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

THE TEMPERATURE AND DURATION OF FIRES
PART II - ANALYSIS OF SOME FULL SCALE TESTS

by

D.L. Simms and H. Wraight

SUMMARY

The form of the temperature-time curves for the class of large scale fire where the entire compartment is involved and the ventilation is restricted has been examined and found to be similar to that obtained from fires in small scale compartments(1), there is a growth period and a development period followed by a decay period. The estimated burning rate during the development period is proportional to the induced air flow. The maximum temperatures reached increase with air flow up to a limit of about 1200°C. Exceptions to this general rule occur at low fire loads when the maximum temperature reached is lower than 1200°C, an explanation for this effect is suggested, but more experimental work on this point is needed. Subject to this limitation the results from small scale models may be used to predict the temperature and duration for this class of large scale

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1. Introduction

An earlier paper(1) analysed the results of experiments which used small scale models to examine the effects of varying the ventilation and fire load on the temperature and duration of fires. In this paper, the results(2-7) of experimental full scale fires are collected together and analysed in a similar manner to enable the effects of scale to be examined. These results are listed in Table I together with details of the fire load, ventilation and shape and size of the fire compartment.

2. Analysis of Results

2.1. Form of Temperature-Time Curves

Most of the temperature-time curves follow a similar pattern to those for small scale fires, Fig.1. There are three comparatively well defined periods; a growth period in which flames spread to involve the entire compartment at time τ_1, a development period in which the temperature rises more slowly to its maximum at time τ_2, and a decay period terminating at time τ_3.

In nearly all Kawagoe's experiments(2) the development period was not clearly demarcated from the growth period.

In Ingberg's experiments(6) the fire compartment was somewhat elongated (8.8m. x 4.6m. x 2.6m.), the development period was unusually short and the decay period unusually long, whilst the growth period was hardly apparent from the temperature-time curves.

2.2. Duration of Development Period ($\tau_2 - \tau_1$)

For a given air flow the duration of the development period ($\tau_2 - \tau_1$) is roughly proportional to the total quantity of combustibles present F, Fig.2., as found in the small scale fires(1).

2.3. Burning Rate in Development Period

The burning rate was measured directly only in Kawagoe's experiments(2), and these results have been used directly. For the other experiments the burning rate has been estimated from the ratio $\frac{1}{2}F/(\tau_2 - \tau_1)$*.

The variation in burning rate with air flow for both small and full scale experiments is shown in Fig.3. Although the points have a wide scatter, part of which is due to the variety of experimental arrangements used, there is no apparent scale effect, and the burning rate is practically proportional to the

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* By the time that the maximum temperature has been reached, most of the volatile content of the wood combustibles, about half the original weight of wood, has been exhausted. For this reason $\frac{1}{2}F$ has been used in estimating burning rates.

air flow as suggested by Kawagoe[2].

2.4. Maximum Temperature Reached

The effect of air flow on the maximum temperatures reached is shown in Fig.4. The values used are the mean of a number of readings taken from thermocouples located near the ceiling of the fire compartment. In general, as the air flow increases so does the maximum temperature reached, the limit being about 1200°C. This temperature was nearly attained in the largest model room[1], approximately 1.0m. x 1.0m. x 0.6m., when it was lagged and the value of $A\sqrt{H}$ was 0.33m.$^{5/2}$. This suggests that models only a little larger will give the maximum temperature likely to be reached in a full scale fire, and that this size of model can be used to investigate the effect of a wide range of air flow on the temperature and duration of a fire.

The maximum temperatures reached in some fires were lower than the curve in Fig.4. would suggest for that particular air flow. In Ingberg's experiments[6], this may be due to the shape of the fire compartment; the combustible material farthest from the air inlet would absorb heat rather than contribute to the fire, at least until an advanced stage. The maximum temperatures in Kawagoe's full scale experiments[2] were lower than in most other tests even though his fire loads were relatively high and this may be due to differences in the positions at which the temperatures were measured.

The maximum temperatures in Kawagoe's small scale experiments in a compartment 1m. cube with a fire load of about 25 kg./m^2 are lower than those obtained with similarly sized models at the Joint Fire Research Organization[1], Fig.4. with a fire load of about 40 kg./m^2. In some full scale experiments[3] also at the Joint Fire Research Organization the maximum temperature with a fire load of 25 kg./m^2 is well below the average maximum temperature for the same air flow, whereas the value at 40 kg./m^2 is near the average level. These results are similar to those found with small scale experiments[1], where at high air flows into a compartment approximately 0.6m. cube the maximum temperatures were lower than those reached at the same air flows into a compartment approximately 1m. cube with a correspondingly larger quantity of combustible material.

The burning rate is determined by the air flow, but if the total amount of combustible material is relatively low the fire does not last long enough for the temperature to reach the value characteristic of the air flow, and the resulting lower temperature presumably depends on the quantity of combustible material present.

A fire load of 40 kg./m^2 appears to be sufficient for a room 3m. cube but higher fire loads may be required for larger compartments. It is important to note that the rate of burning is set by the total quantity of combustible present and not by the fire load.

The upper limit of about 1200°C to the temperature reached is presumed to be set by the increasing heat losses from radiation and convection as the air flow is increased.

2.5. Decay Period

Less is known about the decay period but probably the major part of the fire damage has occurred by this stage. The mean burning rate in this period is plotted against the air flow in Fig.5., there is a much greater scatter with the individual results than there is for the burning rate in the development period shown in Fig.3.

3. Prediction of the Form of the Temperature-Time Curves

Where the fire load exceeds about 40 kg./m^2 and its value and that of the air flow are known, the duration of the development and decay periods can be found. These are shown explicitly in Figs. 6 and 7 respectively. The maximum temperature, which occurs where the development and decay periods adjoin, can be estimated from Fig.4.

4. Conclusions

For the class of fires where the ventilation is restricted the duration of full scale fires may be divided into growth development and decay periods in a similar way to small scale fires. The burning rate in the development period is practically proportional to the air flow over the entire range of scales and experiments, in agreement with the relation found by Kawagoe[2]. The burning rate in the decay period is also a function of air flow.

