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THE TEMPERATURE AND DURATION OF FIRES:

PART I: SOME EXPERIMENTS WITH MODELS WITH RESTRICTED VENTILATION

by

D. L. Simms, D. Hird and H. G. H. Wraight

SUMMARY

Models have been used to measure both the temperatures reached and the duration of fires in compartments of different sizes with various fire loads and amounts of ventilation.

The course of the fire may be divided into three comparatively well-defined periods. An initial period where the fire spreads after ignition to involve the entire compartment, a period of steady development, and a period of decay these last two both increasing in duration with increasing fire load and decreasing ventilation.

The estimated mean rate of burning in the development period was independent of fire load and depended only on the quantity of air entering the compartment; in general, the maximum temperatures reached increased with this induced air flow and were largely independent of fire load.

Fire Research Station,
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January, 1960.

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1. Introduction

In the British Standard Fire Test for building materials and structures[1]* the furnace follows a standard temperature-time curve and the structure must withstand these conditions without collapsing, and in the case of floors and walls without allowing flame to penetrate or the temperature on the face remote from the furnace to rise by more than a certain predetermined value.

The time for which these conditions are satisfied is called the "fire resistance" and the requirement for any one structure is based on an estimated duration of fire in the occupancy of which the structure forms part. For the purpose of present building regulations this has been assumed to depend on the total potential heat available per unit floor area within the compartment[2].

It is recognised[3], however, that the rate and manner in which this heat is liberated depend on both the degree of ventilation probable in the event of fire and the exposed surface area of the combustible materials. The temperatures reached and the duration of fires are not, therefore, independent of the particular fire conditions, and may be very different from those given by the standard curve. This may mean that both fire load and window area should be taken into account in estimating the fire resistance required of structures.

Since a programme of experimental work on full scale would be very costly both in labour and materials, experiments have been carried out with small scale fires of different sizes. They have been done in the lower ranges of fire load and ventilation. Experiments on well ventilated fires are reported elsewhere[9,10], from which it is known that with large window openings the fire behaviour may depend on fire load and ventilation in a way quite different from that described here. The results in this paper therefore apply to low ventilation levels but it is not yet possible to place precise limits on the ranges of restricted and high ventilation.

High fire loads are not possible in small scale compartments.

In experiments over a range of scale including some full scale tests Kawagoe[11] found that the burning rate of a fire within a compartment was proportional to the induced mass air flow.

At the temperatures obtaining in fires the air flow velocity is not greatly affected by temperature differences. Strictly speaking this velocity is affected by the burning rate itself, but this effect may also be neglected in practical conditions because the air flow greatly exceeds the burning rate. The velocity head of the induced air is thus proportional to the height H of the opening, so that the induced air flow is proportional to $A\sqrt{H}$ where A is the area of the opening. In the experiments described in this paper no measurements were made of the air flow and the term $A\sqrt{H}$, which maybe called the air flow factor, is used as an indirect

*Similar tests are in use all over the world[4-8], and it may be taken that any comments relating to the British tests are relevant to the others.

measure. The constant of proportionality may be calculated(11).

2. Experiments and Results

2.1. Apparatus and materials

Three different sizes of model were used with the internal dimensions in the ratio 8 : 8 : 5, the last figure referring to the height. These models were constructed of a $\frac{1}{2}$ in. thick asbestos insulating material with an adjustable opening located centrally in all four sides so that up to 50 per cent of the wall area could be open. The width to height ratio of any one of the four openings was 16 : 11 when fully open. Details are given in Table I.

TABLE I

Details of Equipment and Materials

	Scale I		Scale II		Scale III	
	in.	m.	in.	m.	in.	m.
Length of sides of asbestos model.	12	0.30	24	0.61	36	0.91
Height of asbestos model.	$7\frac{1}{2}$	0.19	15	0.38	$22\frac{1}{2}$	0.57
Height of openings in the model.	$5\frac{1}{2}$	0.14	11	0.28	$16\frac{1}{2}$	0.42
Length of sides of wooden boxes.	2 and 3	0.051 and 0.076	4	0.102	6	0.152
Thickness of wood.	$\frac{5}{8}$ and $\frac{7}{8}$	0.016 and 0.022	$\frac{7}{8}$	0.022	1	0.025

The combustible contents consisted of a floor of nominal 1 in. thick wood and a number of hollow wooden boxes open on one side only with the open face vertical. A perspective drawing of a box is shown in Fig.1.

The fires were started inside the four centre boxes. Temperatures were taken with 26 gauge chromel-alumel thermocouples, six of these being located on the ceiling as shown in Fig.2. Preliminary experiments showed that there was a considerable temperature gradient near the ceiling during a fire, so that the thermocouple junctions were placed in contact with the ceiling.

A list of the experiments carried out is given in Table II.

2.2. Experiments

Experiments were designed to measure the relative effects of the amount and the arrangement of the fire load and the ventilation on the temperatures and durations of fires. The set of experiments was carried out on one particular size of model (Scale II, test Nos. 1-16, 32-35 and 48, Table II). In the second set of experiments the nominal thickness of the timber of the boxes was reduced to $\frac{1}{2}$ in. (Scale II, test Nos. 25-30, Table II), and in the third set the effect of different sizes of models was examined (Scales I and III, test Nos. 17-24, 41-46 and 49, Table II). The dimensions, except thickness, of both the model and the combustible units were scaled linearly by ½ (Scale I) and by 3/2 (Scale III). Thus the fire load per unit area in kg/m^2 (lb/ft^2) was held constant, but the fire load per unit volume in kg/m^3 (lb/ft^3) diminished with increasing size, while the absolute quantity of wood present increased proportionately with increasing floor area.

In a fourth set of experiments (Scales I-III, test Nos. 50-55, Table II), the effect of lagging the walls with 3.8 cm (1½ in.) thick mineral wool board was examined on the three different scales and two different ventilations.

2.3. Results

Nearly all the tests were carried out twice (a, b). The average temperatures and times have been used in the analysis of the results. The course of a typical fire is shown in Plate I, and its temperature-time curve in Fig.3. A schematic diagram of the typical temperature-time curve is shown in Fig.4.

Ceiling temperatures are compared with the flame temperatures for Scale II in Fig.5a and for Scale III in Fig.5b, together with the British Standard curve[1]. Wall temperatures are also included in Fig.5a (Scale II). In two of the four tests for which temperatures are shown as measured by thermocouples in the flame zone there is an early maximum to the temperature curve followed by a decrease and subsequent increase. This may be due to movement of the flame zone which is at first under the thermocouples. Its later position will depend on the extent of the window opening, but in an air starved fire it will be near the window and possibly far enough from the thermocouples to give a decrease in the local mean gas temperature well inside the compartment. Later on the walls of the compartment become heated and the radiation level and temperature inside would rise again.

