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

ATMOSPHERES FROM FIRES IN ROOMS WITH LITTLE VENTILATION

Part 1

by

A. J. Kelly

Summary

Combustion of 500g wood and 30-1000g of fibreboard in a sealed or partially vented container produces carbon monoxide concentrations up to 6.3 per cent and reduction of oxygen to 5.0 per cent. Maximum carbon monoxide results from a large quantity of fuel and an optimum degree of ventilation, and is accompanied by an increasing temperature.

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Introduction

An investigation is being made of the toxicity of an atmosphere resulting from a fire in a confined space with controlled ventilation. The practical situation envisaged was that of a small fire being started in a room with poor or no ventilation, so that gaseous products could accumulate in the room, and these gaseous products suddenly escape from the room because of a door being opened, or burned through, or a window breaking, etc. The problem was the estimation of the toxic hazard of the escaping gases, and the amount of dilution with air that would be necessary to avoid the hazard.

Previous work (1, 2, 3) on the combustion of various materials in enclosures has indicated lethal concentrations of carbon monoxide and oxygen depletion; although the conditions differed from those in the present work which is designed to investigate the maximum toxic hazards occurring, and the conditions condusive to them in enclosures. Wood has been used as being a common constructional material, and fibreboard as representative of low density combustible material such as soft furnishing.

Apparatus

Two containers were used for the experiments:

A The first consisted of an asbestos box, 1 ft cube mounted clear of the floor and provided with a slit for ventilation extending over the whole length of one side from the top of the container to a maximum depth of 3 in. A gas sampling duct was centrally fixed to extract gases from a point 5 in below the top and 5 in from the side opposite the ventilation slit, the end of the tube supporting a chromel-alumel thermocouple whose junction was located 1 in to the side of it. A stirrer was provided which consisted of a plate 7½ in x 3 in moved vertically by a rod passing through a small hole in the top of the box at maximum distance from the ventilation slit. The seams of the box were constructed as tightly as possible but were not completely airtight.

B The second container consisted of a metal box measuring 2ft 10 in high x 13½ in square (3.6 cu ft), standing on the floor, provided with two perspex windows on adjacent sides, one being removable for insertion of the combustible material. A wire net platform 14 in from the bottom supported the burning sample, and the gas was extracted from a point 8 in below the top and 3 in from the sides. Gases were mixed with a rotary stirrer consisting of a blade 10 in x 5 in formed as a propeller, located 4 in below the top of the box and 6 in from the sides opposite the gas sampling tube, and rotated at approximately 5 rev sec^{-1} to lift the gases eccentrically. No thermocouple was provided. The box was not airtight and maintained the contents at atmospheric pressure during combustion; but after cooling had stopped, oxygen checks over a further period indicated a leakage rate of somewhat less than 10 per cent of the volume per hour.

Gas samples of approximately 200ml (0.8 per cent of the volume of box A and 0.2 per cent of box B) were collected at intervals in gas sampling tubes by displacement of 5 per cent v/v sulphuric acid for subsequent analysis with a standard "Orsat" apparatus, each sampling time being approximately 2 minutes.

Material

Cribs were constructed of fibreboard or wood, variations being made in the number of pieces used and in the method of stacking. For the wood fires, each stack weighed 500g, varying from 60 - 72 pieces, each ⅝ in sq (± 50 per cent) x

8 in, stacked either 6 or 12 per stage in a criss-cross fashion. For the fibreboard fires the individual pieces measured 6 x 2 x $\frac{1}{2}$ in, in the case of 3- and 9- piece fires, and 11 x 1 x $\frac{1}{2}$ in in the case of all other fires, the weights being 31 and 28g respectively. Details of construction of the fibre board cribs are given in table 1, and photographs of a 9- piece (square type[x]) and 16- piece (long type[y]) crib are given in plates 1 and 2.

Table 1.

Details of Construction of Fibre board Cribs

Type of Crib	No. of Pieces	Total Weight (g)	Shape of Crib
x	3	92	2 parallel pieces on long edge; 3rd piece as roof.
x	9	280	6 parallel pieces on long edge; spanned by 2 parallel pieces at right angles, and top piece central and parallel to the 2 pieces.
x	18	500	11 parallel pieces on edge spanned by 7 parallel pieces at right angles.
x	36	1 000	2 of 18 stacked.
y	2	60	2 parallel pieces on long edge, $\frac{1}{2}$ in apart.
y	4	120	4 parallel pieces on long edge, $\frac{1}{2}$ in apart.
y	8	240	2 of 4 stacked with pieces over gaps; two layers touching.
y	16	470	5 : 6 : 5 pieces on long edge in 3 layers, pieces over gaps, $\frac{1}{2}$ in space between layers.
y	32	940	6 : 7 : 6 : 7 : 6 pieces similar construction to 16.