The maximum temperature reached increases with air flow to a limit of about 1200°C, but is independent of the fire load[1] provided this is not too low. The limiting temperature of 1200°C is approached in experiments using a lagged model fire compartment about 1m. cube, so that experiments on this scale or a little larger could yield useful information about the temperatures likely to be reached in full scale fires for different air flows. If the fire load is below about 40 kg./m^2, in compartments about 3m. cube, the maximum temperature fails to reach the value expected from Fig.4. for that particular air flow. More work is required to determine the lower limit of fire load for larger compartments in order that the value expected from Fig.4. may be reached. The reason for failure to reach the maximum temperature predicted for that air flow may be due to there being insufficient fire load to maintain the burning rate.

Subject to this limitation the temperature and duration of this type of fire can therefore be predicted from the air flow and fire load by using Figs. 4, 6 and 7. Within this range there appeared to be little or no effect due to the shape of the compartments except possibly in Ingberg's experiments[6]. A similar result should be anticipated whenever the shape or ventilation allows the entire floor of the compartment to be involved in fire at the same time, but results may well be different when the compartment is never fully involved at any stage.

One important result of this work is to emphasise the importance of the total amount of combustible material present on the burning rate and hence the duration of the fire; as opposed to the fire load per unit area which is traditionally used as a measure of the fire resistance requirements. The consequence of this will be discussed in a further note[8].

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RESULTS OF TESTS

Test reference (Date)	Room Size m.	Fire Load kg/m²	Fire Load kg.	Size of openings m.	Air Flow $A\sqrt{H}$ $m^{5/2}$	Duration of Fire: Time to end of growth period τ_1 min.	Duration of Fire: Time to end of development period τ_2 min.	Maximum Temperature Reached θ_m °C	Rate of burning estimated from $\frac{\frac{1}{2}F}{\tau_2-\tau_1}$ kg/min.	Cooling Rate °C/min.	Estimated[2] Burning rate kg/min. (Kawagoe) calculated	Estimated[2] Burning rate kg/min. (Kawagoe) measured
Kawagoe[2] Paskin I 22.9.49.	3.0 x 3.0 x 2.5	47	400	0.93 x 1.80	2.25	-	-	800	-	-	12.5	-
Kawagoe Paskin II 23.12.49.	3.0 x 3.0 x 2.5	47	400	0.93 x 1.80	2.25	11	29	830	11.1	12.5	12.5	-
Kawagoe Paskin III 16.9.50.	3.0 x 3.0 x 2.5	106	890	0.93 x 1.80	2.25	11	69	890	7.7	6.7	12.5	15.0
Kawagoe Paskin IV 7.12.50.	3.0 x 3.0 x 2.5	119	1000	0.93 x 1.80	2.25	17	82	920	7.7	8.0	-	-
Kawagoe Nissa 9.2.51.	4.0 x 4.0 x 3.0	50	800	2 at 1.8 x 1.5	6.5	14	24	800	40.0	10.0	36.5	-
Kawagoe Sasaki 27.5.52	2.6 x 3.6 x 2.6	66	600	0.9 x 1.4 1.8 x 1.4	4.3	10	30	800	15.0	8.0	24.5	23.0
Kawagoe Matsui 24.12.52	4.3 x 3.5 x 2.5	49	665	2 at 1.6 x 1.5	5.8	23	35	900	27.6	10.0	27.0	19.0
Kawagoe Fill-up 17.4.53	4.0 x 4.0 x 2.7	35	500	1.8 x 1.0 1.8 x 1.1	4.5	5	15	780	25.0	22.0	25.0	23.0
Kawagoe Thermocon 10.2.56	5.2 x 5.2 x 2.6	50	1250	4 at 1.0 x 1.7	9.0	10	16	1010	104.0	12.0	47.4	-
Kawagoe Light-weight Lower Floor 28.1.55	4.0 x 4.0 x 3.8	47	800	2 at 2.8 x 2.2	18.0	-	-	1100	-	60.0	72-75	40.0
Kawagoe Nagano 16.9.53	3.6 x 3.6 x 2.5	29	350	2 at 0.7 x 1.2 2 at 1.1 x 1.2	4.6	-	-	c.800	-	28.0	23.0	14.0
Tower Block[3] 10.10.57	3.0 x 2.8 x 2.6	24	210	2.2 x 2.0	6.2 max.	3	15	805	8.8	68	-	-
20. 2.58	3.0 x 2.8 x 2.6	49	420	2.1 x 1.5	4.7 max.	0	15	1005	14.0	67	-	-
1.11.57	3.0 x 2.8 x 2.6	39	336	2.2 x 2.0	6.2 max.	2	6	1015	42.0	102	-	-
24. 4.58	3.0 x 2.8 x 2.6	49	420	2.1 x 2.4	7.8 max.	2	8	960	35.0	30	-	-

Continued.

Table I continued.

Test reference (Date)	Room Size m.	Fire Load kg/m²	Fire Load kg.	Size of openings m.	Air Flow $A\sqrt{H}$ $m^{5/2}$	Duration of Fire: Time to end of growth period τ_1 min.	Duration of Fire: Time to end of development period τ_2 min.	Maximum Temperature Reached θ_m °C	Rate of burning estimated from $\frac{\frac{1}{2}F}{\tau_2-\tau_1}$ kg/min.	Cooling Rate °C/min.	Estimated[2] Burning rate kg/min. (Kawagoe) calculated	Estimated[2] Burning rate kg/min. (Kawagoe) measured
Tower Block[3] 14.5.58.	3.0 x 2.8 x 2.6	49	420	2.1 x 1.5	4.7 max.	2	18	980	13.0	66	-	-
15.5.58.	3.0 x 2.8 x 2.6	49	420	2.1 x 1.5	4.7 max.	2	13	1035	19.0	35	-	-
17.6.58	3.0 x 2.8 x 2.6	49	420	2.1 x 2.4	7.8 max.	2	5	1065	70.0	44	-	-
4.7.58.	3.0 x 2.8 x 2.6	49	420	2.1 x 2.4	7.8 max.	4	10	970	35.0	36	-	-
20.11.58.	3.0 x 2.8 x 2.6	61	525	1.9 x 1.2	2.5 max.	10	23	1080	20	23	-	-
24. 3.59.	3.0 x 2.8 x 2.6	61	525	2.0 x 1.3	3.0 max.	12	21	1120	29	40	-	-
Swedish Test[4] 1.8.47.	4.7 x 4.1 x 2.8	100	1925	1.0 x 2.0 1.0 x 1.1	1.0-3.8	50	120	990	13.8	3.8	-	-
House Fibre[7] Insulating Board Lined. 1949	5.3 x 3.7 x 2.7	c.39	c.720	2.7 x 1.5	5	4	14	1150	36	153	-	-
House Plaster[7] board Lined 1949	5.3 x 3.7 x 2.7	c.24	c.450	2.7 x 1.5	5	10	32	950	10.2	-	-	-
Hird & Fischl Half Scale Room[5] 23.10.52.	2.7 x 1.8 x 1.4	c.15	c.74	1.5 x 0.8	1	7	13	800	6.2	-	-	-
Ingberg[6] Test No.1 -	8.8 x 4.6 x 2.6	72	2930	-	-	53	75	850	67.0	9.8	-	-
Ingberg Test No.2 -	8.8 x 4.6 x 2.6	75	3040	-	-	49	70	910	73.0	9.8	-	-
Ingberg Test No.3 -	8.8 x 4.6 x 2.6	64	2590	-	-	5	27	820	59.0	6.9	-	-
Ingberg Test No.8 -	8.8 x 4.6 x 2.6	270	10360	-	-	12	65	950	103.0	8.7	-	-
Ingberg Test No.16 26.9.49.	-	42	-	-	-	-	39	850	-	11.0	-	-