3. Discussion of Results

3.1. Form of the temperature-time curves

The general form of these curves is shown schematically in Fig.4. The three portions, which to a first approximation may be taken to be linear, correspond to a growth period ($0-\tau_1$), a development period ($\tau_1-\tau_2$) and a decay period ($\tau_2-\tau_3$).

The flames spread from the ignition points until the model fills with flame; this point is usually quite sudden and corresponds roughly to the "flashover" condition discussed elsewhere[12,13]. The flames are then partly outside the box, and the fire may become air controlled. The flame height grows to a maximum and then dies down, until only a glowing mass is left which slowly reduces to ashes (Plates Ia - Ih, test No.34b), but with increasing scale the relative heights of the flames tend to diminish.

The flame temperatures were nearly always higher than the ceiling and wall temperatures, but the British Standard curve was generally between the two, Figs.5a, 5b. The difference between flame and surface temperatures must be affected by the thermal properties of the walls.

3.2. Growth period ($0-\tau_1$)

The time to "flashover" observed visually did not always correspond to the time τ_1, but the variation between the two appeared to be random. This initial period was not always sharply defined in these experiments; slight changes in initial conditions including the way in which the fire was started changed the duration of this period considerably; similar variations have been found elsewhere[10,11]. It was found* at high ventilation rates when more than one side was open that this growth period merged into the development period (Test Nos. 7, 8, 11, 13, 14, 19-22, 41, 43, 45, 48, 49, 51, 53, 55), but with these fires the ventilation may well be above the range described as "restricted".

It appears, from the data listed in Table III, that the time τ_1 is independent of the fire load, ventilation and scale, but depends on the specific surface of fuel. In those experiments in which the wood was only a nominal $\frac{1}{2}$ in. thickness (Test Nos. 18, 20, 22, 24, 25-30) the time $(0-\tau_1)$ was appreciably shorter on both scales I and II.

3.3. Development period $(\tau_1-\tau_2)$

3.3.1. Temperature reached

The maximum temperature reached under these conditions of restricted ventilation was practically independent of fire load on any scale, but increased with increasing air flow, Fig.6. The differences in temperature between fires with thin and thick wood were not significant. The temperature was much higher for the lagged than for the unlagged models, the relative difference being greatest on the smallest scale.

The rate of increase of the maximum temperature with mass air flow was small for the higher values of $A\sqrt{H}$ and on the lagged models it was even smaller because there is relatively less heat loss through the walls. On scale II, increasing the ventilation above a certain value reduced the maximum temperature reached (Test Nos. 8, 11), but insufficient experiments were made to draw any conclusions as to why this should happen.

3.3.2. Burning rates

The rate at which burning took place was not measured directly in these experiments, but the duration of the development period $(\tau_2-\tau_1)$ was found to be proportional to the total fire load, F, Fig.7, for any one rate of ventilation. Up to the time τ_1 the amount of fuel consumed is small, but by the end of the development period most of the volatile material has been burnt. This amounts to about half the contents of the solid so that $\frac{1}{2}F/(\tau_2-\tau_1)$ has been used as a measure of the burning rate during the period $(\tau_1-\tau_2)$. It increases with the air flow factor, Fig.8, and although there is considerable scatter there is little difference between the scales. The burning rate does not correlate either with the ceiling temperatures or the flame temperatures. Although the temperatures reached are higher for lagged than for unlagged models, the burning rates are only higher for some of lagged experiments.

For the larger window areas the burning rates of the $\frac{1}{2}$ in. thick wood are higher than for the 1 in. thick wood, Fig.8. This observation is recorded here but it cannot be explained without at the same time explaining why increasing the fire load, which also increases the surface area of the wood, did not have the same effect. It is hoped to discuss these questions elsewhere in terms

*This is an observation based on the actual temperature-time record of the fires which for reasons of space are not included in this report. Apart from this observation, Table III summarises all the data quantitatively.

of a detailed theory for single compartment fires.

3.4. Decay period

The cooling rate was approximately linear in all the experiments; it decreased with increasing fire load and increased with increasing air flow.

The end of the fire, τ_3, was determined by extrapolation and an estimate was made of the burning rate during this period, assuming it to be constant. This was plotted against air flow factor $A\sqrt{H}$ in Fig.9, and by analogy the burning rate in the decay period can be defined as $\frac{1}{2} F/(\tau_3-\tau_2)$. For any one ventilation it tended to increase with increasing fire load, but there was a tendency for this period to become relatively longer compared with the development period as the scale increased.

4. General discussion and conclusions

It is not proposed in this report to attempt to interpret all the experimental results that have been obtained. In some instances the analysis of the data needs to be taken further and in others more experimental data are required. Nevertheless some important conclusions can be drawn at this interim stage of the work.

Both the temperature and duration of a fire are relevant in determining the damage to the structure. It has been found that the mean burning rate for restricted ventilation is generally independent of the fire load itself and proportional to the quantity $A\sqrt{H}$. This relation holds good over a range of scale, and although there is considerable experimental variation it has not been possible to attribute this to any systematic factor.

The results also show the importance of the thermal properties of the compartment walls in determining the temperatures in the fire.

Although further work is necessary before it is permissible to generalise from the results given in this report, it is clear that because of the importance of ventilation in these experiments, and also because the fire duration is related to the total amount of combustible material present and not the amount per unit area, that the fire resistance required of the structure in these fires is not solely related to the fire load per unit area, which is the existing basis for determining fire resistance.

