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

THE BURNING OF WELL VENTILATED COMPARTMENT FIRES PART III

THE EFFECT OF THE WOOD THICKNESS

by

C. T. Webster, Miss M. Raftery and P. G. Smith

Summary

This report continues the study of fires in cubical enclosures with one side open(1)(2); the results of experiments with cribs of 1 in wood with one packing density have already been reported(2). In this report, results are given for cribs of $\frac{1}{2}$ in, 1 in, 2 in and 3 in square section wood burnt in 2 and 3 ft cubical boxes, with one side open, in order to compare their rates of burning for the same packing density.

Some experiments have also been made with 1 in and $\frac{1}{2}$ in wood at various packing densities.

Cribs made with different thicknesses of stick lose weight at different rates, but maximum rates of loss of weight per unit area in the first 4 minutes for 2 in thick sticks are about the same as those for 1 in wood. It is shown that when $\frac{1}{2}$ in and 1 in sticks are spaced sufficiently far apart they burn at the same rate per unit area. The reasons why cribs of 3 in wood sticks burn more slowly are discussed.

The heights of the flames and the radiation from the enclosure and the flames are also reported and discussed.

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INTRODUCTION

An earlier report "The burning of fires in rooms Part II"[2] described a series of tests in which cribs made from 1 in square section sticks assembled in one packing density were burnt in 1, 2 and 3 ft cube incombustible boxes with one side open.

In this report experiments are described where sticks of different thicknesses were burnt in incombustible boxes 2 and 3 ft cube. Measurements of the radiation, flame height and rate of burning are compared with those for 1 in wood reported in Part II[2] and the influence of thickness of wood on the burning of cribs is discussed.

EXPERIMENTAL

The experiments were carried out in 2 ft and 3 ft cube incombustible boxes having one side completely open. The experimental measurements and procedures adopted for the tests were the same as for the previous series with 1 in wood described in Part II[2]. The cribs burned in the tests were of conditioned pine wood either $\frac{1}{2}$ in, 1 in, 2 in or 3 in square section with unfinished surfaces and a density of approximately 30 lb/cu. ft. For the tests with 2 in wood the packing density was $33\frac{1}{3}$ per cent, that is the stick thickness was $\frac{1}{3}$ of the spacing between the strips, the same as for the previous tests with 1 in wood, but for tests with 3 in, 1 in and $\frac{1}{2}$ in wood other packing densities were also investigated.

The weights of 2 in wood used were greater than in the previous tests with 1 in sticks, since for similar low weights the number of 2 in sticks were insufficient to form a crib.

RESULTS

Rate of burning

The results of the tests are given in Table 1. The average burning rates $R_{90/20}$ are defined by

$$R_{90/20} = \frac{W_{90} - W_{20}}{t_{20} - t_{90}}$$

where W_{90} = 90 per cent of the initial weight

W_{20} = 20 per cent of the initial weight

$t_{20} - t_{90}$ = time during which this percentage weight loss occurred.

Similarly $R_{90/60}$ is defined as the mean rate of weight loss during the period the weight decreases from 90 to 60 per cent of the initial weight.

Figure 1 shows the variation of fractional loss of weight with time for the 2 in sticks in the 3 ft cube box, and Figure 2 shows the average fractional weight loss with time for cribs of 6 sticks or more high for 2 ft and 3 ft cube boxes. These curves show more curvature than was observed with 1 in sticks. Figure 3 shows the variation of loss of weight with time for 3 in sticks in the 3 ft cube box for various initial weights of wood. The mean of these results for each thickness are given in Figure 4. Figure 5 shows the variation of rate of burning per unit area, $r_{90/20}$* of cribs with various packing densities of 1 in and ½ in sticks.

Flame heights and radiation

The maximum flame heights** and peak radiation from the flames above the box and from the box opening are shown in Figures 6, 7 and 8 respectively, in terms of the corresponding maximum burning rates. The lines shown with the points are those obtained from the results in Part II[2]. The ordinates in the log.log curve (Fig. 6) are based on results described and analysed in F.R. Note No. 449[3]. This relation was found more satisfactory for presenting the data in Part II[2] which were shown there as ratios of flame height to cube dimension, a presentation which exhibited a scale effect. The original data are included as well.

DISCUSSION OF RESULTS FOR RATE OF BURNING

From a comparison of the average curves in Fig. 4 it may be seen that the form changes as the thickness of stick increases from 1 in. It will be shown in the course of this report that a large part of these differences can be explained when results are considered in terms of rate of burning per unit area of wood.

The weight loss for ½ in sticks

The results for the cribs made with ½ in sticks are given in Table 1. It may be seen from Fig. 5 that the rate of burning per unit area $r_{90/20}$ increases rapidly as the packing density decreases below 30 per cent. Except when the sticks widely spaced the values of $r_{90/20}$ are significantly lower for cribs of ½ in sticks than for those of 1 in sticks.

The weight loss for 1 in sticks

The results in Fig. 5 for the 1 in sticks show that the rates per unit area remains substantially constant at 0.78 mgm $cm^{-2}s^{-1}$ over the packing density ranges of 100-30 per cent. As the packing density decreases from 30 per cent the rate increases until it approximates to the same as that for ½ in wood. The experiments could not be extended beyond packing densities of 7.5 per cent because for this extreme packing density the number of sticks per layer was only two.