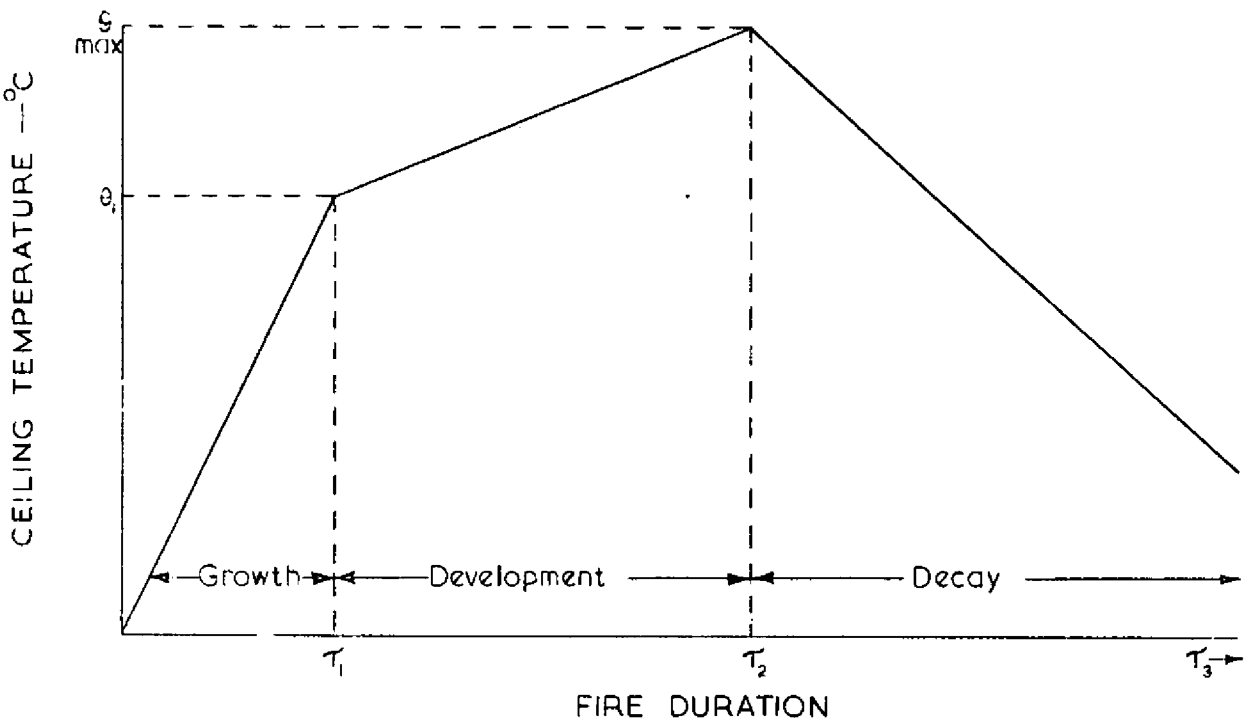


FIG.1. SCHEMATIC DIAGRAM OF A TEMPERATURE-TIME CURVE FOR A LARGE OR SMALL SCALE FIRE

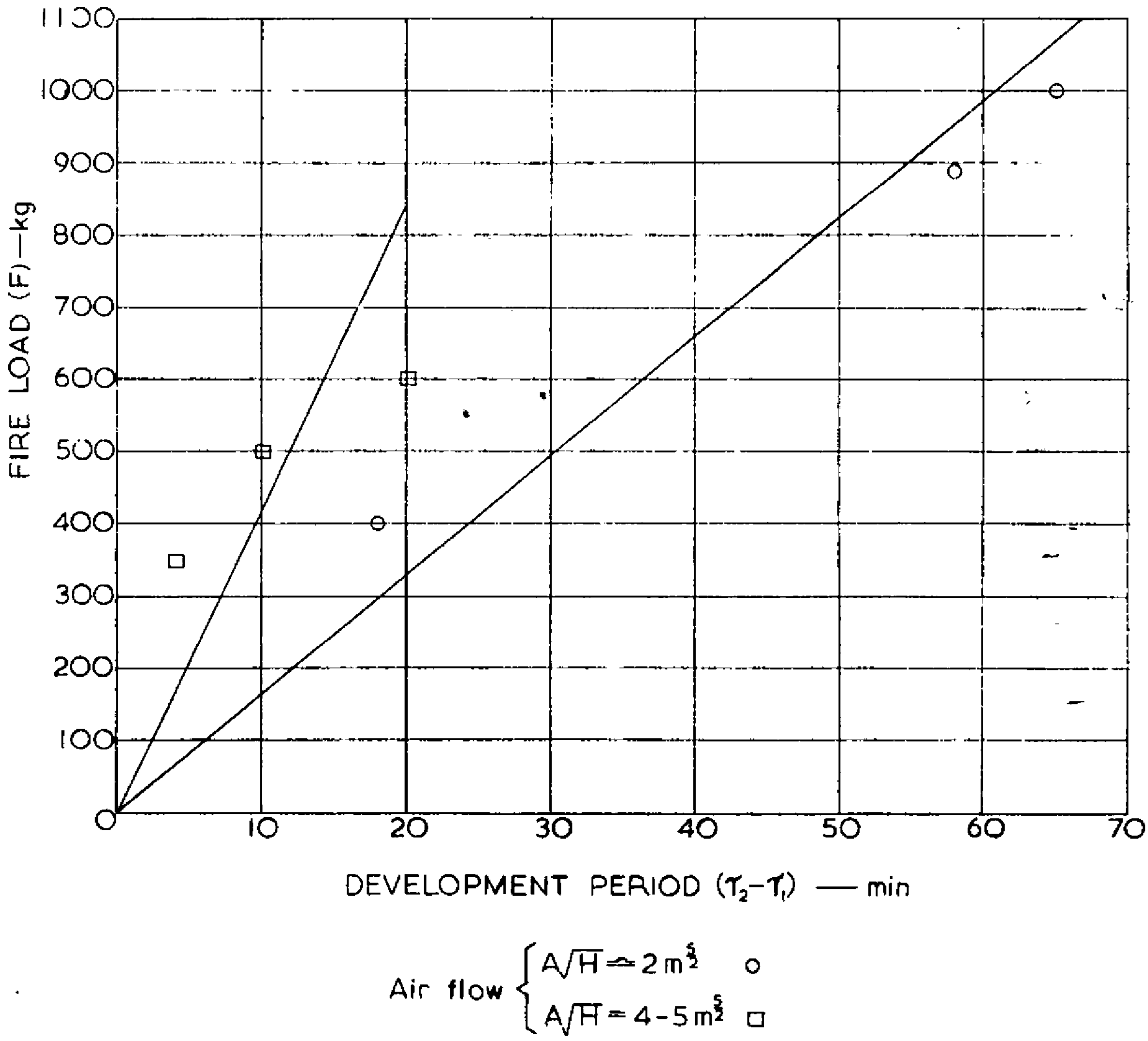
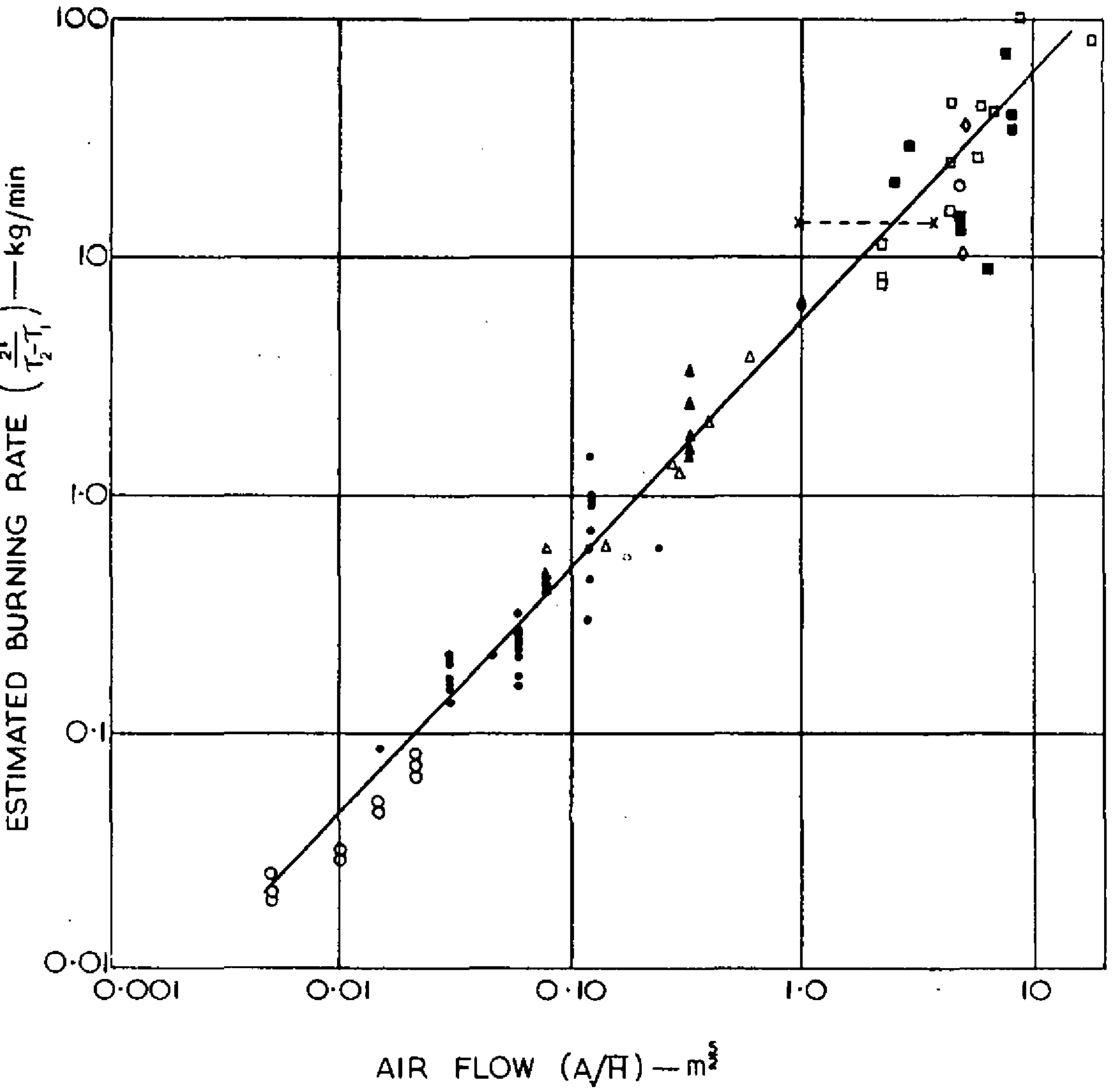


FIG.2. FIRE LOAD AND DURATION OF DEVELOPMENT PERIOD



	Scale I size c. 0·3 m cube	Scale II size c. 0·7 m cube	Scale III size c. 1·0 m cube	Half scale size c. 1·9 m cube	Full scale size c. 3·0 m cube
Hird and Wraight[1]	○	•	▲		
Hird and Fischl[5]				◆	
Kawagoe[2]			△		
Malhotra[3]					■
Swedish test[4]					x- - - - -x
Dwelling house[7]					◊