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TABLE II

Experiments carried out

Test No.	Arrangement of Fire Load on 1 in. wooden floor	Fire Load		Surface area of Wood		Width of opening		Area of opening	
		lb/ft^2	kg.	ft^2	m^2	ft.	m.	ft^2	m^2
	Tests carried out at Scale II								
1 ab	25 boxes 5 x 5 x 1	6.6	12.0	19.3	1.79	1.33	0.41	1.22	0.11
2 ab	16 boxes 4 x 4 x 1	4.9	8.9	13.8	1.28	1.33	0.41	1.22	0.11
3 ab	32 boxes 4 x 4 x 2	7.8	14.2	23.6	2.19	1.33	0.41	1.22	0.11
4 ab	48 boxes 4 x 4 x 3	10.8	19.6	33.3	3.10	1.33	0.41	1.22	0.11
5 ab	24 boxes 4 x 3 x 2	6.4	11.6	18.7	1.73	1.33	0.41	1.22	0.11
6 ab	40 boxes 5 x 4 x 2	9.4	17.1	28.5	2.64	1.33	0.41	1.22	0.11
7 ab	32 boxes 4 x 4 x 2	7.9	14.4	23.6	2.19	2.67	0.81	2.44	0.23
8 ab	32 boxes 4 x 4 x 2	8.1	14.7	23.6	2.19	4.0	1.22	3.67	0.34
9 ab	32 boxes 4 x 4 x 2	8.2	14.9	23.6	2.19	0.67	0.20	0.61	0.06
10 ab	32 boxes 4 x 4 x 2	8.1	14.7	23.6	2.19	1.0	0.30	0.92	0.09
11 ab	32 boxes 4 x 4 x 2	8.2	14.9	23.6	2.19	5.33	1.63	4.89	0.45
12 ab	32 boxes 4 x 4 x 2	8.1	14.7	23.6	2.19	0.33	0.10	0.31	0.03
13 ab	16 boxes 4 x 4 x 1	5.3	9.6	13.8	1.28	2.67	0.81	2.44	0.23
14 ab	48 boxes 4 x 4 x 3	11.4	20.7	33.3	3.10	2.67	0.81	2.44	0.23
15 ab	16 boxes 4 x 4 x 1	5.0	9.1	13.8	1.28	0.67	0.20	0.61	0.06
16 ab	48 boxes 4 x 4 x 1	11.4	20.7	33.3	3.10	0.67	0.20	0.61	0.06
32 ab	16 boxes 4 x 2 x 2	5.0	9.1	13.8	1.28	1.3	0.41	1.22	0.11
33 ab	32 boxes 3 x 3 x 3+5	7.8	14.2	23.6	2.19	1.3	0.41	1.22	0.11

Cont'd ...

(Table II cont'd.)

Test No.	Arrangement of Fire Load on 1 in. wooden floor	Fire Load		Surface area of Wood		Width of opening		Area of opening	
		lb/ft^2	kg.	ft^2	m^2	ft.	m.	ft^2	m^2
	Tests carried out at Scale II								
34 ab	48 boxes 5x5x2-2	10.8	19.6	33.3	3.10	1.3	0.41	1.22	0.11
35 No floor	24 boxes 4 x 3 x 2	4.3	7.8	16.0	1.49	1.3	0.41	1.22	0.11
48 Scale III boxes	7 boxes 6 in. cube	6.1	11.1	14.9	1.38	2.67	0.81	2.44	0.23
25 ab	32 boxes 4 x 4 x 2	6.4	11.6	27.5	2.56	2.67	0.81	2.44	0.23
26 ab	32 boxes 4 x 4 x 2	6.2	11.3	27.5	2.56	0.67	0.20	0.61	0.06
27 ab	48 boxes 4 x 4 x 3	8.5	15.5	39.3	3.66	0.67	0.20	0.61	0.06
28 ab	24 boxes 4 x 3 x 2	5.2	9.5	21.7	2.01	0.67	0.20	0.61	0.06
29 ab	48 boxes 4 x 4 x 3	8.5	15.5	39.3	3.66	2.67	0.81	2.44	0.23
30 ab	24 boxes 4 x 3 x 2	5.2	9.5	21.7	2.01	2.67	0.81	2.44	0.23
	Tests carried out at Scale I								
17	9 boxes 3 x 3 x 1	5.6	2.54	3.75	0.35	0.67	0.20	0.31	0.03
18	28 boxes 4x4x2-4	5.5	2.50	5.28	0.49	0.67	0.20	0.31	0.03
19	9 boxes 3 x 3 x 1	5.6	2.54	3.75	0.35	1.33	0.41	0.61	0.06
20	28 boxes 4x4x2-4	5.7	2.59	5.28	0.49	1.33	0.41	0.61	0.06
21	9 boxes 3 x 3 x 1	5.0	2.27	3.75	0.35	1.00	0.30	0.46	0.04
22	28 boxes 4x4x2-4	5.4	2.45	5.28	0.49	1.00	0.30	0.46	0.04
23	9 boxes 3 x 3 x 1	5.0	2.27	3.75	0.35	0.33	0.10	0.15	0.01
24	28 boxes 4x4x2-4	5.4	2.45	5.28	0.49	0.33	0.10	0.15	0.01

Cont'd ....

(Table II cont'd)

Test No.	Arrangement of Fire Load on 1 in. wooden floor	Fire Load		Surface area of Wood		Width of opening		Area of opening	
		lb/ft^2	kg	ft^2	m^2	ft.	m.	ft^2	m^2
	Tests carried out at Scale III								
41 ab	16 boxes 4 x 4 x 1	5.9	24.1	33.9	3.15	4.00	1.22	5.56	0.52
42 ab	16 boxes 4 x 4 x 1	5.8	23.7	33.9	3.15	1.00	0.30	1.39	0.13
43 ab	32 boxes 4 x 4 x 2	9.7	39.7	58.8	5.46	4.00	1.22	5.56	0.52
44 ab	32 boxes 4 x 4 x 2	10.0	40.9	58.8	5.46	1.00	0.30	1.39	0.13
45 ab	48 boxes 4 x 4 x 3	13.7	56.0	83.4	7.77	4.00	1.22	5.56	0.52
46 ab	48 boxes 4 x 4 x 3	13.7	56.0	83.4	7.77	1.00	0.30	1.39	0.13
49 ab Scale II boxes	40 boxes 7x6x1-2	6.0	24.5	33.4	3.11	4.00	1.22	5.56	0.52
	Tests carried out in lagged box								
50 Scale I	9 boxes 3 x 3 x 1	6.1	2.77	3.75	0.35	0.33	0.10	0.15	0.01
51 Scale I	9 boxes 3 x 3 x 1	6.3	2.86	3.75	0.35	1.33	0.41	0.61	0.06
52 Scale II	16 boxes 4 x 4 x 1	5.4	9.8	13.8	1.28	0.67	0.20	0.61	0.06
53 Scale II	16 boxes 4 x 4 x 1	5.2	9.5	13.8	1.28	2.67	0.81	2.44	0.23
54 Scale III	16 boxes 4 x 4 x 1	6.3	25.8	33.9	3.15	1.00	0.30	1.39	0.13
55 Scale III	16 boxes 4 x 4 x 1	6.3	25.8	33.9	3.15	4.00	1.22	5.56	0.52