The rate of weight loss for the 2 in sticks

In Fig. 1 it may be seen that for the 3 ft box the fractional rates of weight loss increases with the number of layers of sticks in the crib up to a limit reached when there are 6 or more layers in the crib. The maximum value of $r_{90/60}$ is not approached until the cribs are 6 or more sticks high, presumably because the heat loss from the crib is too large when the number of layers is small. It may be seen from Fig. 2 that for practical purposes the weight loss/time relationships for the 2 ft and 3 ft boxes are almost the same, i.e. there is only a small scale effect. This scale effect may be a consequence of greater heat loss from the walls of the smaller box. The mean value of $r_{90/20}$ for cribs of 6 sticks high or more was 0.60 mgm $cm^{-2}s^{-1}$ (Test Nos. 132, 130, 134, 124, 125, 126) which is about 30 per cent lower than the results with the 1 in square wood, 0.78 mgm $cm^{-2}s^{-1}$ (see Fig. 2) Part II[2]. On the other hand, the mean value of $r_{90/60}$ for the same tests was 0.86 mgm $cm^{-2}s^{-1}$ which is in reasonable agreement with the corresponding value (0.78 mgm $cm^{-2}s^{-1}$) for the 1 in sticks. It appears that initially the 2 in wood cribs start burning at effectively the same rate as the 1 in wood cribs, then the rate falls off possibly because of the formation of a layer of charcoal insulation which, in the later stages of the fire, is thicker than it was for the 1 in wood.

* The symbols $r_{90/20}$ and $r_{90/60}$ refer to the rates of burning $R_{90/20}$ and $R_{90/60}$ when expressed per unit area of exposed wood surface.

**The quantity recorded as maximum flame height was obtained visually and refers to an estimate of the mean of the rapidly fluctuating height of continuous flame during the period when this mean reaches a maximum value.

The rate of weight loss for the 3 in sticks.

Two tests, results shown in Figure 3, were made with 3 in square section sticks in the 3 ft cube box, with a 28.6 per cent packing density, i.e. sticks $10\frac{1}{2}$ in apart, that is 3 sticks per layer and 3 layers. Both cribs ceased to burn with more than 70 per cent of the wood left unburnt. A further two tests were made on cribs, one with 100 per cent packing density, sticks 3 in apart, 10 sticks in 2 layers, and the other with 50 per cent packing density, sticks 6 in apart, 8 sticks in 2 layers. Flaming persisted with both these cribs until the wood was fully burnt. With the closer packing of these two cribs more heat was retained. For the two cribs that were fully burnt, the maximum rate of burning was obtained with the highest and heaviest crib, but the value of $r_{90/20}$ was 0.34 mgm $cm^{-2}s^{-1}$ (Test No. 141, 3 sticks high), about 50 per cent lower than for the 1 in sticks. The value of $r_{90/60}$ for this test was 0.43 mgm $cm^{-2}s^{-1}$. These results suggest that a much larger crib in a larger box would have to be burnt to obtain the same maximum rate of burning as for the 1 in sticks.

MAXIMUM FLAME HEIGHT

The heights of flame from the base to above the top of the enclosure are shown in Figure 6 plotted as $\log L/D$ against $\log \frac{(\rho\, Q)^2}{D^5}$

where L is the height of flame from base of box
D is the size of the cube
Q mass fuel flow rate equal to the rate of burning of the crib in the early stages when there is only burning of volatiles.

The line through the points in Fig. 6 is identical with that shown in Fig. 3, F. R. Note No. 449 and has the equation $\frac{L}{D} = 4.4\left(\frac{\rho^2 Q^2}{D^5}\right)^{1/5}$

The results extend over a range of Reynolds Number defined by $\frac{\rho Q D}{\mu}$ from 1580 - 8950 with μ taken as 10^{-4} c.g.s.

The flames may be regarded as fully turbulent over the major part of the range of the experiments.

RADIATION FROM FLAMES ABOVE THE BOX

The maximum radiation intensities from the flames above the box show a linear relation with maximum burning rate per unit floor or window area (Fig. 7). The results, particularly those for the higher burning rates, tend to be higher than those previously obtained. The correlation in these terms is empirical. Further analysis is required before it is possible to discuss the interpretation of these data.

MAXIMUM RADIATION FROM THE BOX OPENING

Figure 8 shows the maximum radiation from the box opening and the maximum rate of burning per unit floor or window area. The radiation tends to be only slightly higher, about 10 per cent, than in the previous experiments, Part II[2].

GENERAL DISCUSSION AND CONCLUSIONS

The influence of crib design on the burning rate is complex. It has been shown

(a) that the rates of burning per unit area of wood for 2 in sticks is comparable with that for 1 in sticks in the early part of the fire, that is the $r_{90/60}$ value does not vary much between 1 in and 2 in sticks. This only holds good for 2 in sticks if the cribs are six or more layers high;

(b) there is a greater variation of burning rate with time for the 2 in compared with the 1 in thick sticks, probably as a result of the rate of burning decreasing as the charcoal layer increases in thickness to a greater value with 2 in sticks than with 1 in sticks;

(c) it is not been possible on these small scales to make cribs of 3 in wood of sufficient depth to reach a burning rate per unit area as high as those obtained for 1 in and 2 in sticks. Within the range of conditions explored decreasing the spacing led to an increased burning rate and in fact made a continuing fire possible;

(d) for the $\frac{1}{2}$ in and 1 in wood there was a considerable range of packing density which did not influence the rate of burning per unit area of wood. However, the minimum space between sticks in this region was not the variable horizontal spacing, but the smaller vertical spacing which was smaller for the $\frac{1}{2}$ in sticks. This smaller space between layers may be the controlling factor in limiting the air flow, but for these cribs a proportion of the volatiles may have burnt outside the crib rather than inside, thus affecting the heat transfer rates within the crib. At the wider spacings where flames could surround the individual sticks the rates per unit area for the $\frac{1}{2}$ and 1 in sticks then tend to approach the same value.

The way the crib design affects the burning rate is still somewhat obscure, the features of design appearing to be controlling factors varying with the design. It may be preferable in the future to adopt a simpler form of fuel bed, e.g. a series of parallel boards. However, at present it is not possible to say that any one fuel arrangement represents a certain quantity of fuel and a certain surface area, except perhaps the cribs of 1 and $\frac{1}{2}$ in sticks widely spaced, and the early stages of a crib of 2 in wood. Nevertheless, other features of the fire behaviour, e.g. height of flame, radiation from the opening, appear to be related to rate of burning in a way which is largely if not wholly independent of crib design.

