F. R. Note No. 469

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

SOME FIRES IN A SINGLE COMPARTMENT WITH INDEPENDENT VARIATION OF FUEL SURFACE AREA AND THICKNESS

by

A. J. M. Heselden

SUMMARY

Previous experiments on the rate of burning of fires in single compartments with small windows have shown that over a wide range of scale the rate of burning is proportional to the air flow into the compartment. There was, however, some variation in the results unaccounted for by this effect and accordingly in this note experiments are described in which various amounts and surface areas of one type of fuel were burnt in a model room with a small window. The results show that over the range of experiments the burning rates varied by a factor of nearly 2:1, although the window opening was kept constant. This variation could not be simply correlated with a surface area effect as might be imagined at first sight, but because it is sufficiently large to make any prediction of the required fire resistance of a structure liable to up to 100 per cent error, it cannot be neglected, and a further, more detailed study of fire behaviour in rooms is called for.

Data on flame height outside the room and internal temperature are also reported and discussed.

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September 1961

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by

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1. Introduction

Studies of the development of fires in single compartments with relatively small window openings have shown that the maximum burning rate is proportional to the air flow which, for a room with a single window, is proportional to $A\sqrt{H}$ where A is the area and H the height of the window[1, 2, 3]. In these experiments covering a wide range of scale there was a considerable scatter in the burning rates, and although none of this could be directly attributed to variations in amount and surface area of fuel, these could not be ruled out as relevant factors since little information was available on the effective fuel surface area. Further experiments in which surface area and total quantity of fuel were separately varied have therefore been carried out, and are described in this report. The height of the flames emerging from the window opening was also measured to accumulate data for studies of the spread of fire between buildings by radiation.

2. Apparatus

The model room used for these experiments was made from $\frac{1}{2}$ in asbestos wood and measured internally $28\frac{1}{2}$ in high, 31 in wide and 36 in from front to back. The front was open, but could be closed by two sheets of asbestos wood fitting tightly round the edges and leaving a window opening running the full width of the box. The upper sheet extended above the box so that flame emerging from the window was single sided (see Fig. 1 and Plate 1).

The fire load consisted of sheets of fibre insulation board held vertically and perpendicularly to the plane of the window in metal frames to prevent undue buckling of the boards as they burned. These frames were bolted in place in a larger framework which could be lifted in and out of the compartment. From 4 to 12 boards were burned at any one time, the spacing between boards being altered so that they were evenly spaced over the whole width of the compartment. Two heights of board, 12.4 and 18.6 in., and three thicknesses, $\frac{1}{2}$ in, $\frac{3}{4}$ in, and 1 in were used; all the boards were homogeneous and were made by the same manufacturer (some manufacturers make 1 in board by cementing $\frac{1}{2}$ in board together). A few tests were made in which the board thickness was increased to 2 in by cementing thinner sheets together and binding the resulting sheet with wire to prevent the components splitting apart as they became hot. The boards were weighed on a platform balance underneath the compartment connected to the frame holding the boards by struts passing through small holes in the bottom of the box, as shown in Fig. 1. Plate 1 is a general view of the apparatus and instruments.

Four 28 S.W.G. chromel-alumel thermocouples were installed with their hot junctions in a vertical line, 3 in apart, 8.5 in from the window plane, 11 in from the side of the box with the lowest junction 14 in from the floor of the box. (See Fig. 1).

3. Experiments

3.1. Ignition

After trial experiments the following method of ignition was made standard. Fibre insulation boards conditioned in an atmosphere at 65°F and 65 per cent relative humidity were loaded into the frames and wired in. The upper front asbestos board was bolted into position on the front of the box, and the thermocouples placed in position. Strips of fibre insulation board, measuring $\frac{1}{2}$ x 1 x 32 in., each containing 80 ml kerosine were placed one between each sheet at the bottom with one on the outside of each outer sheet (thus for n sheets, n + 1 strips were used). They were lit by a gas flame run along the front and 20 sec. after ignition, the lower board was rapidly bolted into position on the front leaving a window opening 10 in high and 31 in wide.

3.2. Measurements

The following measurements were made during the fires:-

(a) Weight of sheets. The most convenient method of following the change in weight with time was to note the time at each ½ lb decrement.

(b) Height of flames emerging from the window. These were estimated by eye, with the flame against a scale.

(c) Temperatures inside the compartment. Measured in four positions. (See Section 2).

Table 1 shows the various combinations of number and thickness of boards used.

4. Results and discussion

4.1. Preliminary tests

Some tests were carried out before the main series to find a suitable size for the window opening and a suitable method for ignition. It was found that, with a 6 or 8 in high window opening, the flame zone appeared to be unstable and alternated between two positions. The boards ignited at the front and burning took place in a narrow zone which travelled slowly back into the box. After some minutes the flame moved forward and after staying at the front of the box for a period, moved back approximately to its former position. In some fires this happened several times. The burning rate with the flame at the front of the box was appreciably lower than with the flame deeper in the box.

This effect of flame movement is probably related to the stages in which the boards burn. The flame moves back into the box as the material which can supply volatiles is exhausted from the fibre insulation board at the front and combustion of the residual charcoal can then take place, producing the high temperatures in the board at the front. Volatiles may then be extracted from the residual material at a sufficiently high rate for the flame to move back to the front. The supply of volatiles will then diminish owing to the fall in temperature due to the charcoal being prevented from burning by lack of oxygen. The flame will then move back into the box. With a window opening 10 in high the flames were stabilised and occupied a much deeper zone in the box, although even then they did not completely fill the box. All further tests were, therefore, carried out with a 10 in high window. A similar instability appears in those tests with composite 2 in thick boards even though the window was 10 in high.

4.2. Main series

The results are summarised in Table 1.