TABLE III

DERIVED RESULTS

Test No.	Air Flow Factor $A\sqrt{H}$ $m^{5/2}$	Maximum Mean Temperature °C (θ_m)	Cooling Rate °C/min.	Time to 1st max (τ_1)	Temperature at 1st max (θ_1)	Time to 2nd max (τ_2)
	Tests with 7/8 in. wood, Scale II fire load, 8 lbs/ft^2, 7 ventilations					
12 ab	0.015	630	5.0	12	400	101
9 ab	0.030	750	9.8	16	430	76
10 ab	0.045	790	11.2	12	530	48
3 ab	0.060	800	12.1	12	600	40
7 ab	0.120	900	16.3	20	780	28
8 ab	0.180	850	20.0	22	700	36
11 ab	0.240	760	14.4	20	670	32
	Tests with 7/8 in. wood, Scale II, 3 fire loads, 3 ventilations					
15 ab	0.030	790	15.0	24	530	52
9 ab	0.030	750	9.8	16	430	76
16 ab	0.030	780	5.8	36	460	100
2 ab	0.060	790	14.8	16	550	44
3 ab	0.060	800	12.1	12	600	40
4 ab	0.060	810	10.9	20	570	68
13 ab	0.120	700	15.3	24	490	40
7 ab	0.120	900	16.3	20	780	28
14 ab	0.120	880	13.5	16	600	40
48	0.120	910	17.1	12	730	20
	Tests with 7/8 in. wood, Scale II, 10 fire loads, 12% ventilation					
35	0.06	840	17.1	8	580	20
2 ab	0.06	790	14.8	16	550	44
32 ab	0.06	840	15.0	6	440	24
5 ab	0.06	860	15.6	12	600	32
1 ab	0.06	770	13.6	32	430	68
3 ab	0.06	800	12.1	12	600	40
33 ab	0.06	810	10.6	10	500	36
6 ab	0.06	810	12.0	16	610	56
4 ab	0.06	810	10.9	20	570	68
34 ab	0.06	790	9.9	9	470	52
	Tests with 1/2 in. wood, Scale II, 2 ventilations, 3 fire loads					
28 ab	0.03	800	15.8	8	510	32
26 ab	0.03	790	15.0	8	500	36
27 ab	0.03	800	11.6	8	400	56
30 ab	0.12	880	19.4	7	680	12
25 ab	0.12	850	19.0	8	700	12
29 ab	0.12	810	17.1	8	600	16

Cont'd.....

(Table III Cont'd)

Test No.	Air Flow Factor $A\sqrt{H}$ $m^{5/2}$	Maximum Mean Temperature °C (θ_m)	Cooling Rate °C/min.	Time to 1st max (τ_1)	Temperature at 1st max (θ_1)	Time to 2nd max (τ_2)
Tests with $\frac{7}{8}$ in. and $\frac{3}{8}$ in. wood, Scale I, fire load 5 lb/ft^2, 4 ventilations						
23	0.005	630	8.3	12	400	64
24	0.005	640	6.5	12	390	72
17	0.010	660	11.1	20	360	60
18	0.010	640	11.3	8	420	48
21	0.015	750	14.8	8	470	32
22	0.015	720	16.9	4	370	28
19	0.021	720	17.1	8	530	28
20	0.021	710	18.1	4	430	20
Tests with 1 in. wood, Scale III, 3 fire loads, 2 ventilations						
42 ab	0.08	940	14.6	12	640	32
44 ab	0.08	900	10.3	10	480	56
46 ab	0.08	920	8.1	12	530	76
41 ab	0.33	930	17.5	7	800	12
43 ab	0.33	1050	17.8	12	750	26
45 ab	0.33	940	13.3	8	670	24
49	0.33	900	13.0	20	710	28
Tests on lagged boxes, Scales I, II and III, 2 ventilations $\frac{7}{8}$ or 1 in. wood, 1 fire load						
Sc.I. 50	0.005	850	9.0	12	450	68
" 51	0.021	850	10.3	4	500	24
Sc.II 52	0.03	930	10.9	8	530	32
" 53	0.12	920	11.5	6	800	14
Sc.III 54	0.08	960	15.1	6	560	36
" 55	0.33	1030	12.5	6	700	10

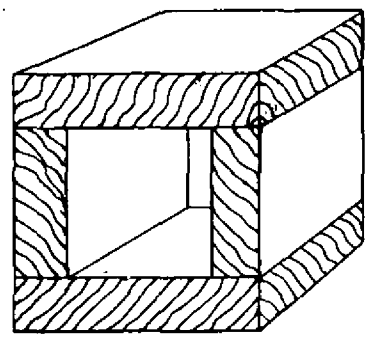

FIG. 1. WOOD BOX USED AS FUEL

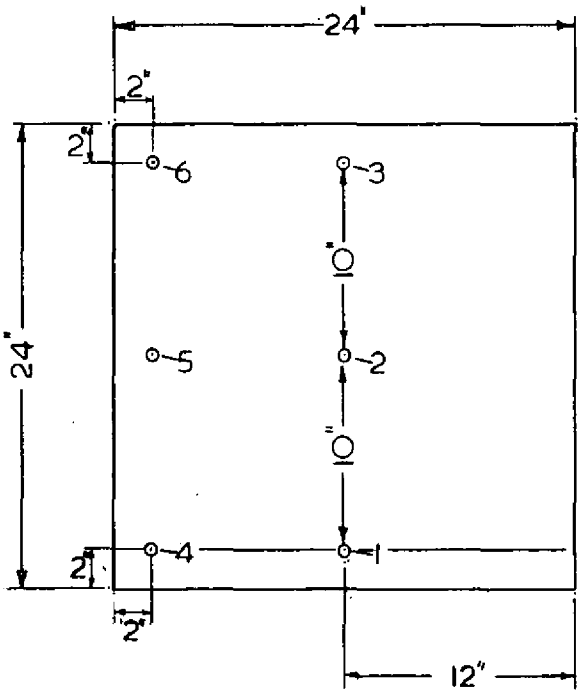

FIG. 2. PLAN SHOWING POSITION OF THERMOCOUPLES IN CEILING OF TEST BOX (SCALE II)