Procedure

In all cases except for two wood fires (expts. 8 and 9), the cribs were completely assembled before ignition and burned in the box for several minutes before the slit was closed to give the correct aperture. In the case of fibreboard fires of cribs of type y, the crib was fully ignited at one end and the flames allowed to burn back approximately 4 in before the slit was adjusted, while in other cases, the crib was ignited at several points and burning was allowed to continue until about half the surface was judged to be blackened.

The stirrer was operated continuously at approximately 5 rev sec^{-1} in box B, but not continuously or at all in every experiment with box A, as its operation had an undesirable pumping action with respect to gases passing through the ventilation slit.

Gas samples were taken four or six times during and after combustion, and in addition, for box A, a temperature record was kept.

Results

After ignition and adjustment of the slit, the flames either went out immediately leaving smouldering material for narrow slits, or continued until the fuel was exhausted for wide slits, or burned intermittently for intermediate ventilation. A single experiment involving 9 pieces of fibreboard in box A ventilated with a $\frac{1}{4}$ in slit produced a series of explosive ignitions which ejected flame during the course of the combustion.

After extinction of the flame, smouldering continued reducing the fibreboard crib to a mixture of carbon and ash in box A, while in box B, smoking continued for approximately 15 minutes but the blackened area did not increase. Wood fires invariably left considerable quantities of unburnt material in both boxes.

Fibreboard Fires. (a) General

Fig 1 shows the maximum concentrations of carbon dioxide and carbon monoxide and minimum oxygen obtained during combustion of 9 and 18 pieces of fibreboard in box A, together with two single results for 3 and 36 pieces. It was not possible to obtain a reliable sample from a fire of 18 pieces ventilated with a slit of 3 in width as the sampling tube was covered by flames during a considerable part of the test.

While greatest oxygen depletion occured with a slit of nominal zero width, maximum carbon monoxide occured with some ventilation, the larger quantity of fuel requiring a wider slit. Carbon monoxide production was greater with 18 pieces of fibreboard than with 9 for all slit widths, and this together with the two isolated tests with 3 and 36 pieces indicates that increase of fuel causes an increase in carbon monoxide concentration, reaching 6.3 per cent under present conditions. The lower values of carbon monoxide obtained with a 9- piece fire with slits of width greater than $\frac{1}{8}$ in result in all cases from fires which flamed continuously, whereas flaming was absent from the 18- piece fires except the highly ventilated fire omitted as giving unreliable gas samples.

The lowest oxygen figure obtained under these conditions was 5.0 per cent (accompanied by 6.3 per cent carbon monoxide and 11.5 per cent carbon dioxide) for a 36- piece fire with a 1 in slit for ventilation.

Table 2 shows the gas concentrations obtained from fibreboard fires in box B, which was not ventilated. Samples were generally taken at 3, 16, 31 and 61 minutes, and the table shows the maximum values of carbon dioxide and carbon monoxide and minimum values of oxygen. The high value of carbon monoxide in expt. 7 results from a close-packed crib ignited at the centre which would be expected to maintain a higher temperature (see below) than that of expt. 5 with 32 pieces comparatively loosely packed and ignited at one end. The dependence of gas concentrations on size of fire has been obscured by greater dilution with air of the larger fires due to greater contraction of the contents on cooling. Table 3 gives the results of analysis of the first example taken in each case, its time and the duration of flaming after closing the box. These results will not be affected by cooling to the same extent as those in table 2.

(b) Temperature

The maximum temperature attained during 9- piece and 18- piece fibreboard fires with different ventilation is shown in fig 2 and the variation of temperature during the progress of fires involving 9, 18 and 36 pieces of fibreboard is shown in fig 3. The general pattern in each experiment was a period of constant or slowly increasing temperature followed by a generally shorter period in which the temperature rose sharply, though the comparatively quiescent stage is shortened or disappears altogether with decreasing fuel and increasing ventilation.

The maximum values of carbon monoxide obtained during a fire are almost invariably from those samples taken during the sharp increase in temperature and these are generally associated with maximum carbon dioxide and minimum oxygen.

Wood Fires

The results for wood fires are shown in table 4. The maximum carbon monoxide concentration always occurred in the first sample taken, and the temperature always showed a general decrease without the sharp increase associated with fibreboard fires. In expts. 11 and 12 the flame continued to burn for a short period after adjustment of the slit, and the carbon monoxide and dioxide concentrations and oxygen depletions were less.