4.2.1. Course of individual test

When the kerosine-soaked strips were lit, flame rapidly travelled down their whole length to the back of the box but when, 20 sec. later, the lower front board was placed in position and the ventilation was reduced, the flames became confined to the front of the box. As the fibre insulation board ignited the flame zone moved deeper into the box until at time t_1 about the front ⅔ of the boards was enveloped in flame. This took from 5 – 20 min., depending on the fire load and board height. The flame was observed through mica windows in the side of the box. The position of the flame zone then appeared to be constant, although this was not easy to observe, until at time t_2, when the volatiles were nearly exhausted, the flame zone fell quite suddenly to the back of the box where there was still material available for producing volatiles. The burning rate was than taken as the mean over the period t_1 to t_2 when the flame zone appeared to be in a constant position.

Over this period the burning rate in most tests was constant. The flame height increased to a maximum value during the period t_1 to t_2. Fig. 2 shows the variation of weight, flame height, and average temperature with time for a typical test (Number 19).

In most fires, just after the flames fell to the back of the box the flames emerging from the box increased in height. (See Fig. 2). This was presumably because active combustion of charcoal then took place and the gaseous contents of the box contained less oxygen so that the volatiles required a long flame, even reaching to outside the box, to entrain sufficient oxygen for combustion.

4.2.2. Burning rate

In the analysis of these experiments the total surface area of boards, board thickness and board height were taken to be the most important of the parameters whose effect on burning rate was to be found. Only those parameters could be taken which were varied independently of the others. This limits the number to three in the present experiments and excludes certain combinations, for example area, thickness and fireload, since fireload is proportional to the product of area and thickness and was not therefore varied independently of both area and thickness.

A multiple regression analysis was carried out excluding those tests with composite board, in which the flames behaved rather differently from those tests with the homogeneous board (See Section 4.3), and the burning rate was found to depend significantly on each parameter. These three parameters are uncorrelated and it is therefore permissible[4] to calculate the confidence limits for the regression coefficients.

Table 2 gives the coefficients and confidence limits in the units implied by the regression equation (1):-

$$R = a_o + a_1 A + a_2 T + a_3 H \qquad (1)$$

where R = burning rate (lb/min)

A = total surface area of fibre insulation board, neglecting area on the edges of the boards (ft^2)

T = board thickness (in)

H = board height (in)

TABLE 2

Regression coefficients for burning rate
(The units are those implied in equation (1))

Factor	Coefficient		Significance level (per cent)	95 per cent confidence limits	Residual standard deviation
	a_o	0.45			
Area	a_1	0.0033	<0.1 (Highly significant)	0.0016 to 0.0050	0.07
Thickness	a_2	0.17	2 (Significant)	0.03 to 0.31	(23 d.f.)
Height	a_3	0.014	0.5 (Highly significant)	0.004 to 0.023	

The mean burning rate depends on fuel surface area, and on the fuel thickness, but is not proportional to area as might be expected, the burning rate increasing by between 8 and 26 per cent for an increase in fuel surface area from 22 to 67 ft^2. One possible explanation[5] is that the flame zone may be driven further out of the box by the greater supply of volatiles from a larger fuel surface area. Increasing the area would not, therefore, produce a proportional increase in burning rate because the heat transfer from flame to unit area of fuel would be lowered.

In Fig. 3 the regression lines are plotted for a mean board height as lines of equal burning rate on a graph of area versus thickness. The straight lines from the partial regression are of approximately the same slope as the curved lines of constant fire load (proportional to Area x Thickness) and over the range of these experiments both families of lines are roughly equally spaced for equal increments of burning rate or fire-load. Thus, although burning rate varies with both area and thickness, it appears that the more fundamental relation is a dependence of burning rate on fire load.

If fire load is employed as an independent variable the effect due to area alone disappears and the burning rate of panels of one height is dependent only on the fire-load in the range of these experiments. One might expect that this could not be valid over the whole range of possible experimental conditions - a finely divided dust would be expected to burn faster than a solid block of equal weight so that the physical basis of these results requires further examination before the rate-controlling mechanism can be understood sufficiently to establish general scaling laws.

4.2.3. Flame height

As in Section 4.2.2. a multiple regression analysis was carried out of flame height on fuel surface, thickness and board height. Table 3 gives the regression coefficients and confidence limits, the units being those implied in the regression equation (2):-

$$L = b_0 + b_1 A + b_2 T + b_3 H \qquad (2)$$

where L is the flame height (ft) measured from the base of the boards and A, T and H are the same as before. Flame height was found to depend only on area although a larger experiment might have shown that it also depended on board height, since this was found to be significant at the 8 per cent level.

Table 3. Regression coefficients for flame height
(The units are those implied in equation (2))

Factor	Coefficient		Significance level (per cent)	95 per cent confidence limits	Residual standard deviation
	b_0	+ 1.39	-	-	
Area	b_1	0.039	≪0.1 (Highly significant)	0.031 + 0.047	0.31
Thickness	b_2	0.34	(Not significant)	-	(23 d.f.)
Height	b_3	0.038	8 (Not significant)	- 0.005 to 0.081	

The simple linear relation assumed in calculating the regression and found significant is likely to be only a first approximation. A relation of the form $L = cA^n$ shown in Fig. 4 where c is a constant and n is about $\frac{1}{2}$, can fit the data at least as well. It is surprising that flame height and burning rate do not vary in the same way with A,T and H since one would expect a close correlation between flame height and burning rate.

Thomas[6] has obtained a relation between dimensionless flame height L/D and the parameter R^2/D^5 from experiments with cribs of wood burning in cubical boxes with one side completely open. The relation found was

$$\frac{L}{D} = K\left(\frac{R^2}{D^5}\right)^m \qquad (3)$$

where L is the flame height from the base of the crib, D is the length of one side of the box, and K and m are constants with m about $\frac{1}{3}$. If for the present we take $m = \frac{1}{3}$ then (3) can be rewritten

$$L = Kr^{\frac{2}{3}} \qquad (4)$$

where r is the burning rate per unit width of window opening. The range of r in the present experiments is too small (less than 2 : 1) to test whether this type of relation holds here but even when the burning rate was constant, flame height varied with fuel surface area. The reason for this is not yet known but it may be an effect of the mixing pattern of the gases. The dependent parameter might not be area at all, but spacing between boards, since these two parameters are negatively correlated and it is not known which of the two causes the variation with flame height.