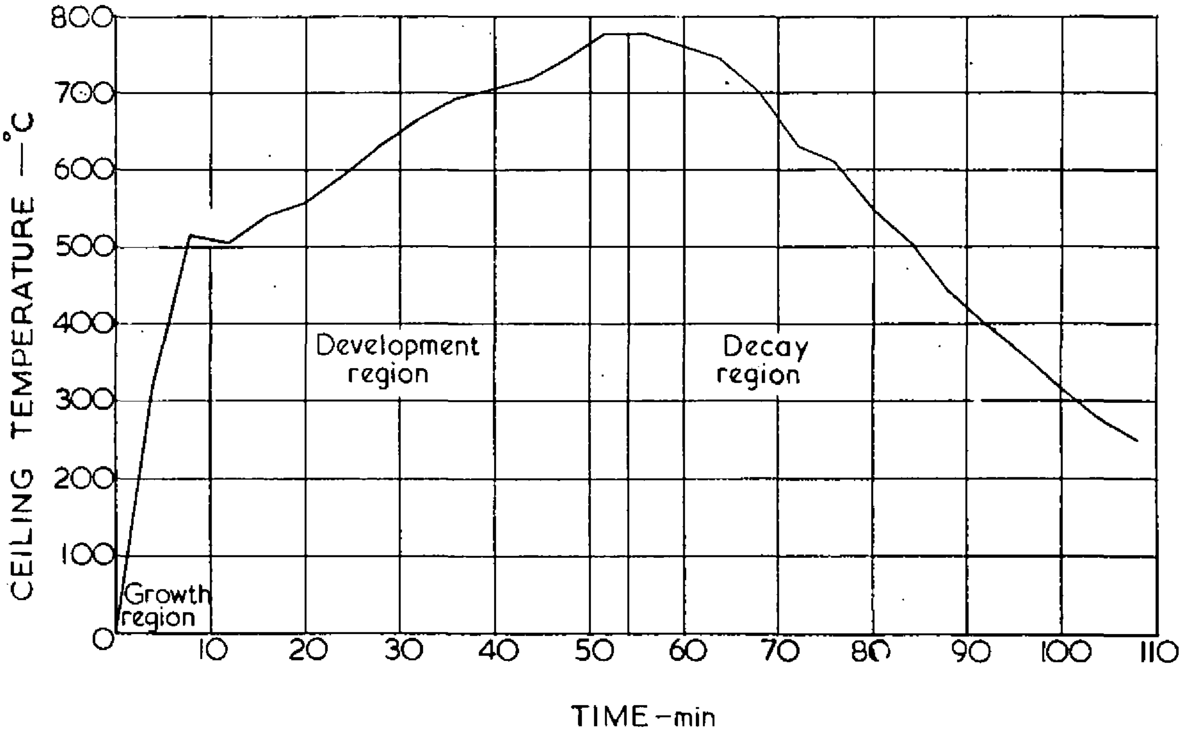

FIG. 3. TEMPERATURE-TIME RECORD FOR A TYPICAL FIRE (TEST 34b)