References

1. WEBSTER, C. T., WRAIGHT, H. and THOMAS, P. H. The burning of fires in rooms. Small scale tests with high ventilation (Part I) F.R. Note No. 398.

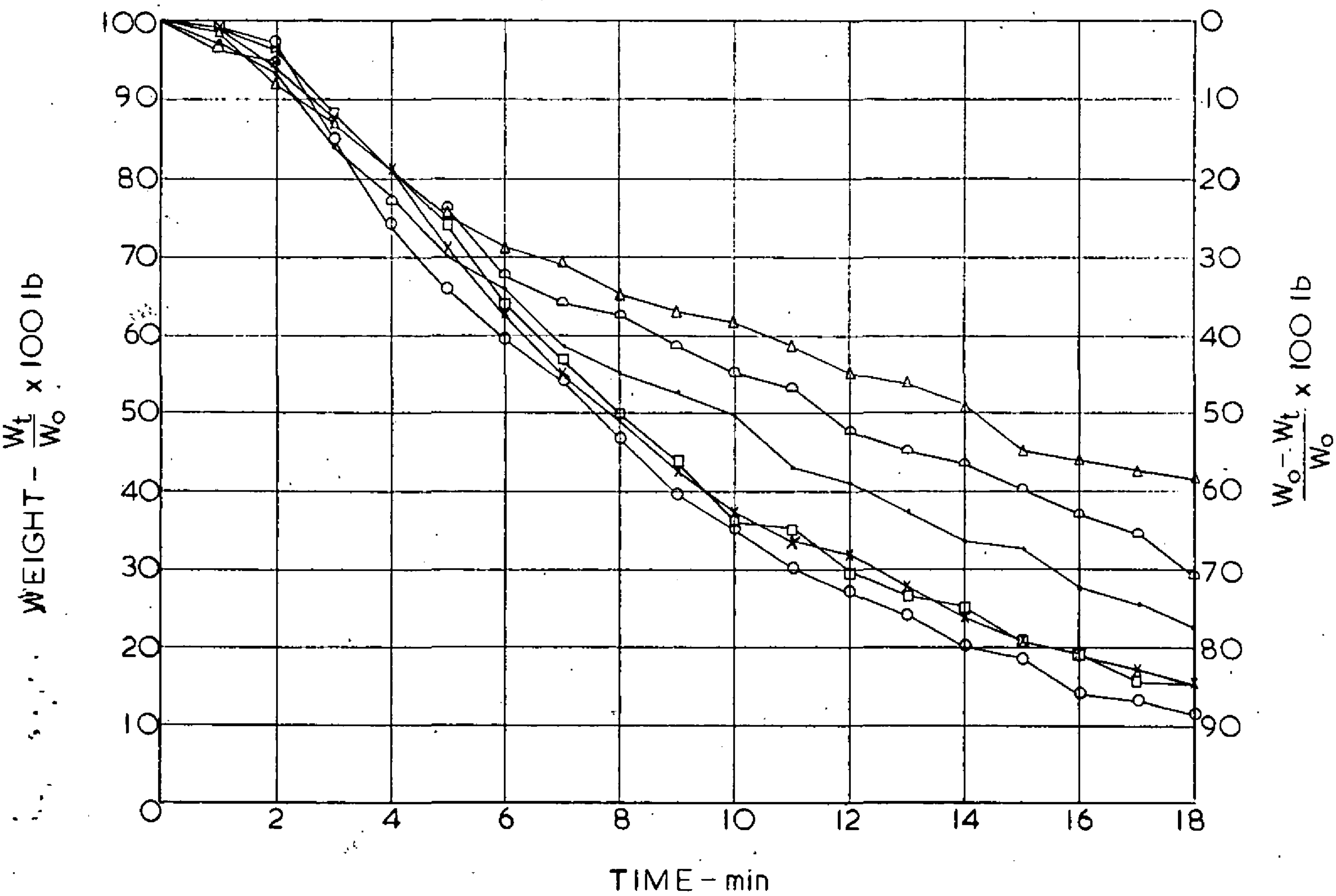
2. WEBSTER, C. T. and RAFTERY, Monica M. The burning of fires in rooms. Tests with cribs and high ventilation (Part II) F. R. Note No. 401.

3. THOMAS, P. H., WEBSTER, C. T. and RAFTERY, Monica M. "Some experiments on buoyant diffusion flames". F. R. Note No. 449.