A few experiments with a model in which the burning of the volatiles from wood is simulated by a flame of town gas have shown that K depends on the geometry of the box and its opening (a more extensive series of these experiments will be carried out later).

For a ventilation-controlled fire, Kawagoe[1] and Simms, Hird and Wraight[2,3] have shown that over a wide range of scale burning rate is proportional to an air flow factor $A\sqrt{H}$, i.e.

$$R = b \quad A\sqrt{H} \qquad (5)$$

where A is the window area, H the window height. They were not able to find any systematic variation in b with scale, fireload, or fuel surface area. It is shown in Sections 4.2.2. and 4.3. that even with a constant window shape and size, the burning rate depended on fire load in the range of these experiments, the lowest burning rate being about 0.8 lb/min, and the highest about 1.4 lb/min, a variation of nearly 2 : 1. Thus b is not constant but can vary by a factor of nearly two depending mainly on the fire load.

Combining (4) and (5)

$$L = K r^{\frac{2}{3}} = K (b H\sqrt{H})^{\frac{2}{3}} = K b^{\frac{2}{3}} H$$

$$\text{or} \qquad \frac{L}{H} = K b^{\frac{2}{3}} \qquad (6)$$

$$\text{or} \qquad \frac{L}{H} = \text{is a function of box geometry and fire load} \qquad (7)$$

Thus, it is possible that variation in the height of flames emerging from a window of a burning room when expressed as units of window height is due to secondary effects of room geometry and fuel area and thickness.

Correlations between flame size and fuel area or disposition have been noted by Yokoi[7] and Shorter[8]. Yokoi (Chapter 6) found that in a short period after flashover a fire in a room lined with plywood gave much larger flames than a fire in the same room with no lining. In the full-scale tests carried out by the National Research Council of Canada in the St. Laurence Burns project, it was found that the radiation from those buildings in which some of the rooms were lined with combustible material was greater than from those with incombustible linings. In these tests the radiation from the window opening was small compared with the radiation from the flames, implying that the flames from rooms with combustible linings were larger than from those with incombustible linings. The burning rate during these tests is not known but the houses were chosen to be reasonably comparable apart from the intended differences in wall lining so that presumably the amounts of air which could be induced by a fire to flow through the windows were also comparable. There seem to be two main possibilities. Either the burning rates were similar and the flames were different owing to differences in fuel area or disposition, or differences in fuel area or disposition caused differences in burning rate which affected flame heights.

4.2.4. Temperature

For every minute of any one test the mean of all four thermocouple readings was calculated. The highest mean was called the maximum mean temperature and is given in Table 1. The maximum mean temperature is correlated with burning rate (Fig. 5), but the extreme variation observed, some 250°C, can make not more than about 3 per cent difference in the induced air flow into the box. This is insufficient to cause an increase in heat release in the box which could account for the observed variation in rate of burning. These considerations suggest, therefore, that it is not the total quantity of heat which varies, but the distribution of heating rates in different parts of the compartment.

Changes in local temperature, however, lead to changes in the local heat transfer rate to the solid fuel and thereby change the rate of decomposition, i.e. weight loss, and the results confirm this qualitatively. But because it is not easy to allow for configuration effects and the difference between gas and wall temperature, it is not possible to estimate simply the actual heat transfer rates to the fibre insulating board.

4.3. Tests with boards cemented together

The tests with 2 in fibre insulation board, formed by cementing thinner sheet together, are not strictly comparable with the tests with thinner boards, because of differences in the flame positions. In most tests much oscillation of flame occurred, the flames jumping from back to front of certain spaces between boards. This oscillation was not observed in tests 28 and 29 (4, 1 in boards formed by cementing $\frac{1}{2}$ in boards together) and in these tests and in tests 22, 23 and 24 (4, 1 in homogeneous boards) the fires behaved similarly. The oscillation is, therefore, probably related to the extra thickness of the 2 in board rather than in some way to the cement. Fig. 6 shows the variation of burning rate and flame height with time for tests 31 to 34.

In test 31 the burning rate was constant, but the flames were alternating between back and front.

In test 32 the flame zone occupied the front $\frac{2}{3}$ of the box up to 20 min when, after a few oscillations, the flame changed to a thin flame about 1 in thick covering the whole surface of the boards. This change was accompanied by an increase in burning rate from 1.0 to about 1.4 lb/min.

Tests 33 and 34 show two peaks in the flame height, but these tests are complicated by the $\frac{1}{2}$ in sheets splitting away from the 1 in central sheet at 19-23 min., i.e. in the trough between the peaks. The first peak flame height was attained in about half the time of tests 31 and 32.

Even though a strict comparison with the tests with boards $\frac{1}{2}$ to 1 in thick is impossible owing to the differences in flames it was thought necessary to have some estimate of the average burning rate over a period comparable with that of tests with the thinner board. By inspection of Table 1 this period was taken as 10 to 30 min, but the burning rate values calculated will not be much affected by the exact period chosen so long as the part at the start of the test where the burning rate is still increasing and part at the end where the material which can produce volatiles is nearly exhausted, are not included.

The values obtained were about 1.4 lb/min and this is much higher than in any of the tests with ½ to 1 in thick board. By increasing fuel thickness and surface area, the rate of burning of a fire in a compartment with a constant window opening has been caused to increase from 0.8 to 1.4 lb/min.

The temperatures measured in this series are low. This is probably related to the difference in position of the flame zone.

5. General conclusions

(1) Kawagoe[1] and Simms, Hird and Wraight[2,3] have established a relation between burning rate and air flow factor $A\sqrt{H}$ from experiments over a range in $A\sqrt{H}$ of 2000 : 1. Up to now it has been thought that the burning rate of fires in rooms with small window openings is very largely controlled by the value of $A\sqrt{H}$. The experiments described in the present report show that superimposed on this relation are relations between burning rate and fuel thickness and surface area, which in the present experiments have caused the burning rate to vary by a factor of nearly 2:1, for one value of $A\sqrt{H}$.

