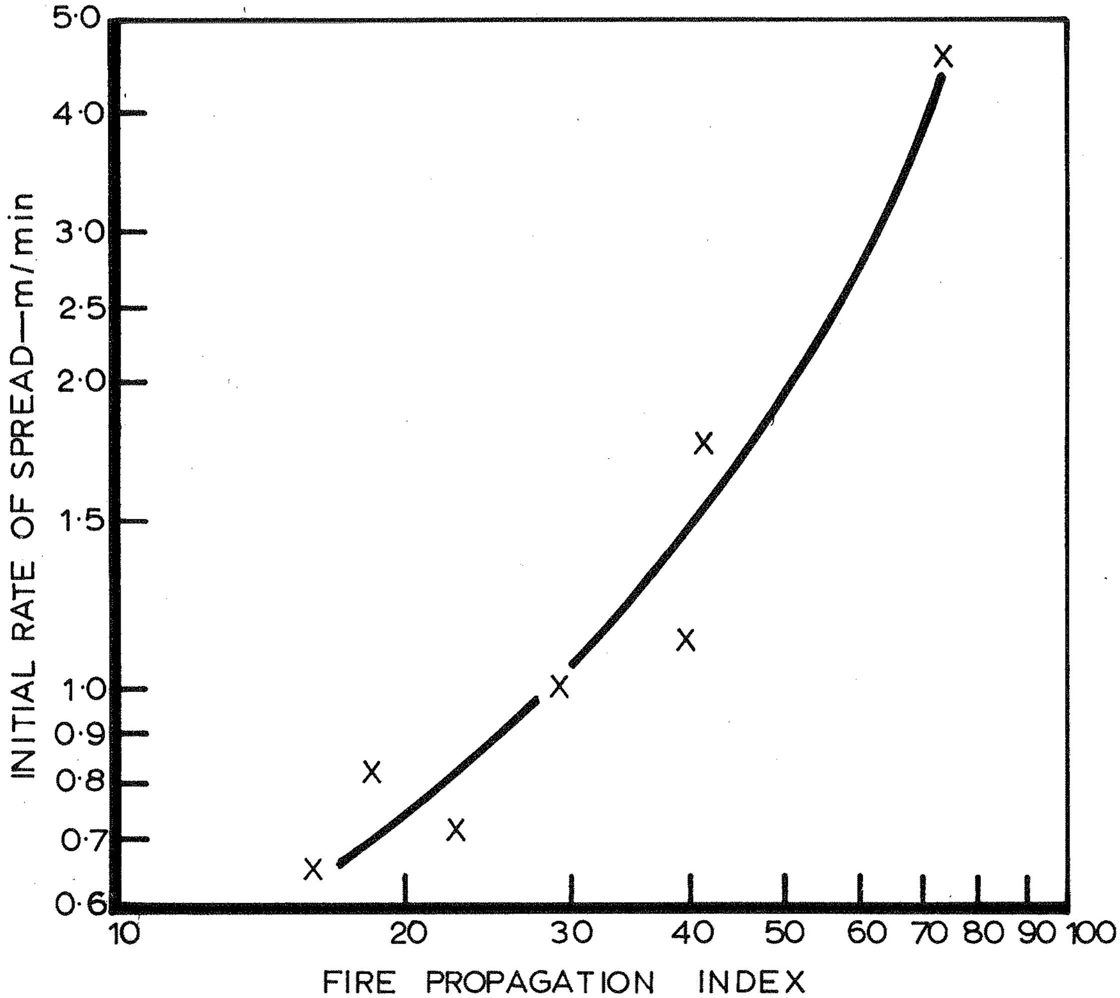


FIG. 14. CORRELATION BETWEEN INITIAL RATE OF FIRE SPREAD AND FIRE PROPAGATION INDEX

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F.R. 743.