TABLE I

RESULTS FROM TESTS WITH DIFFERENT THICKNESSES OF WOOD

Test No	Box size ft	Weight of firewood lb	Weight of firewood kg	Density of wood lb/cu.ft	Density of wood g/cc	No. of sticks	Packing density per cent	Crib height in	Crib height cm	Fireload lb/sq.ft	Fireload g/cm²	Area of wood exposed A_W sq.ft	Area of wood exposed A_W sq.cm x 10^3	$R_{90/20}$ Burning rate $\frac{W90\% - W20\%}{\Delta T}$ lb/min	$R_{90/20}$ Burning rate g/sec	$T_{90/20}$ Time interval T sec	$r_{90/20}$ Burning rate/unit area of wood exposed $\frac{R}{A_W}$ lb/ft²/min	$r_{90/20}$ mg/cm²/sec	$R_{90/60}$ Maximum burning rate $\frac{W_{90} - W_{60}}{\Delta T}$ lb/min	$R_{90/60}$ g/sec	Time interval $T_{90/60}$ sec	$r_{90/60}$ Maximum burning rate /unit area of wood exposed lb/ft²/min	$r_{90/60}$ mg/cm²/sec	Flame height in.	Flame height cm.	Peak flame radiation cal.cm⁻²sec⁻¹	Peak radiation from opening Configuration factor 0.56 cal.cm⁻²sec⁻¹
½ in (1.27 cm) Wood																											
136	3	4.37	19.9	29	0.47	347	33.3	12	30.5	4.85	2 37	134.5	125.0	4.28	32.4	429	0.0318	0.259	5.22	39.6	125	0.039	0.315	78	200	0.538	0.988
137	3	33.0	15.0	30	0.48	257	33.3	9	22.9	3.67	1.79	99.5	92.4	3.85	29.1	360	0.0387	0.315	4.78	36.2	247	0.048	0.387	66	170	0.585	1.10
211	3	46.4	21.0	35	0.57	301	50	11	28	5.16	2.52	104	96.5	4.7	35.5	414	0.045	0.368	5.6	42	150	0.044	0.55	60	150	0.63	1.35
212	3	46.4	21.0	33	0.52	321	33.3	11½	29	5.16	2.52	117	108	5.6	42.3	345	0.048	0.39	6.8	51.1	123	0.058	0.47	72	180	0.643	1.32
213	3	46.4	21.0	33	0.53	324	25	12½	32	5.16	2.52	120	107	6.5	49.0	296	0.054	0.456	7.9	60	105	0.066	0.54	72	180	0.645	1.35
214	3	46.4	21.0	33	0.54	316	16.7	15½	39	5.16	2.52	122	113	8.5	64.5	228	0.071	0.57	8.1	61	103	0.066	0.54	96	240	0.795	1.42
215	3	25.4	11.5	37	0.58	160	7.1	16	41	2.82	1.38	64.4	60	8.9	67.3	123	0.138	1.12	7.9	60	57	0.123	1.00	84	210	1.005	1.72
216	3	38.0	17.2	34	0.55	256	13.5	16	41	4.22	2.07	100	93	10.2	77.2	160	0.102	0.83	8.5	69	75	0.085	0.74	96	240	0.88	1.35
1 in (2.54 cm) wood																											
207	3	40	18.1	29	0.47	79	50	8	20	4.44	2.17	55.4	51	5.3	40.1	315	0.095	0.777	5.8	44	123	0.105	0.86	72	180	0.36	0.97
209	3	40	18.1	27	0.43	85	33.3	12	30	4.44	2.17	61.8	57.5	5.7	43.0	288	0.092	0.75	6.6	50	108	0.107	0.87	72	180	0.395	1.38
210	3	40	18.1	28	0.45	82	16.7	17	43	4.44	2.17	63.4	59	6.4	48.5	261	0.105	0.82	7.5	56.6	96	0.11	0.96	84	210	0.68	1.73
217	3	17	7.7	31	0.49	32	7.4	11	28	1.9	0.92	25.8	24	3.1	23.3	221	0.120	0.97	5.1	38.5	60	0.198	1.60	72	180	0.41	0.91
218	3	20.6	9.3	28	0.45	42	11.6	11	28	2.3	1.12	33.3	31	4.7	35.0	186	0.141	1.13	5.6	42.3	66	0.168	1.21	72	180	0.53	0.91
221	3	26.0	11.8	30	0.48	50	100	4	10	2.9	1.41	31.2	29	3.3	25.0	333	0.106	0.86	3.9	29.4	120	0.125	1.02	36	90	0.23	0.85
2 in (5.08 cm) wood																											
132	3	53.0	24.1	29	0.47	26	33.3	14	35.6	5.90	2.88	37.60	35.0	3.20	24.20	696	0.085	0.693	4.8	36.3	125	0.129	1.04	42	110	0.360	1.220
130	3	49.2	22.4	32	0.52	22	33.3	12	30.5	5.47	2 68	31.80	30.0	2.76	20.85	750	0.0868	0.707	3.8	28.7	128	0.123	0.904	36	90	0.156	0.924
134	3	44.4	20.2	29	0.47	22	33.3	12	30.5	4.93	2 41	31.80	39.0	2.47	18.69	756	0.0777	0.633	3.56	26.9	127	0.112	0.915	30	80	0.285	0.987
128	3	36.5	16.6	29	0.47	18	33.3	10	25.4	4.06	1.99	26.00	24.2	1.595	12.08	960	0.0613	0.499	2.82	21.4	125	0.108	0.88	18	50	-	-
129	3	30.0	13.6	31	0.50	14	33.3	8	20.3	3.33	1.63	20.25	18.8	0.905	6.85	1390	0.0446	0.364	1.70	12.9	66	0.084	0.683	6	20	0.018	-
131	3	29.65	13.5	30.5	0.49	14	33.3	8	20.3	3.30	1.61	20.25	18.8	1.075	8.135	1158	0.0530	0.432	1.95	14.8	126	0.096	0.78	6	20	0.030	0.378
124	2	29.6	13.5	28	0.45	23	33.3	16	40.6	7.40	3.62	21.65	20.1	1.295	9.80	960	0.0598	0.484	1.84	13.9	187	0.085	0.692	42	110	0.435	1.035
125	2	26.7	12.1	29	0.47	20	33.3	14	35.6	6.68	3.27	18.80	17.5	1.23	9.30	963	0.0655	0.533	1.825	13.8	67	0.097	0.79	36	90	0.435	0.848
126	2	23.1	10.5	29	0.47	17	33.3	12	30.5	5.77	2.82	16.00	14.9	1.035	7.83	936	0.0647	0.527	1.63	12.4	66	0.102	0.815	24	60	0.328	0.875
122	2	19.1	8.7	29	0.47	14	33.3	10	25.4	4.77	2.33	13.20	12.3	0.76	5.75	1055	0.0575	0.470	1.35	10.2	125	0.102	0.83	18	50	0.115	0.835
123	2	14.9	6.8	29	0.47	11	33.3	8	20.3	3.73	1.82	10.30	9.5	0.39	2.95	1595	0.0378	0.308	0.87	6.6	66	0.085	0.69	3	10	0.035	0.348
3 in (7.62 cm) wood																											
139	3	52.2	23.7	30	0.48	11	28.6	12	30.5	5.80	2.840	23.25	21.6	Cribs ceased burning before				-	1.5	11.4	126	0.064	0.53	No flames outside the			0.085
138	3	37.4	17.0	30	0.48	8	28.6	9	22.9	4.15	2.025	16.9	15.7	W20% was reached			-	-	0.59	4.5	187	0.035	0.28	box during these			0.05
140	3	46.8	21.3	29	0.47	10	100	7	17.80	5.20	2.540	22.7	21.1	0.75	5.67	2610	0.033	0.269	0.87	6.6	630	0.038	0.30	-		tests -	0.11
141	3	52.3	23.7	30	0.49	12	50	10	25.4	5.81	2.840	24.9	23.2	1.03	7.80	2130	0.041	0.337	1.2	9.1	502	0.048	0.43	-	-	-	0.175