An empirical correlation of the results has been made by regression analysis and it has been found that burning rate increases as fuel surface area or thickness increases.

(2) The experiments do not cover a large enough range of burning rate for determining accurately the relation between burning rate and flame height, but with constant burning rate, flame height varies with an additional factor – either fuel surface area or separation. No explanation for this effect can be offered at present.

(3) The maximum mean temperature in the upper part of the box increases with burning rate, but the temperature differences found are insufficient to cause appreciable differences in the induced air flow into the box and hence in the gross heat release rate.

(4) It is not possible at this stage to explain these results but the study of fires in single compartments is being continued with a new model. When wood or any cellulose material burns, the rate of production of volatile fuel from any given area of solid fuel depends on the heat transferred to this area by combustion of the volatile fuel. In the new model this interaction between burning rate and heat transfer is avoided by burning town gas at controlled flows. It will then be possible to explore the relations between burning rate and mixing pattern and heat transfer rates to the fuel more directly.

Acknowledgments

The author wishes to acknowledge the guidance and valuable advice of Dr. P. H. Thomas during this work.

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Table 1 Notes

1. t_1 and t_2 are defined in Section 4.2.1.

2. For each minute of the test the mean of all four thermocouple readings was calculated. The highest mean was called the maximum mean temperature.

3. $\frac{1}{2}$ in boards cemented with silicate paint.

4. $\frac{1}{2}$ in boards cemented with resorcinol formaldehyde cement.

5. 1 in boards cemented with resorcinol formaldehyde cement, but boards split apart early in test.

6. 1 in boards cemented with silicate paint

7. 1 in board in centre with $\frac{1}{2}$ in board cemented on both sides with silicate paint. Test 34 also had aluminium foil between the 1 in and $\frac{1}{2}$ in boards.

8. Average burning rates for the arbitrary period 10 to 30 min after ignition. This was judged to be roughly the period corresponding to the t_1 to t_2 period in tests 1 - 29.

9. Including weight of ignition strips.

TABLE 1

Summary of results

Board height (in)	Test Number	Number of boards	Board thickness (in)	Spacing between boards (in)	Surface area (ft²)	Total weight of combustibles(9) (lb)	t_1 (1) (min)	t_2 (1) (min)	Time to peak flame height (min)	Maximum flame height from base of boards (ft)	Average burning rate (lb/min)	Maximum mean temperature (2) °C
	1	12	1	1.5	67	50.0	23	44	35	5.25	1.00	-
	2	12	¾	1.7	67	37.0	16	35	23	5.0	1.01	770
	3	12	½	2.0	67	28.7	13	27	19	5	1.00	-
	4	12	½	2.0	67	28.7	14	32	22	4.5	0.81	-
	5	12	½	2.0	67	28.7	16	35	24	4.25	0.84	-
	6	8	¾	3.1	44	24.8	13	25	21	4.25	0.98	-
	7	8	½	3.4	44	19.3	10	20	15	3.75	0.87	720
	8	8	½	3.4	44	19.3	6	16	11	3.75	0.89	-
12.4	9	6	1	4.4	33	25.2	11	17	13	3.5	1.00	750
	10	6	1	4.4	33	25.2	8	18	11	3.75	0.93	-
	11	5	¾	6.1	28	15.6	7	15	12	3.5	0.83	670
	12	5	¾	6.1	28	15.6	12	19.5	16	3.25	0.80	670
	13	4	1	8.0	22	16.9	11	15	14	2.75	0.95	620
	14	4	1	8.0	22	16.9	11.5	16	16	2.5	0.65	580
	15	4	1	8.0	22	16.9	9	15	14	2.75	0.80	640
	16	4	½	8.7	22	9.8	9	13	10	2.75	0.82	640
	17	8	1	2.9	67	47.2	12	36	22	4.75	1.06	800
	18	8	¾	3.1	67	34.6	9	26	17.5	4.75	1.01	760
	19	8	¾	3.1	67	34.6	8	25	15	5.25	1.12	750
	20	8	½	3.4	67	26.3	5	19	13	4.5	0.99	740
	21	8	½	3.4	67	26.3	6	21	16	4.5	1.00	700
	22	4	1	8.0	33	23.8	8	19	9	3.75	0.99	700
	23	4	1	8.0	33	23.8	8	19	13	4	1.00	-
18.6	24	4	1	8.0	33	23.8	7	18	11	3.75	0.98	720
	25	4	¾	8.3	33	17.5	7	14	10	3.75	0.94	700
	26	4	½	8.7	33	13.3	5	11	8	3.75	0.87	670
	27	4	½	8.7	33	13.3	4.5	10	7	4	0.91	680
	28	4	1 (3)	8.0	33	23.8	7	19	10.5	3.25	0.95	-
	29	4	1 (4)	8.0	33	23.8	10	18	9.5	3.25	0.95	-
	30	4	2 (5)	6.7	33	45.6	-	-	23	4.75	1.4 (8)	-
	31	4	2 (6)	6.7	33	45.6	-	-	21	4.25	1.4 (8)	-
	32	4	2 (6)	6.7	33	45.6	-	-	22	4.25	1.3 (8)	-
	33	4	2 (7)	6.7	33	45.6	-	-	12.5 & 27	4.5 & 4.75	1.5 (8)	660
	34	4	2 (7)	6.7	33	45.6	-	-	10 & 27	4.25 & 4.75	1.4 (8)	690