FIG.3. ESTIMATED BURNING RATE IN DEVELOPMENT PERIOD

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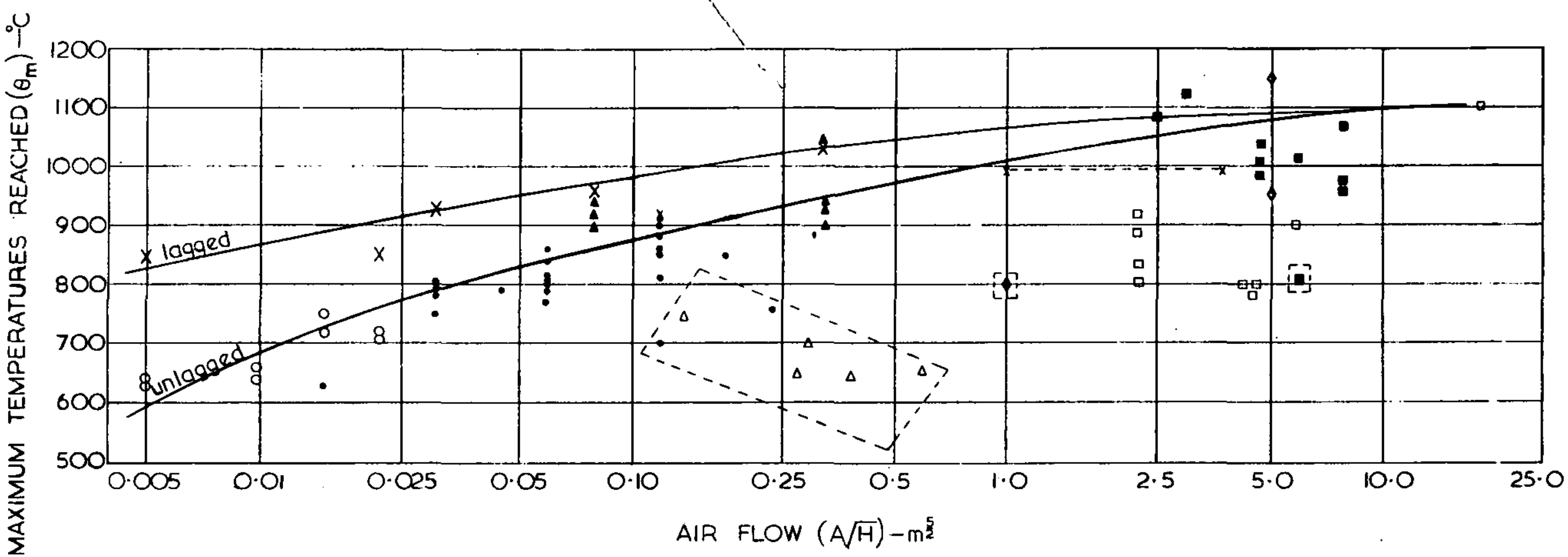


	Scale I Floor area (·3 x ·3) m	Scale II Floor area (·7 x ·7) m	Scale III Floor area (1·0 x 1·0) m	Half scale Floor area (1·8 x 2·75) m	Full scale Floor area (3·0 x 3·0) m
Hird and Wraight [1]	○	•	▲		
Hird and Wraight (lagged boxes)	X	X	X		
Kawagoe [2]			△		□
Malhotra [3]					■
Swedish test [4]					×----×
Hird and Fischl [5]					◆
Dwelling house [7]					◇

Points within the broken lines are those where the fire load is relatively low

FIG. 4. MAXIMUM TEMPERATURES AND AIR FLOW

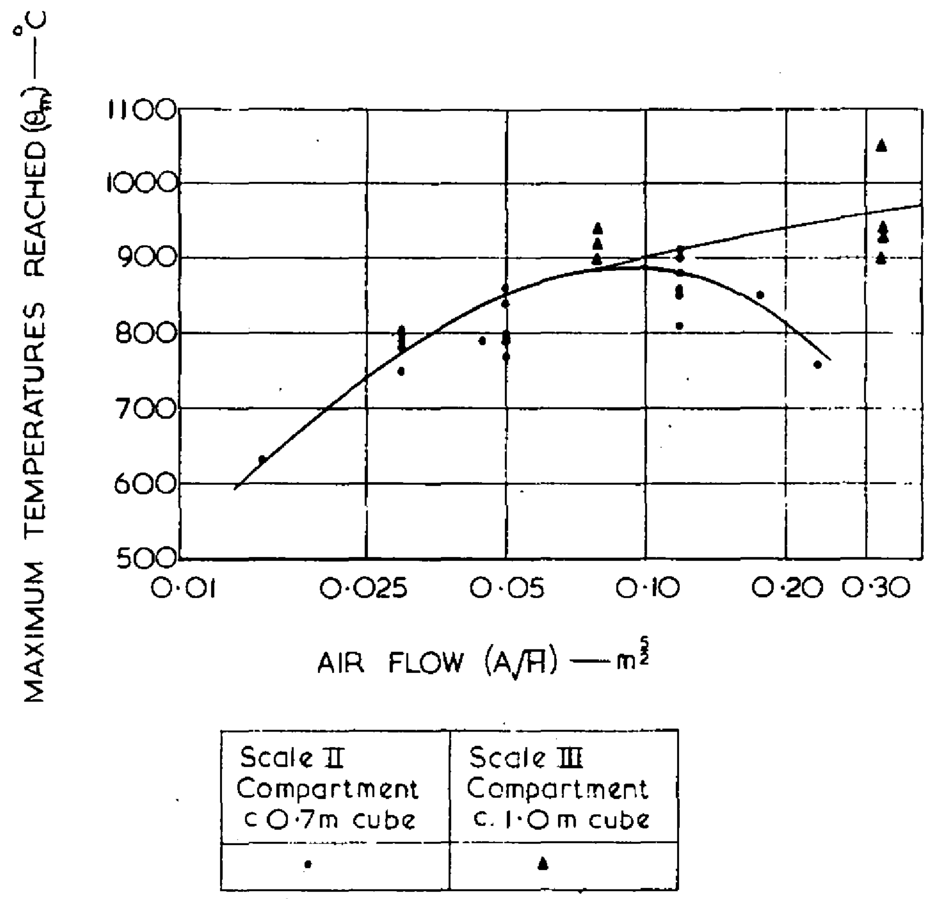


FIG. 4a. EFFECT OF AIR FLOW ON MAXIMUM TEMPERATURE IN SMALL SCALE FIRES[1]