Initial weight - lb	Sticks high
○ 53	7
□ 49·2	6
x 44·4	6
· 36·5	5
△ 30·0	4
⌓ 29·65	4

FIG. 1. THE BURNING OF WOOD CRIBS
(3 FT CUBE BOX, 2 IN STICKS)

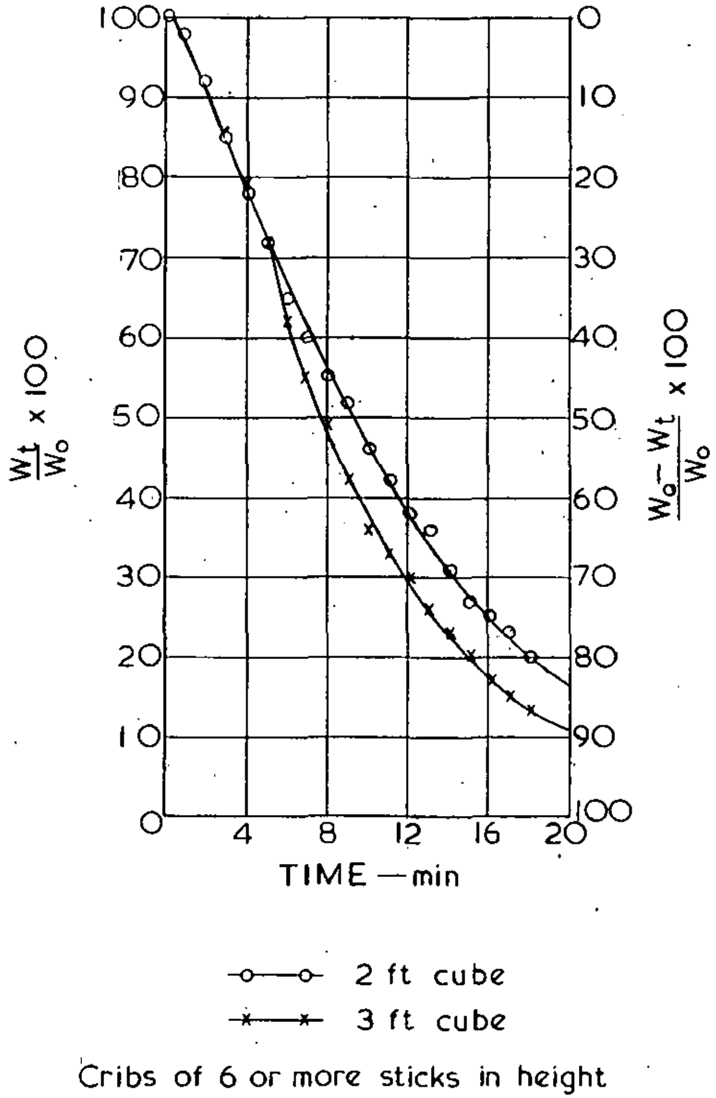