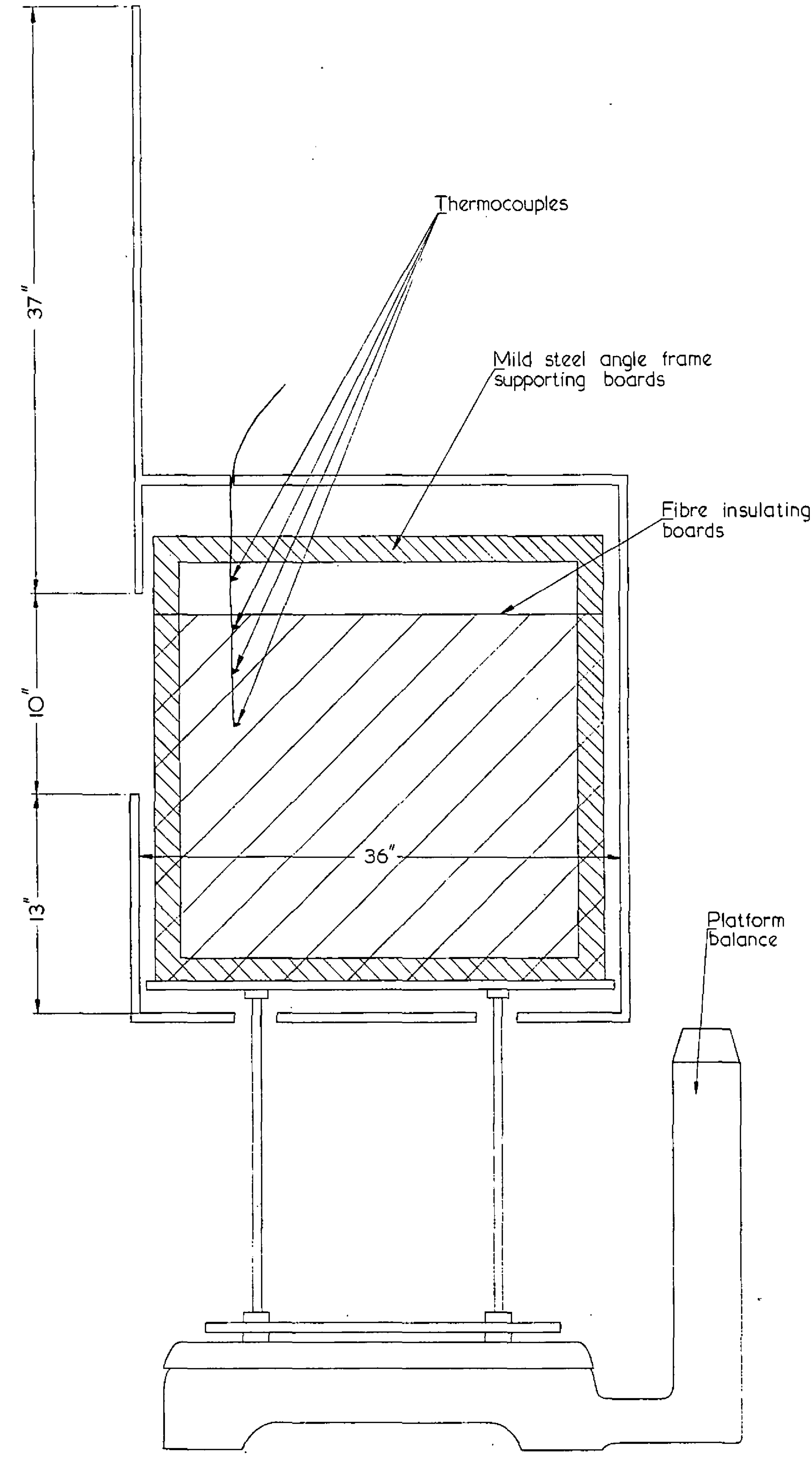


FIG. 1. SECTION THROUGH MODEL ROOM

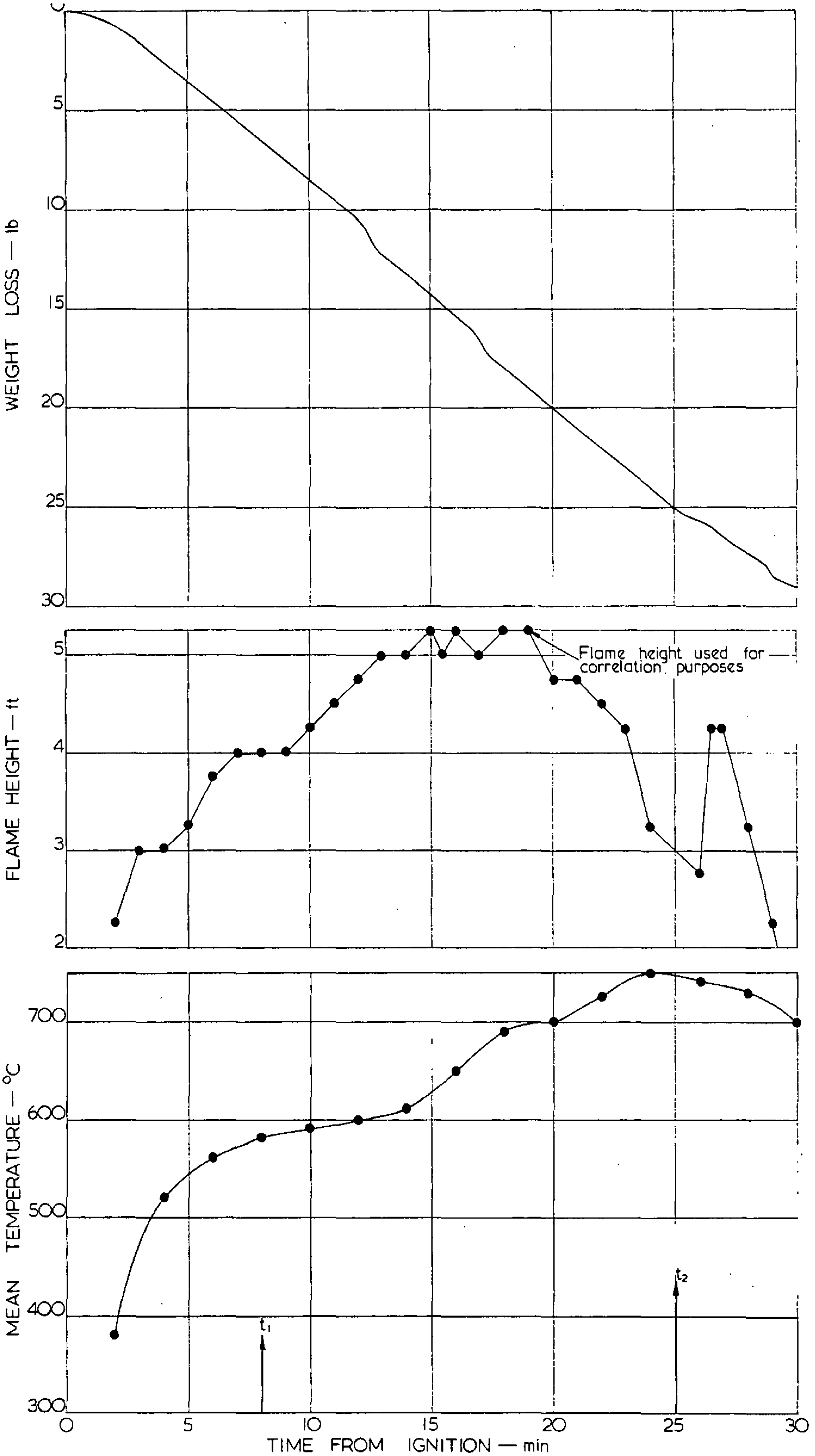