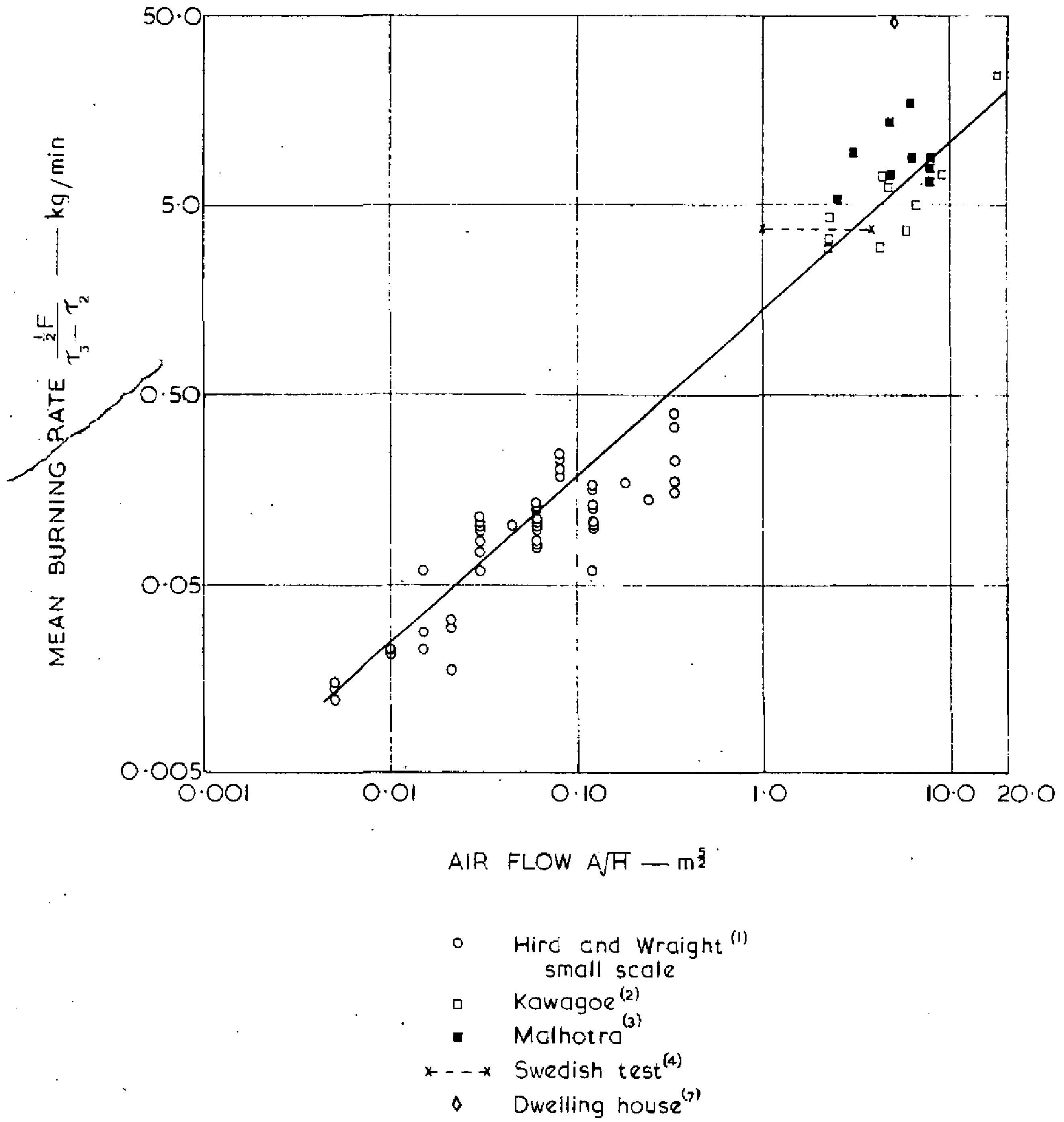
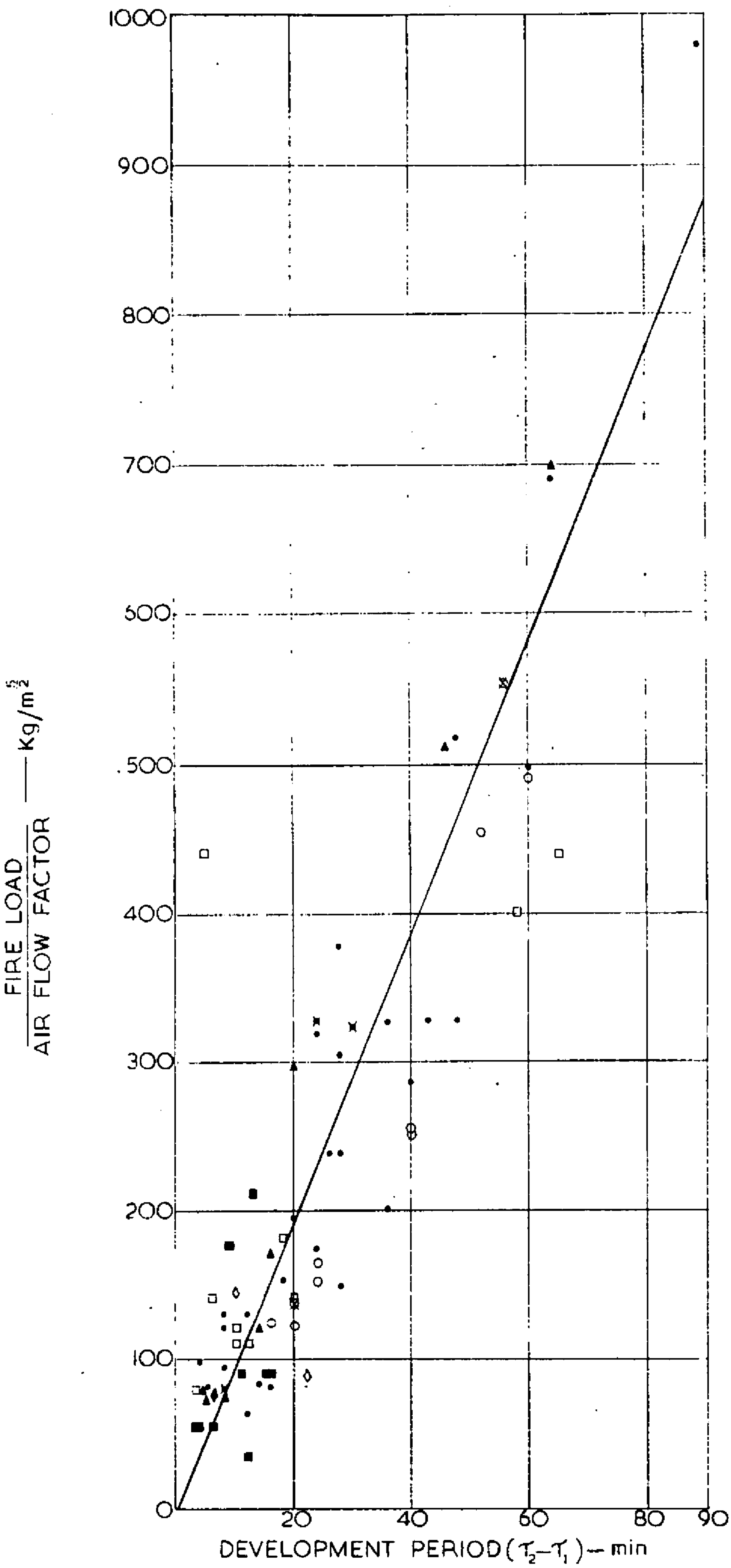
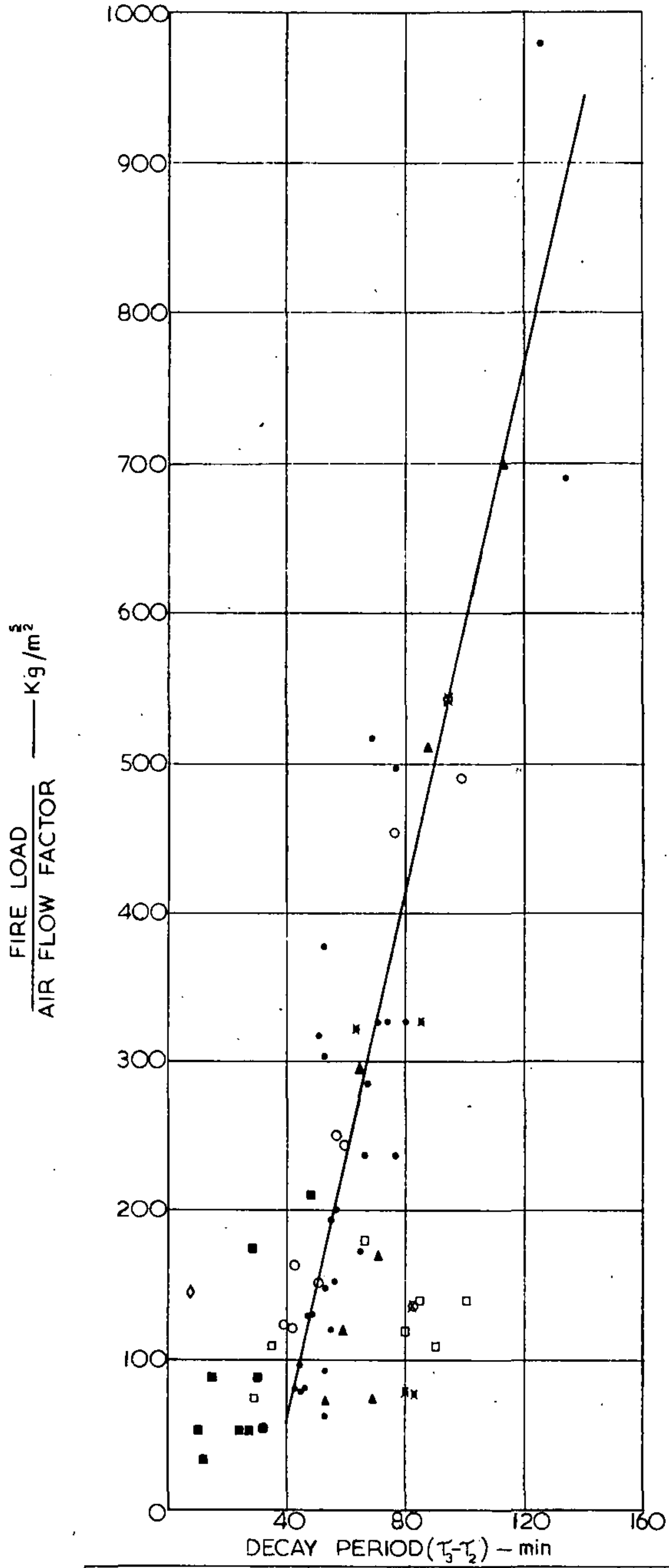