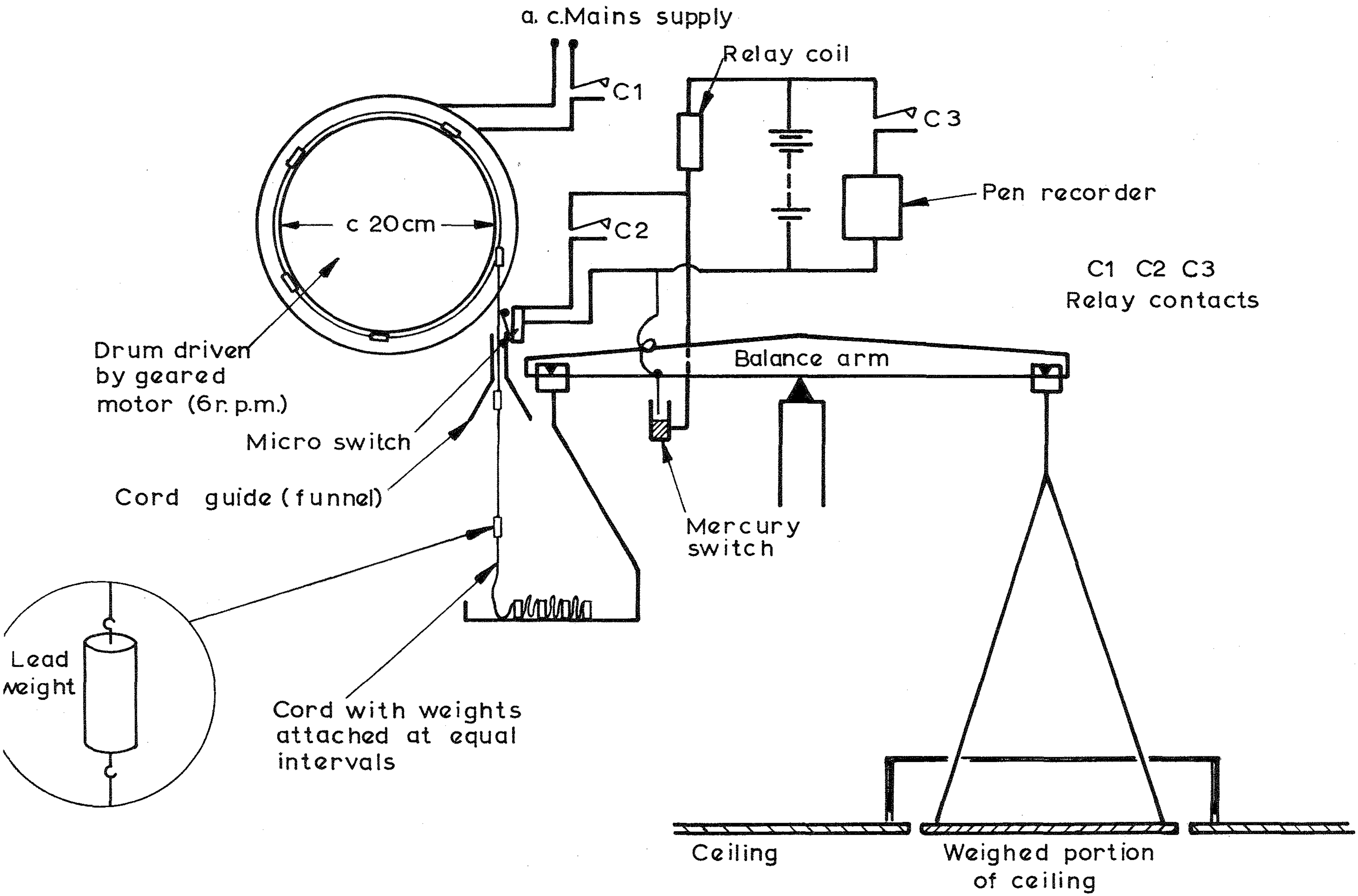
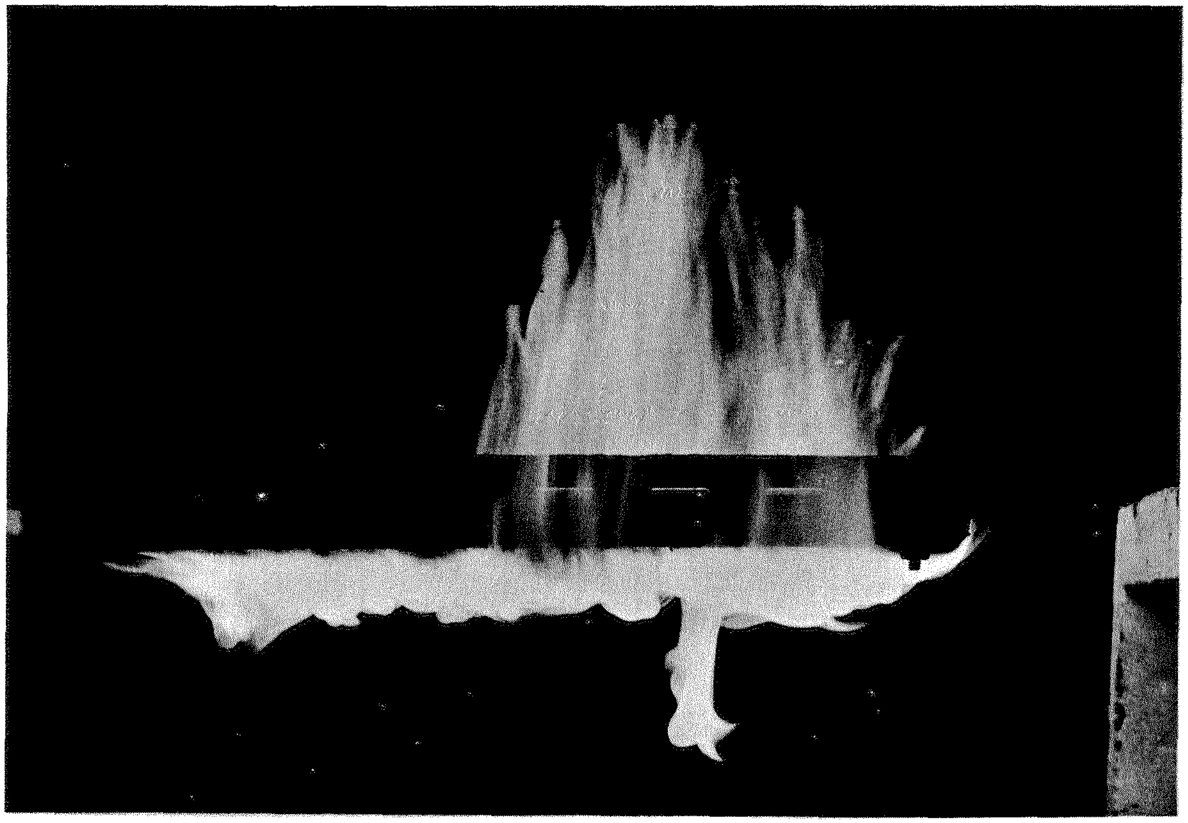


FIG. 15. AUTOMATIC WEIGHT UNLOADING DEVICE



BURNING STOVE-ENAMELLED HARDBOARD SHOWING JETS OF FLAME

PLATE 1

BURNING FIBRE INSULATING BOARD SHOWING ONLY TENUOUS FLAME

PLATE 2