FIG. 2. AVERAGED RESULTS FOR BURNING OF CRIBS 2 in STICKS

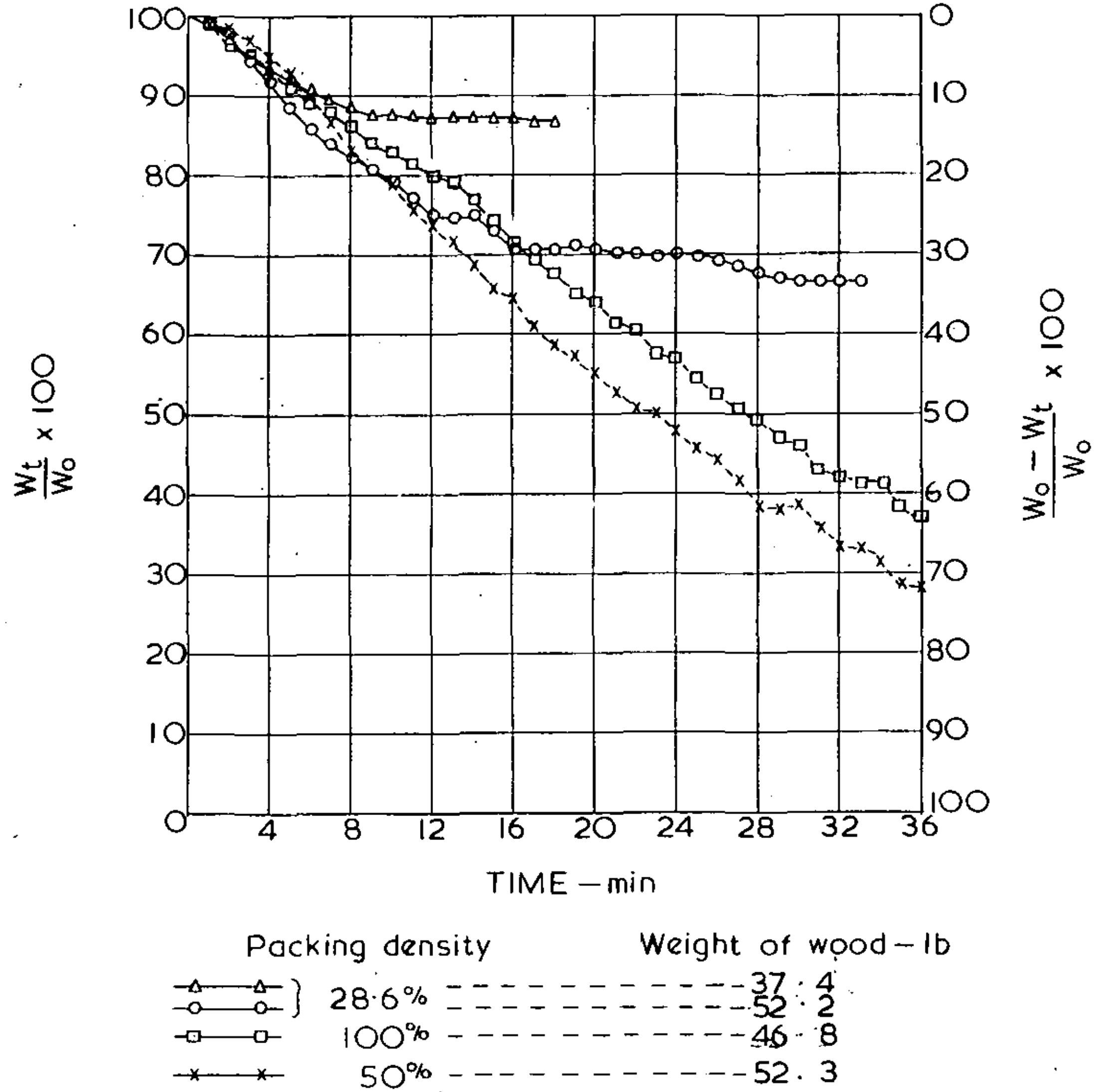


FIG. 3. THE BURNING OF WOOD CRIBS 3 ft CUBE BOX 3 in STICKS