FIG. 5. MEAN BURNING RATE IN DECAY PERIOD



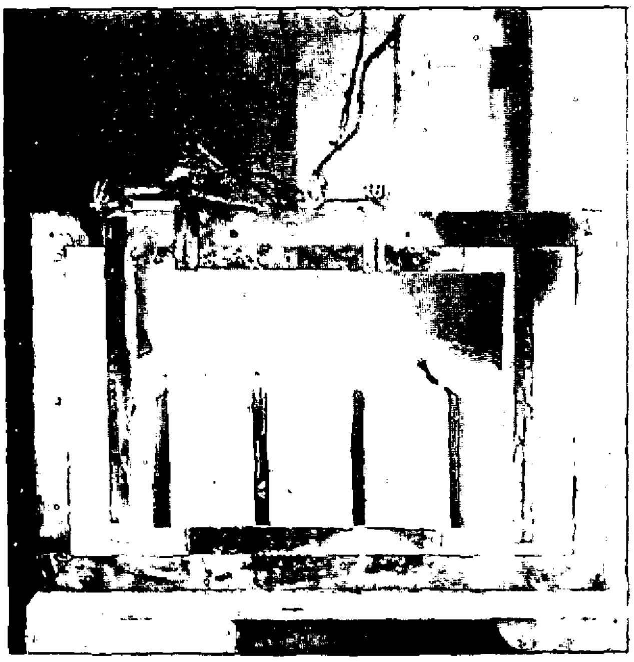
Hird and Wraight[1]	Scale I ○	Scale II •	Scale III ▲	Half scale	Full scale
Hird and Wraight lagged boxes	⊠	✱	✱		
Kawagoe[2]					□
Malhotra[3]					■
Dwelling house[7]					◊
Hird and Fischl[5]				♦	