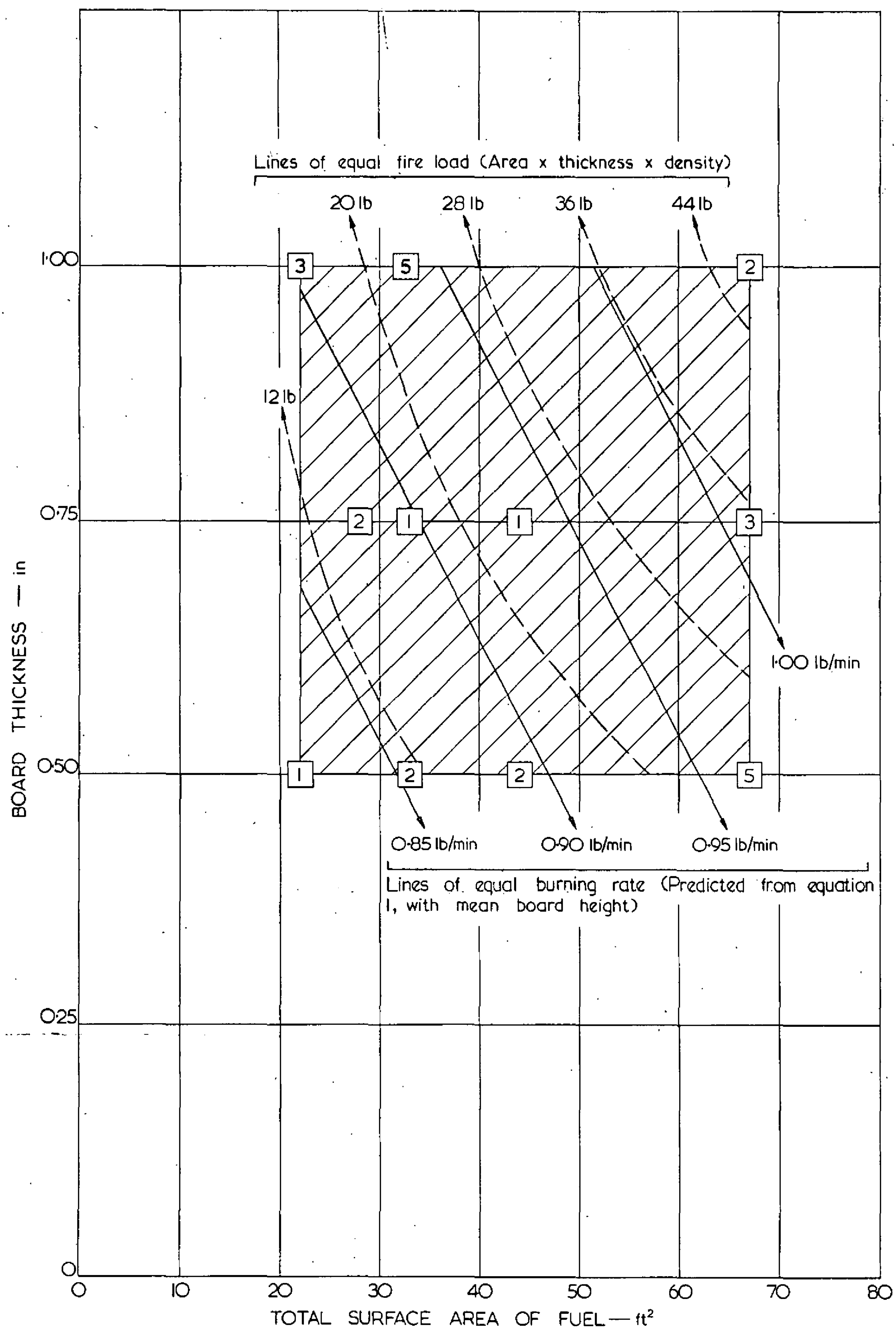
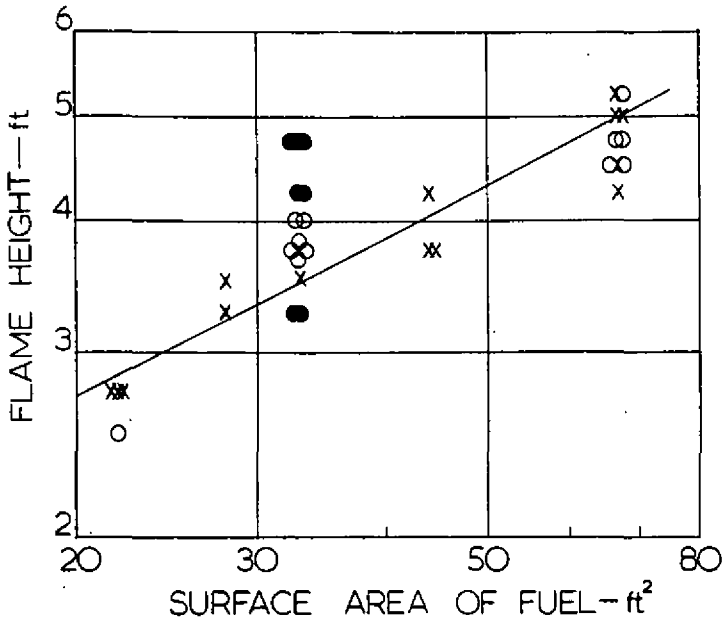