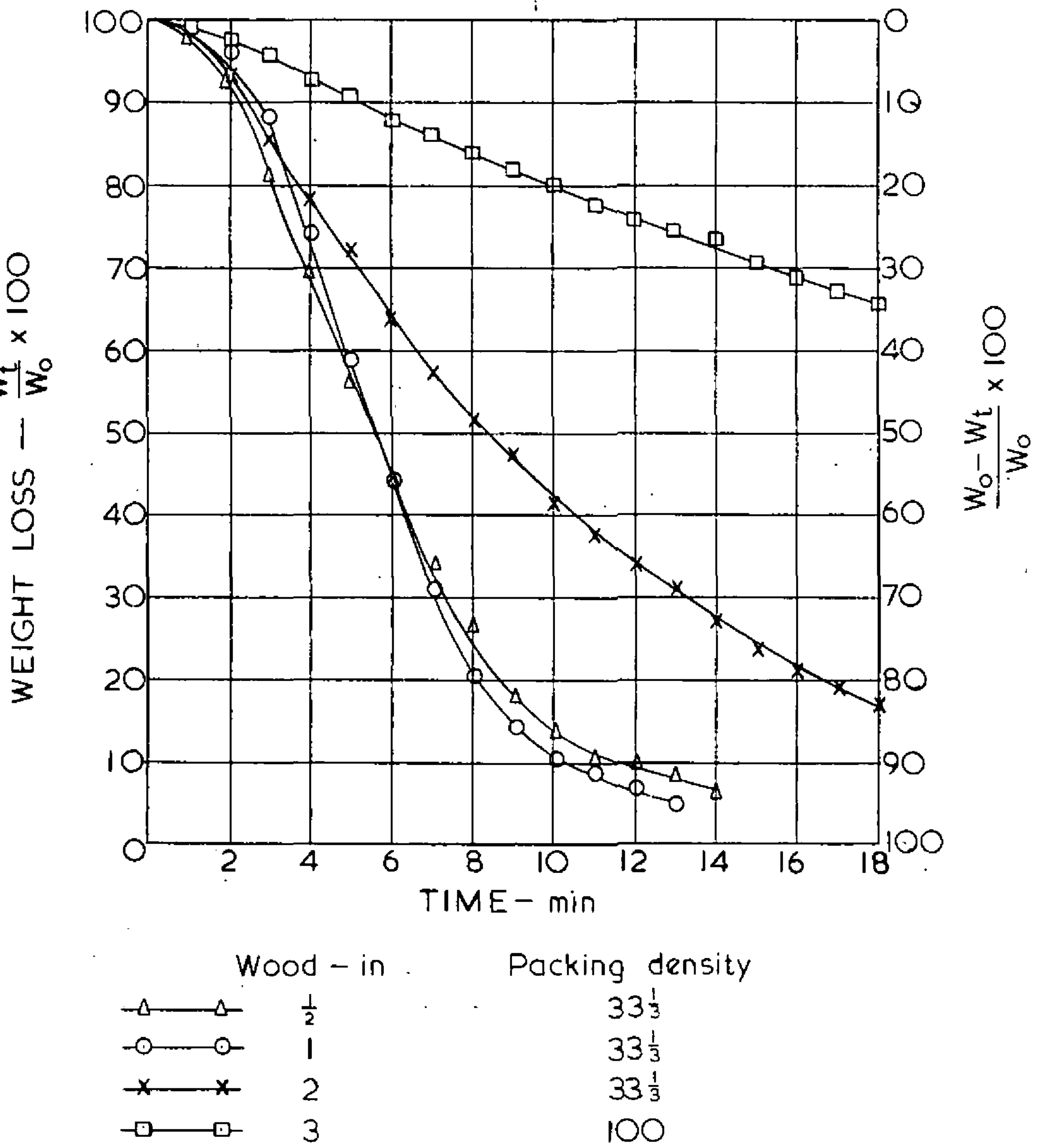


FIG. 4. AVERAGE RESULTS FOR WEIGHT LOSS IN BOTH 2 ft & 3 ft CUBES

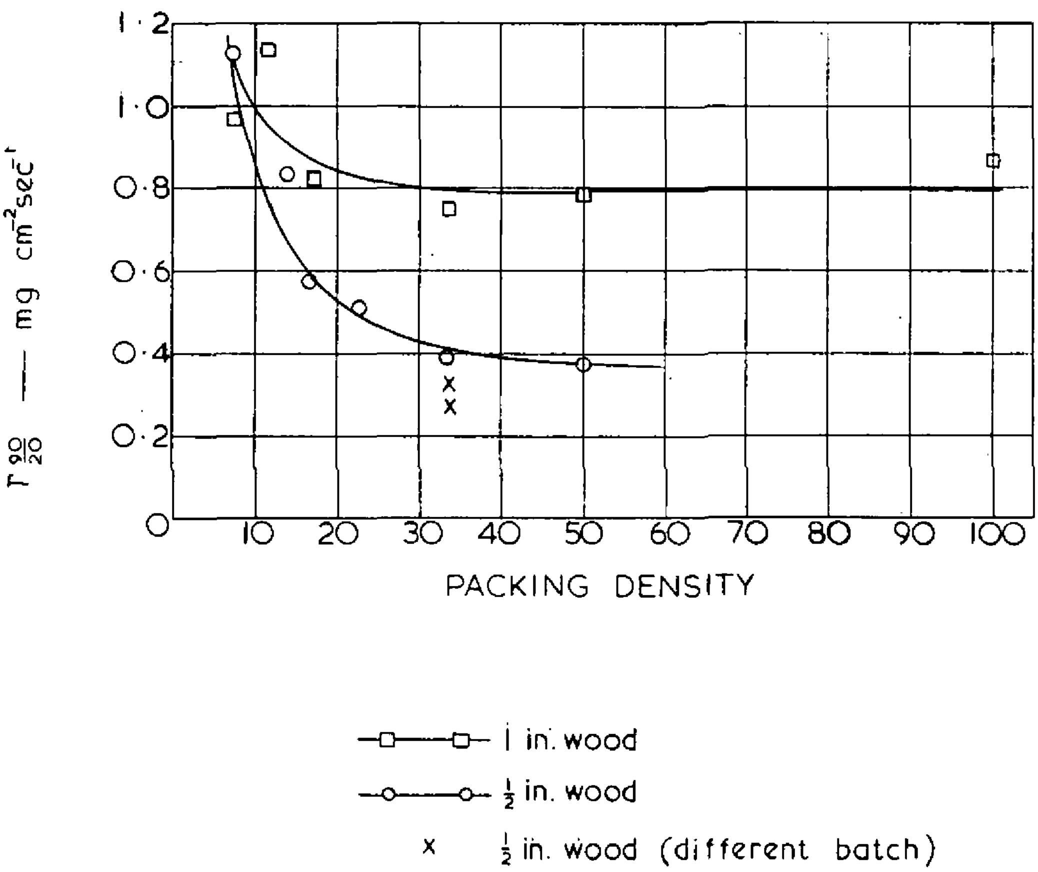
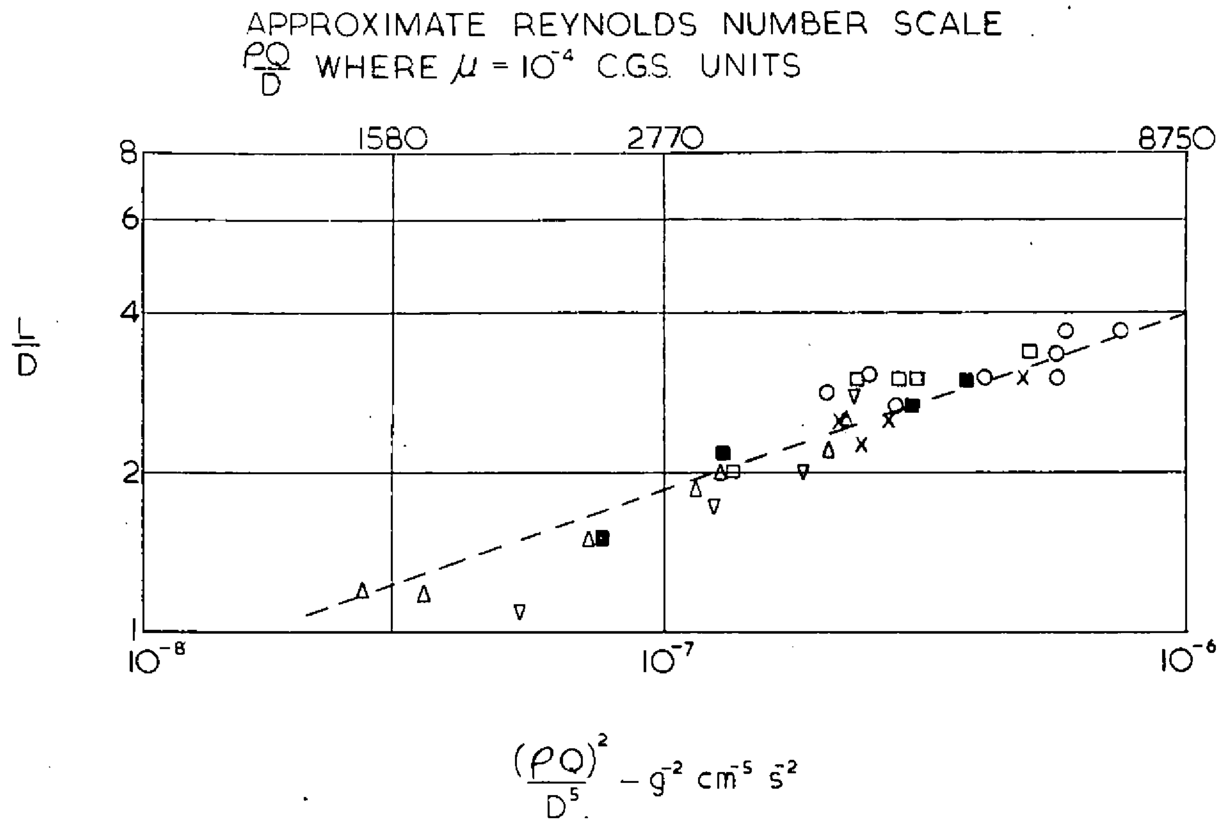