FIG.6. LENGTH OF DEVELOPMENT PERIOD

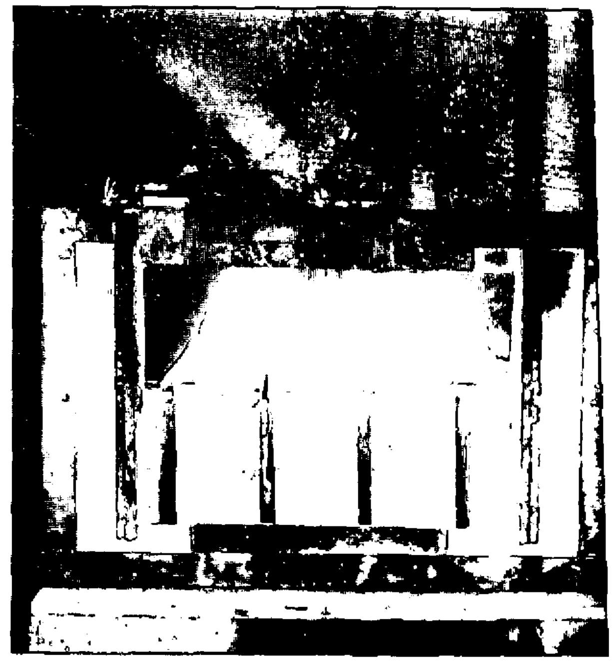


	Scale I	Scale II	Scale III	Half scale	Full scale
Hird and Wraight[1]	○	•	▲		
Hird and Wraight lagged boxes	⊠	×	✖		
Kawagoe[2]					□
Malhotra[3]					■
Dwelling house[7]					◊
Hird and Fischl[5]				♦	

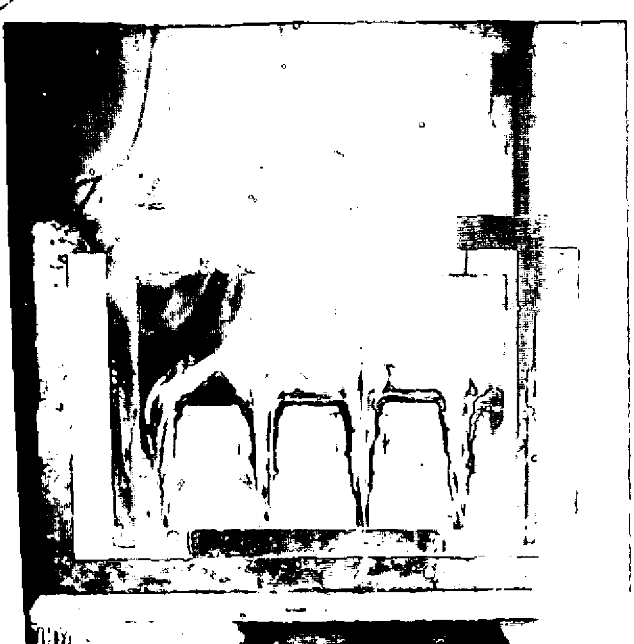
FIG. 7. LENGTH OF DECAY PERIOD



(a) at 4.50 minutes



(b) at 5.50 minutes



(c) at 16 minutes

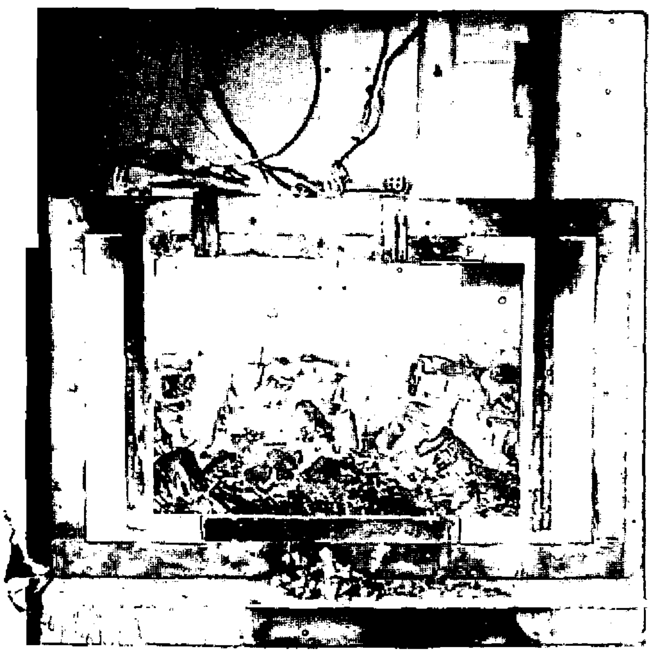
(d) at 23.30 minutes

PLATE I (a - d)

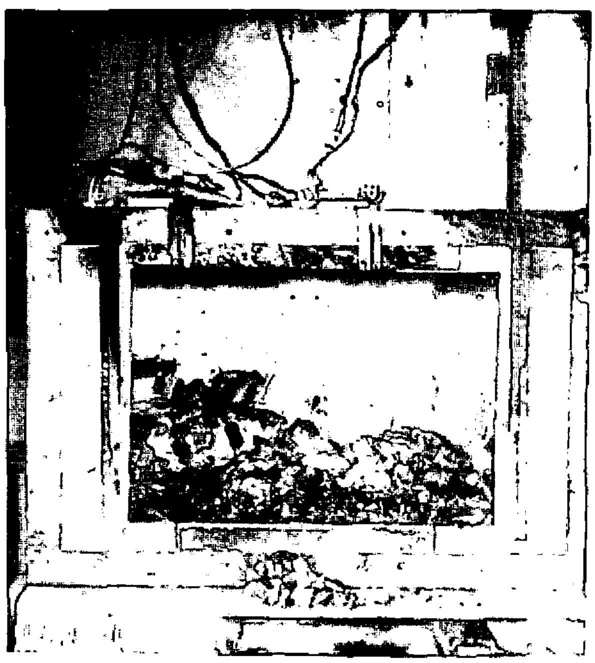
COURSE OF A TYPICAL FIRE

(e) at 38.10 minutes

(f) at 52.00 minutes



(g) at 66.30 minutes



(h) at 87.00 minutes

PLATE I (e - h)

COURSE OF A TYPICAL FIRE