Table 2.

Extreme Values of Gas Analyses: Fibreboard; No Ventilation

Expt. No.	Pieces of Fibreboard	CO_{max} %	$CO_{2\,max}$ %	$O_{2\,min}$ %
1	2	1.6	5.3	13.9
2	4	1.6	6.5	12.4
3	8	2.8	7.5	10.7
4	16	2.5	6.8	11.6
5	32	2.4	6.5	12.0
6	18	2.6	7.2	10.9
7	36	3.5	7.7	8.9

Table 3.

Initial Sample Gas Analyses: Fibreboard; No Ventilation

Expt. No.	Pieces of Fibreboard	CO_{init} %	$CO_{2\,init}$ %	$O_{2\,init}$ %	Flaming time sec	Time of Sample min
1	2	0.4	3.4	16.6	180	4½
2	4	0.6	5.0	14.7	90	3
3	8	1.1	5.1	14.4	10	2
4	16	2.4	5.0	13.5	30	3
5	32	2.2	6.0	12.3	30	7
6	18	2.5	6.5	10.9	10	3
7	36	3.5	7.7	8.9	30	3

Table 4.

Wood Fires Gas Anaylses (Extreme = initial values) 500g Wood

Expt. No.	Box	Flaming time sec	CO_{max}	$CO_{2\,max}$	$O_{2\,min}$	Pieces per stage	Slit Width in
8	A	0	3.8	11.9	7.0	6	1
9	A	0	4.1	11.6	7.5	6	¼
10	A	0	3.9	11.2	7.5	12	¼
11	A	90	0.5	2.7	18.4	6	⅛
12	B	13	2.0	4.6	15.1	6	0

Discussion

The composition of the atmospheres produced in the containers during combustion was highly toxic (4, 5). A reduction of oxygen concentration to 8 per cent rapidly causes death while a reduction even to 11 per cent causes loss of consciousness which could be equally serious in a practical situation. Loss of efficiency increases with depletion of oxygen and an atmosphere cannot be considered safe when the partial pressure of oxygen has fallen below 14 per cent (4). The lethal concentration of carbon monoxide has been represented by the formula $xt = 1500$ (4) where x is the concentration in parts per million and t the time of exposure in hours, though concentrations of 1 per cent or above cause immediate unconsciousness and death within 3 minutes according to Claudy (5).

Minimum oxygen concentrations have in nearly all tests reached a dangerous level, generally being unable to sustain consciousness, and becoming directly lethal when there was no ventilation or when the fuel was considerably increased. However, owing to the acrid nature of the atmosphere and its temperature of about 300°C, oxygen depletion would not be a significant hazard by comparison, and the safe level of 14 per cent would be reached on dilution with 0.4-1.3 volumes of air at which dilution the gases would still be intolerable because of high temperature and acridity.

Carbon monoxide presents a more serious hazard owing to the fact that the effect is cumulative over the period of time encompassed by a practical situation, and that over a period of 30 minutes, even 0.3 per cent is lethal, so that considerable dilution of the gases would be necessary. With the concentrations of carbon monoxide produced in the present series of tests dilutions of 20-40 volumes must be considered as the minimum dilution required to render the gases nonlethal for a 30 minute exposure (or 7-15 volumes for a 10 minute exposure), and with dilutions of this order and particularly sometime after a fire, the gases could cool sufficiently and have lost a sufficient degree of acridity to render them breathable, but nevertheless still highly dangerous.

Present results together with results obtained by Kingman et al [2] in burning buildings indicate that the maximum concentration of carbon monoxide has not been reached, and that higher concentrations would be expected under suitable conditions, viz., a high temperature of combustion, and ventilation restricted to prevent actual flaming. As these two conditions cannot be realised fully together, it would be expected, as the results indicate (fig. 1), that for a given quantity of fuel, there would be an optimum amount of ventilation above which carbon monoxide would be largely burned to carbon dioxide, and below which, smaller quantities of carbon monoxide would be produced owing to the lower temperature of combustion. The dependence of carbon monoxide concentration on the temperature of combustion has been shown by Boudouard (6) and is illustrated in the present series of fibreboard fires by the following consideration:-

(a) Widening the slit for a given amount of fuel increases the maximum temperature attained. (fig.2) This is accompanied by an initial increase in the carbon monoxide concentration (fig.1).

(b) The sharp increase in temperature during the later stages of combustion (fig.3) is associated with the peak of carbon monoxide production.