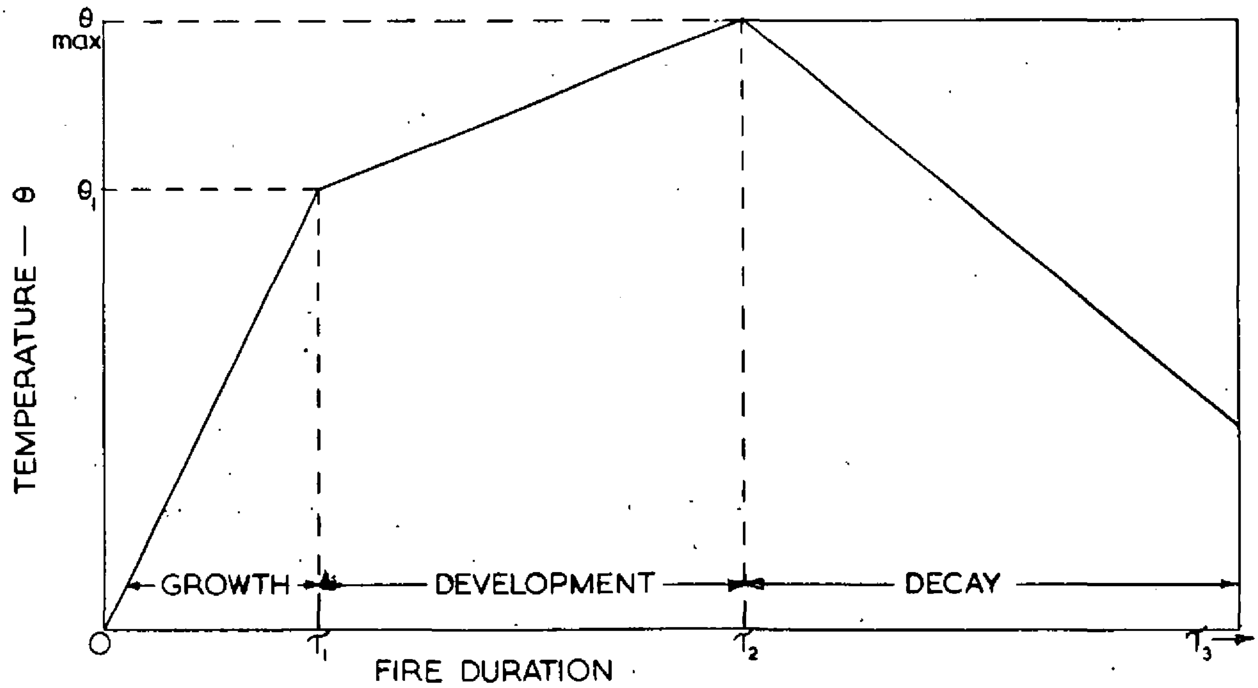

FIG. 4. SCHEMATIC DIAGRAM OF A TEMPERATURE-TIME CURVE

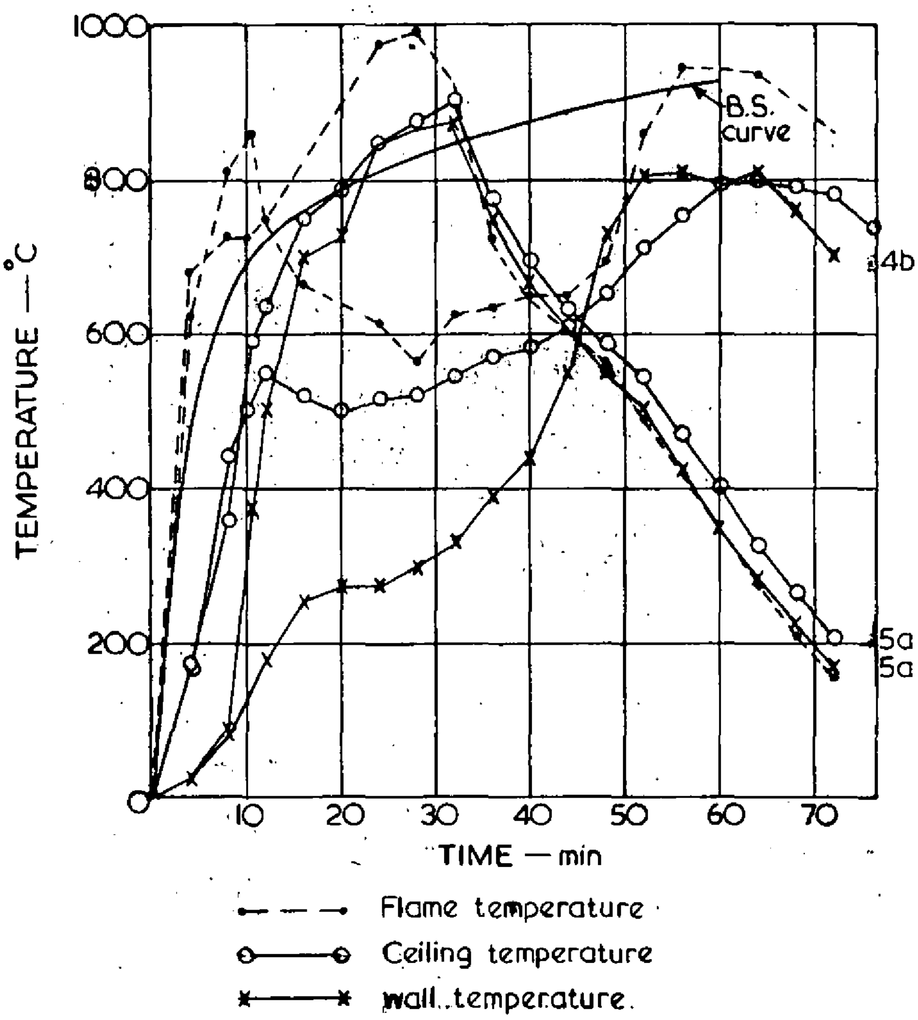

FIG. 5a. FLAME, CEILING AND WALL TEMPERATURES FOR TWO TESTS AT SCALE II (4b AND 5a)

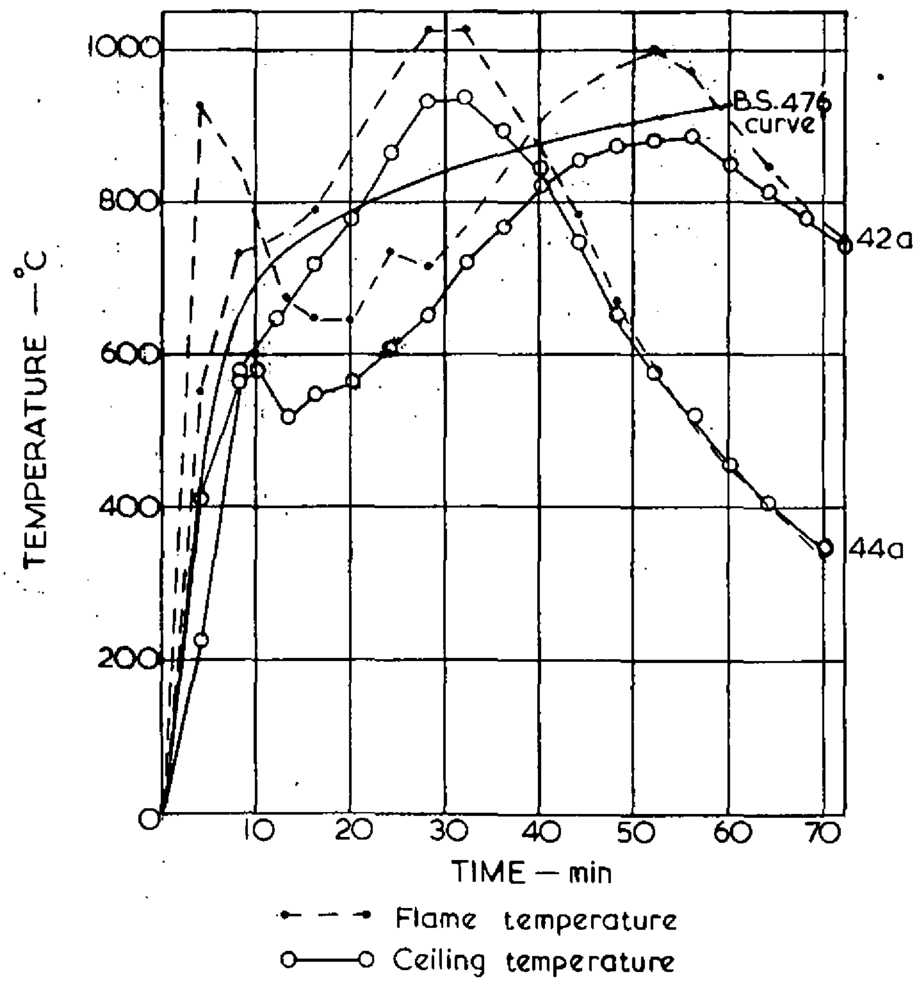

FIG. 5b. FLAME AND CEILING TEMPERATURES FOR TWO TESTS AT SCALE III (42a AND 44a)