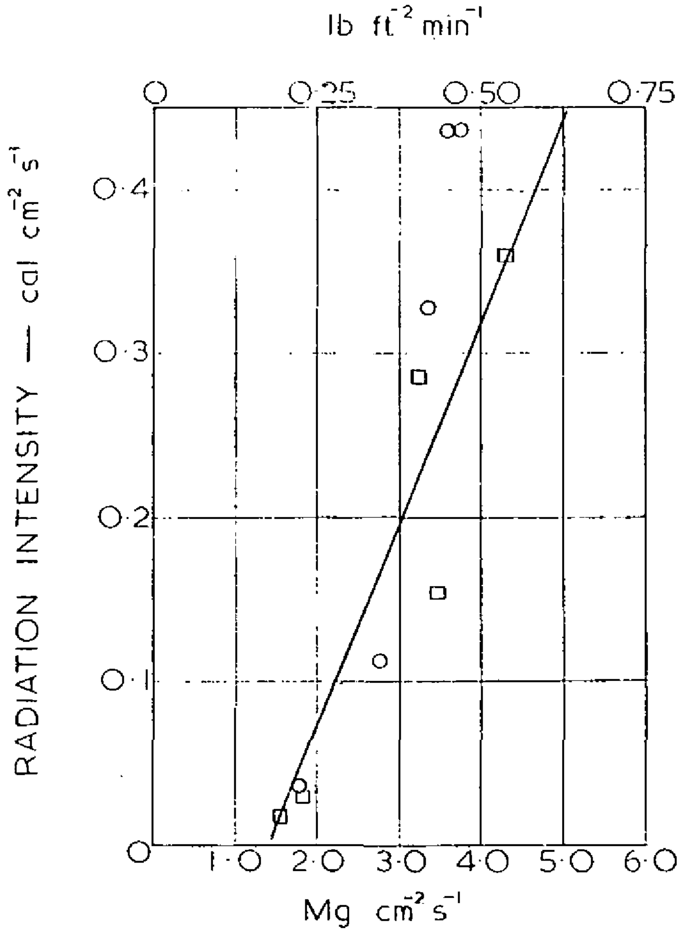
FIG. 5. THE EFFECT OF PACKING DENSITY



Present series of experiments

	Thickness cm	D – cm
○	1·27	91·5
□	2·54	91·5
△	5·08	91·5
▽	5·08	61·0
Earlier series of experiments		
■	2·54	91·5
×	2·54	61·0

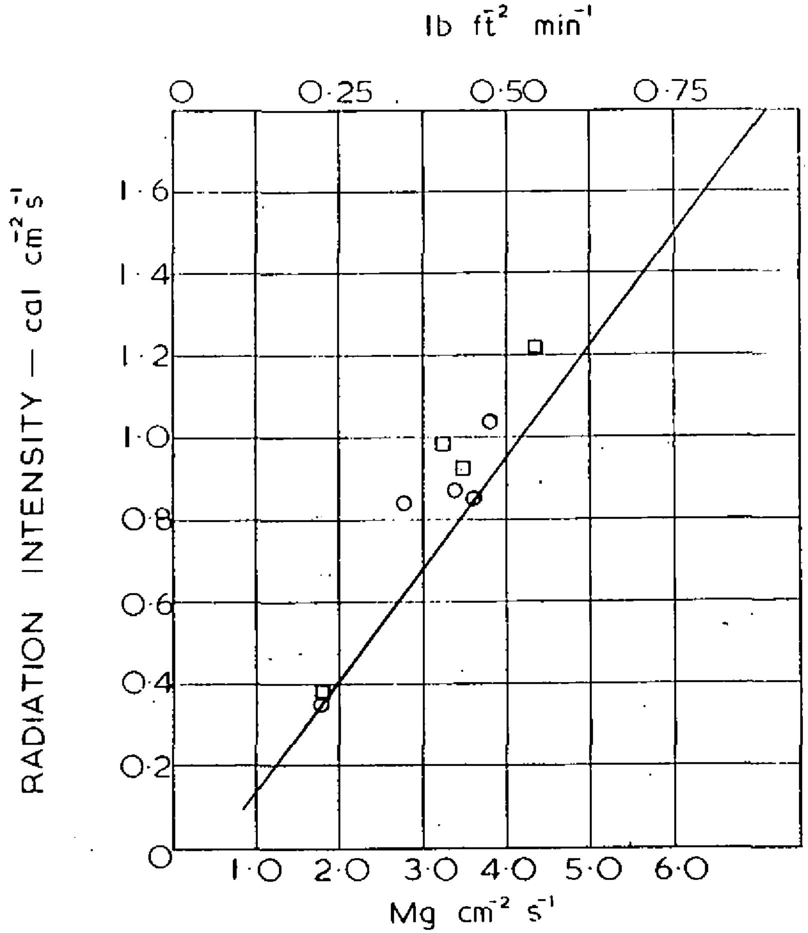
FIG.6. FLAME HEIGHT AND RATE OF BURNING



o 2ft box 2in sticks

□ 3ft box 2in sticks

The line is the results from 1in. wood (part 2)



o 2ft box 2in sticks

□ 3ft box 2in sticks

The line is the results from 1in. wood (part 2).

MAXIMUM BURNING RATE PER UNIT FLOOR (OR WINDOW) AREA

FIG. 7. MAXIMUM RADIATION FROM FLAMES

FIG. 8. MAXIMUM RADIATION FROM BOX OPENING