FIG. 2. VARIATION OF WEIGHT, FLAME HEIGHT AND MEAN TEMPERATURE WITH TIME FOR A TYPICAL TEST (No 19)



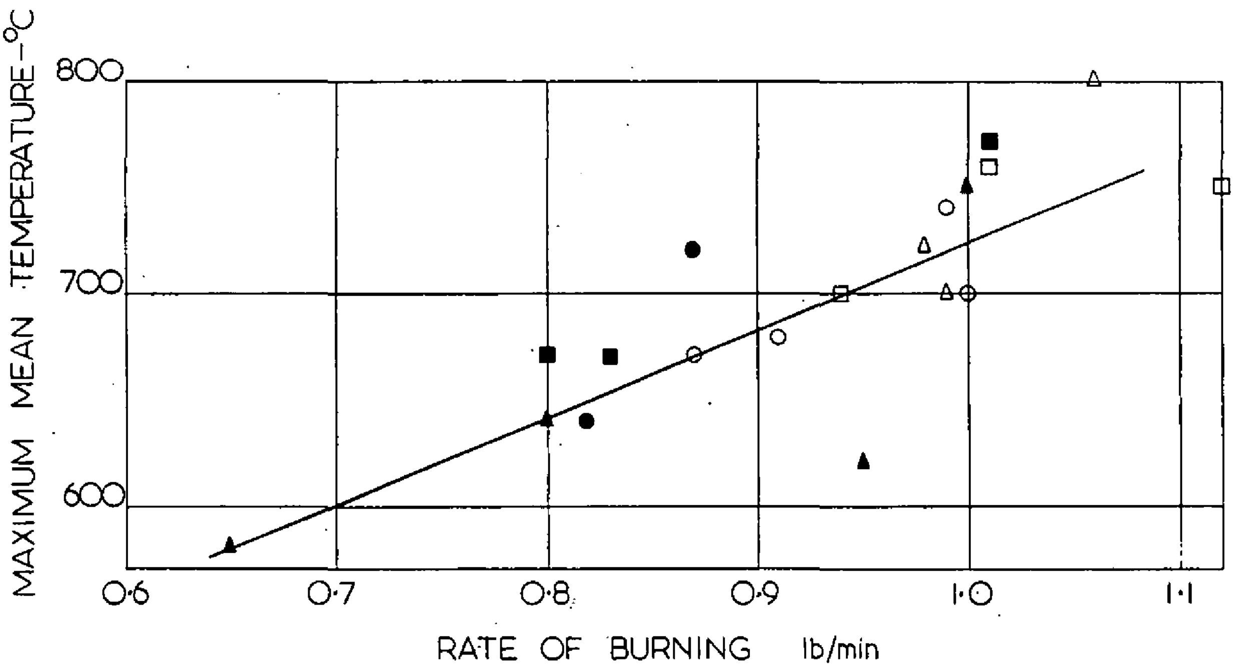
Numbers in squares show number and position of experimental points
Shaded region is experimental region

FIG. 3. BURNING RATE AND FIRE LOAD AS FUNCTIONS OF BOARD THICKNESS AND AREA



Board height (in)	Symbol
12·4	x
18·6 homogeneous	o
18·6 composite	●

FIG. 4. VARIATION OF FLAME HEIGHT WITH FUEL SURFACE AREA



Board height (in)	Thickness (in)	Symbol
18·6	1	△
	0·75	□
	0·5	○
12·4	1	▲
	0·75	■
	0·5	●