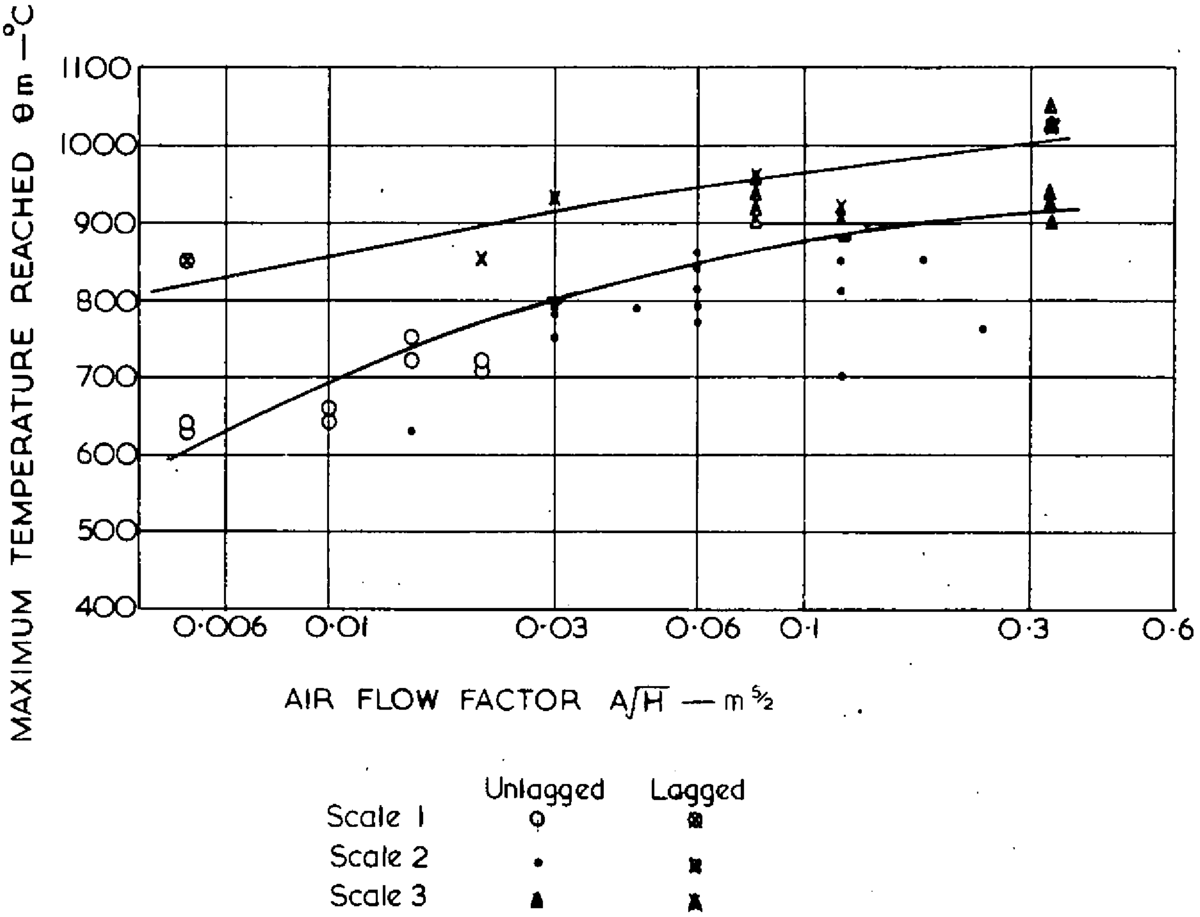

FIG. 6. VARIATION OF TEMPERATURE WITH A√H

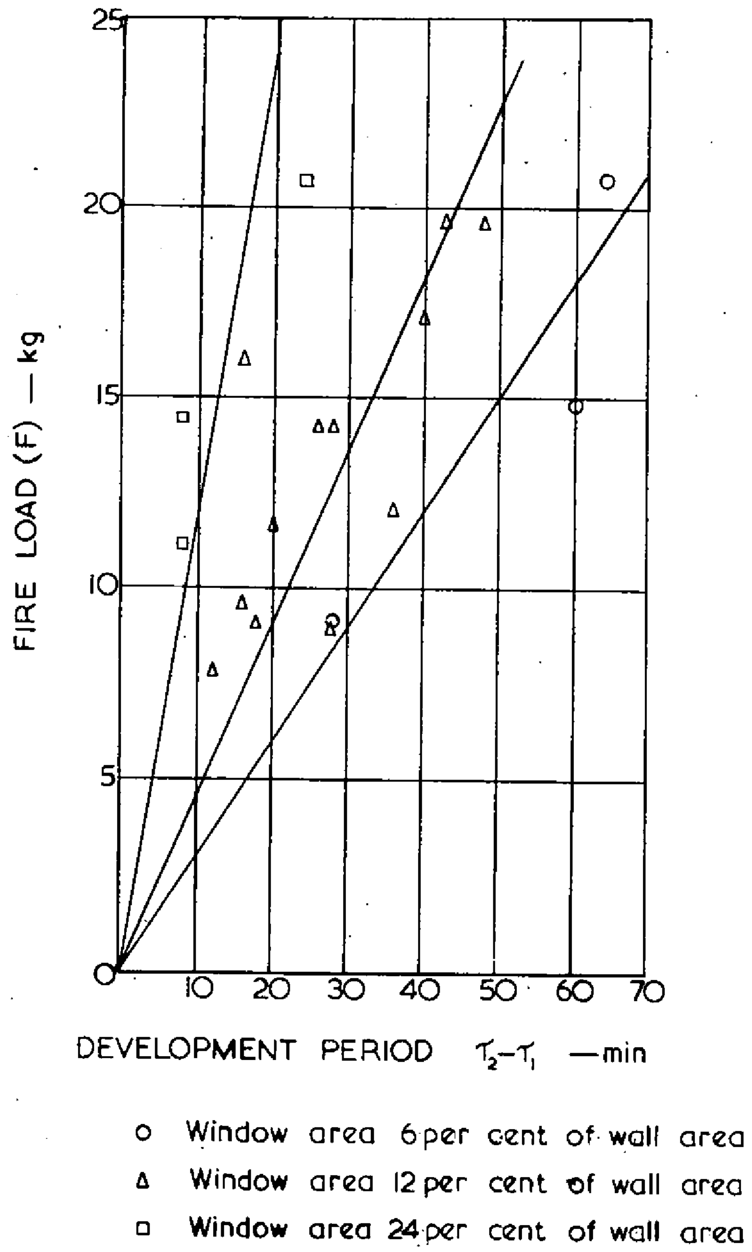

FIG. 7. FIRE LOAD AND DURATION OF DEVELOPMENT PERIOD