FIG. 5. TEMPERATURE AND BURNING RATE

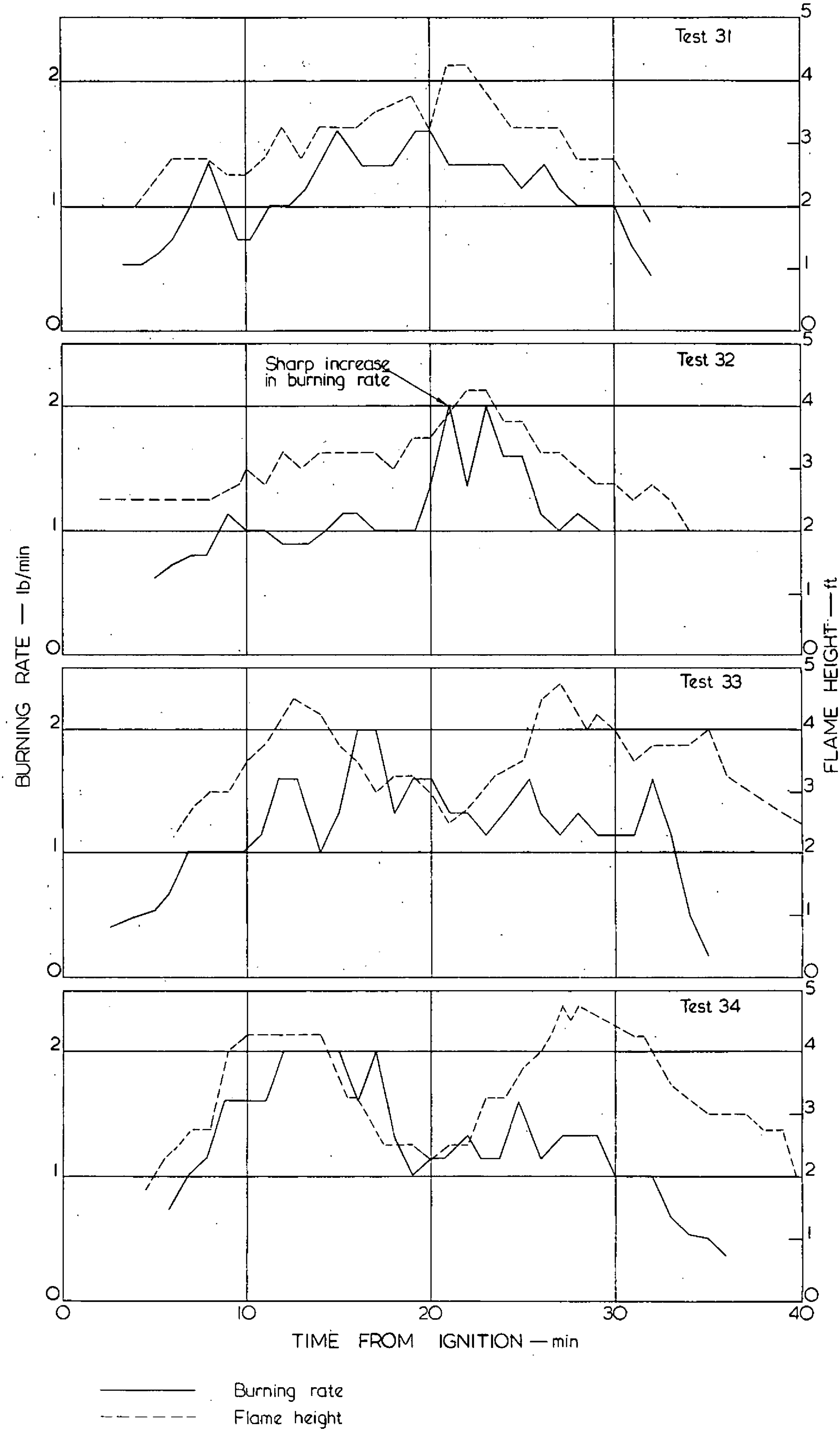


FIG. 6. VARIATION OF BURNING RATE AND FLAME HEIGHT WITH TIME FOR TESTS 31 TO 34 (COMPOSITE BOARD)

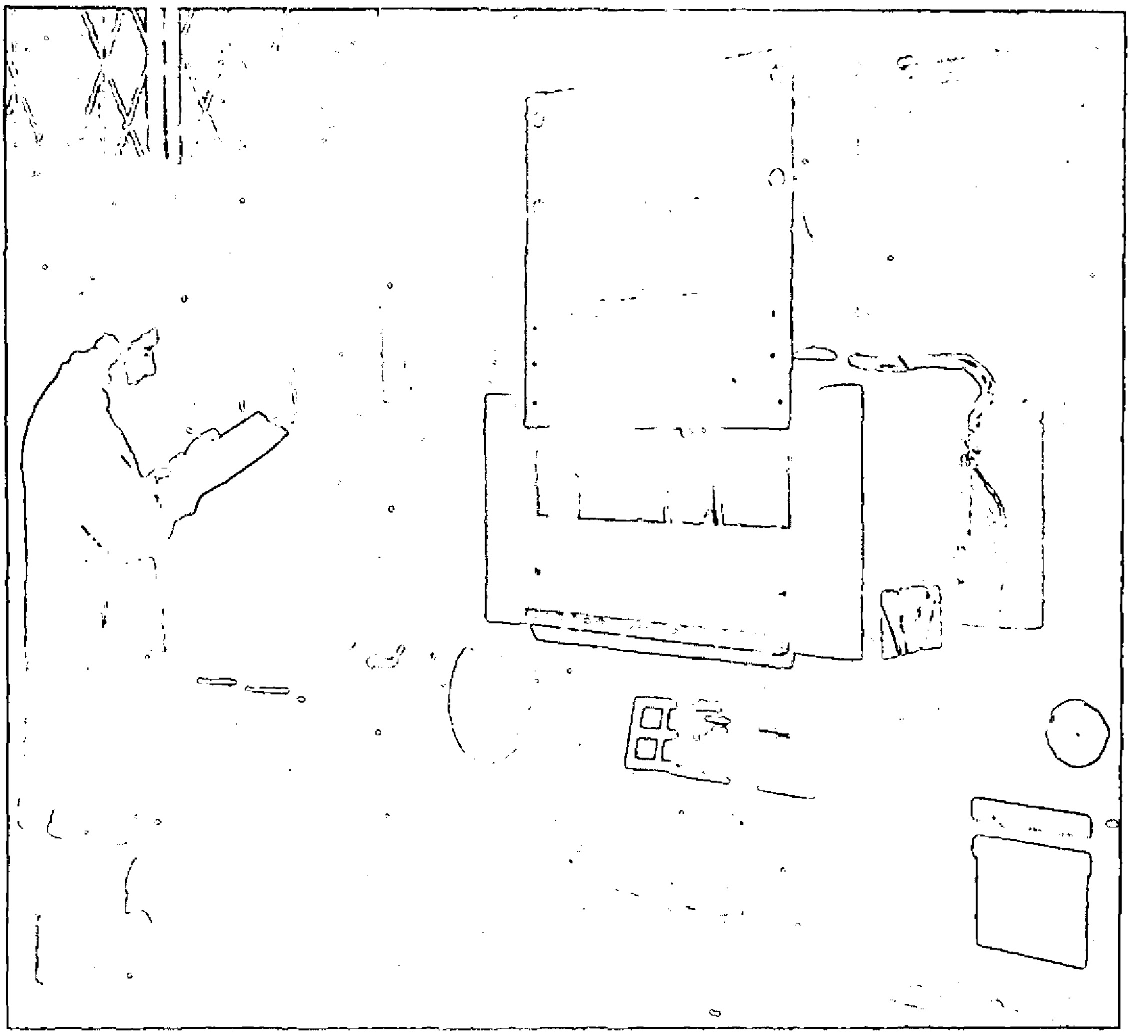


PLATE 1. GENERAL VIEW OF MODEL