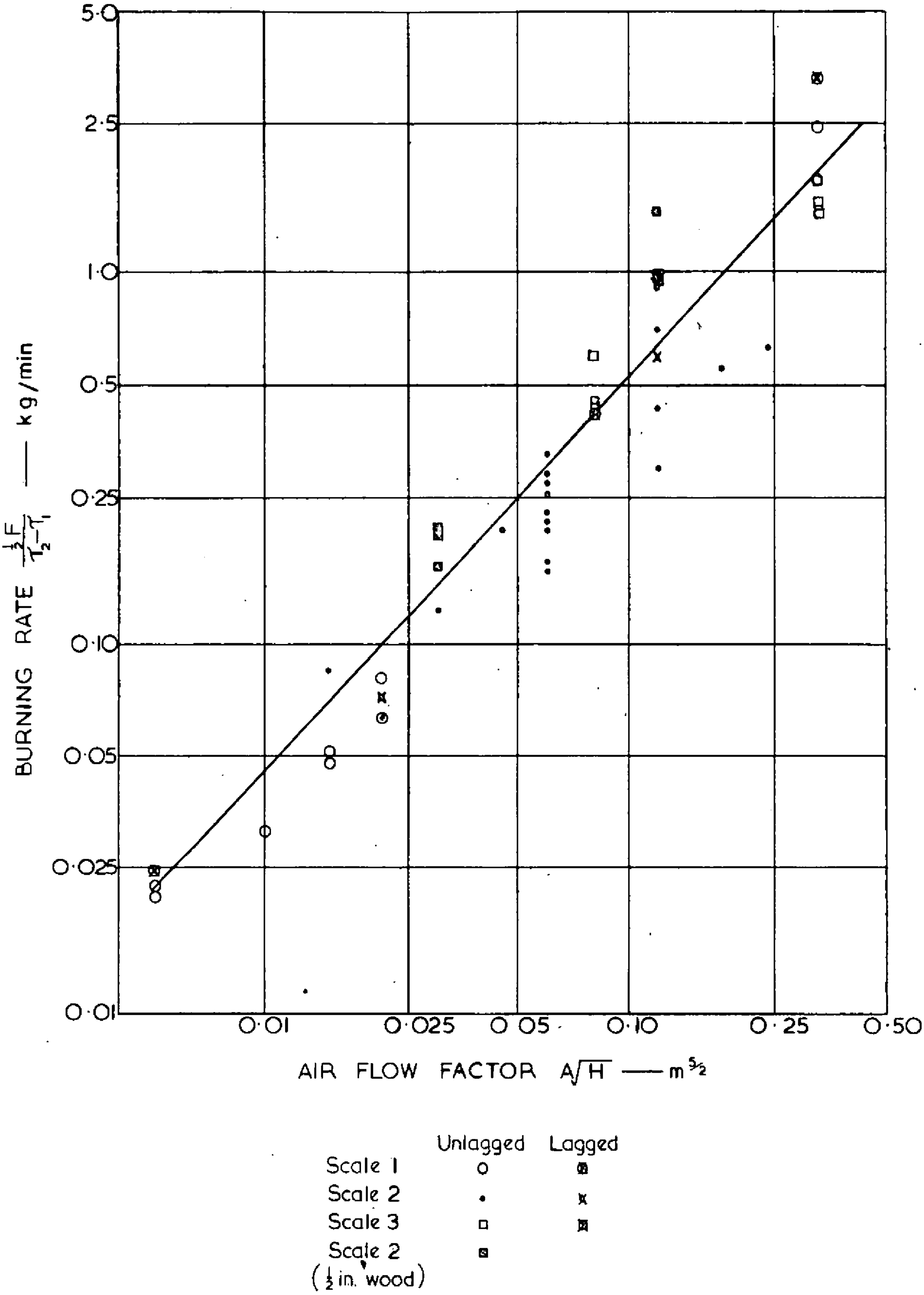

FIG. 8. BURNING RATE

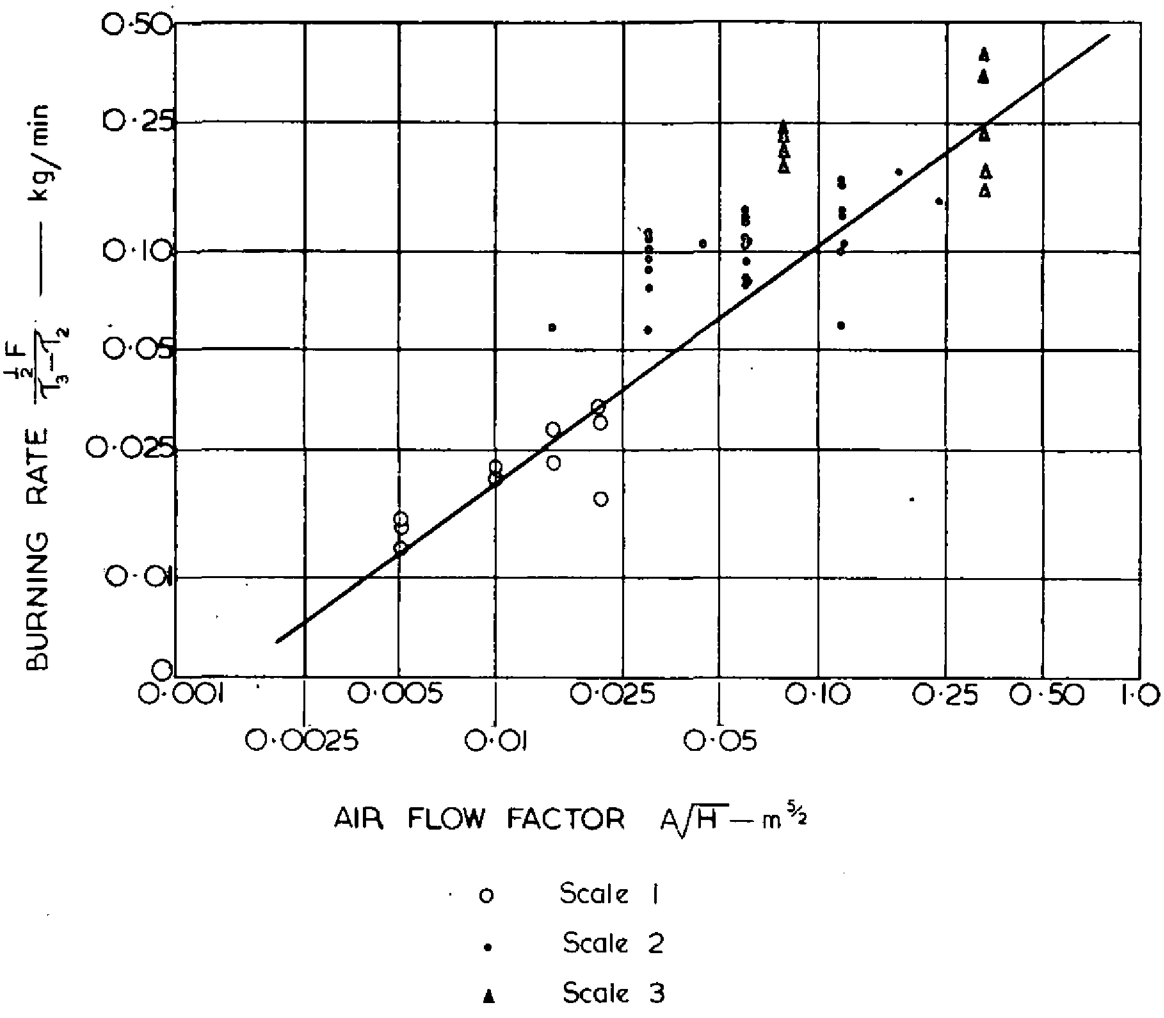

FIG. 9. BURNING RATE IN DECAY PERIOD