The concentration of carbon monoxide and to a lesser extent the depletion of oxygen are dependent on the quantity of fuel burning, so that more extreme values of these might be expected with increase of fuel which would be possible in a larger container. The erratic results obtained with wood fires are possibly due to insufficient wood to maintain burning after adjustment of the slit, and with a larger container, more consistent results might be obtained. Further work in this direction is in hand.

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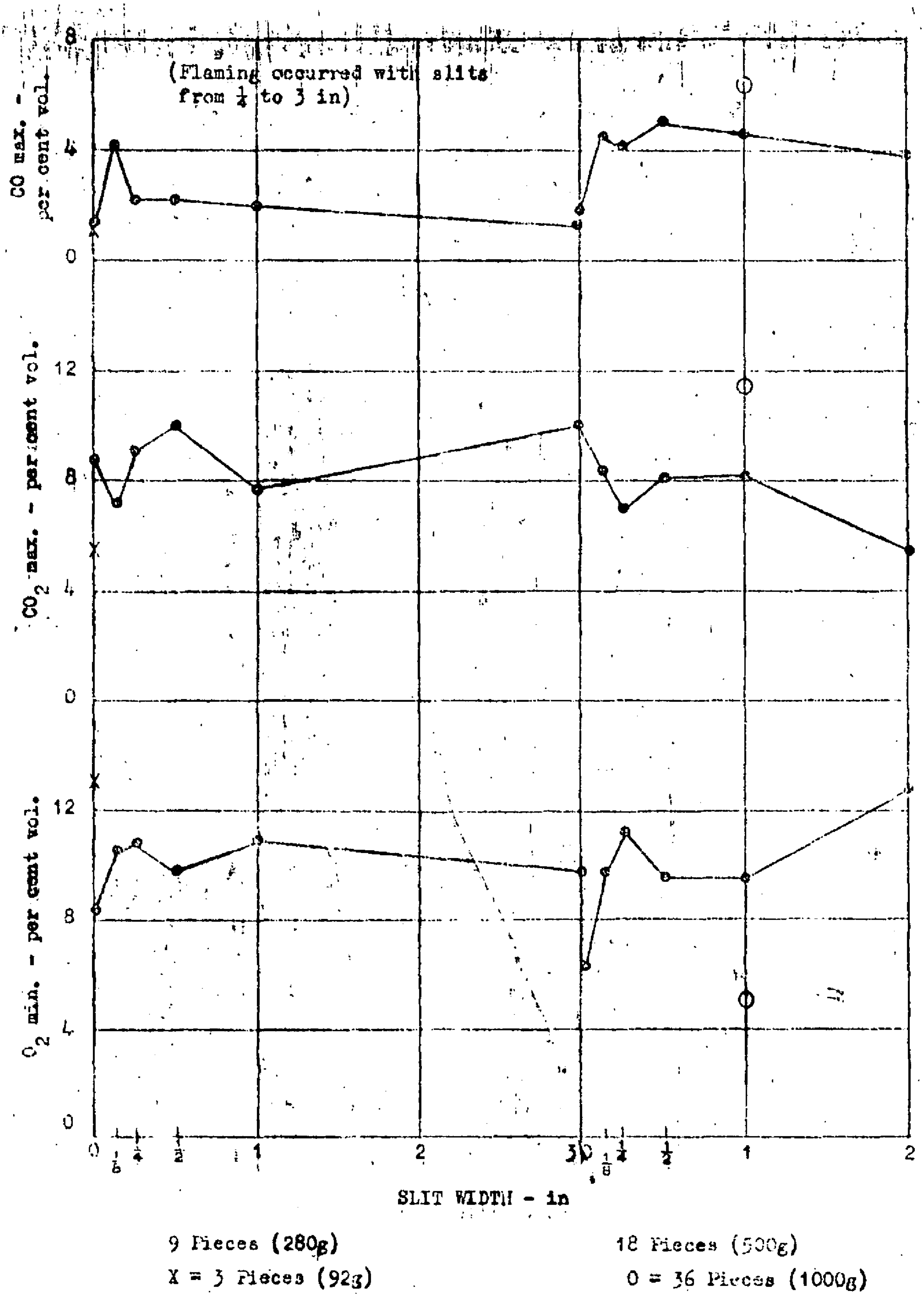

FIG. 1

EXTREME VALUES OF GAS CONCENTRATIONS FOR FIRES WITH DIFFERENT QUANTITIES OF FIBRE BOARD AND DIFFERENT DEGREES OF VENTILATION IN A 1 FT CUBE

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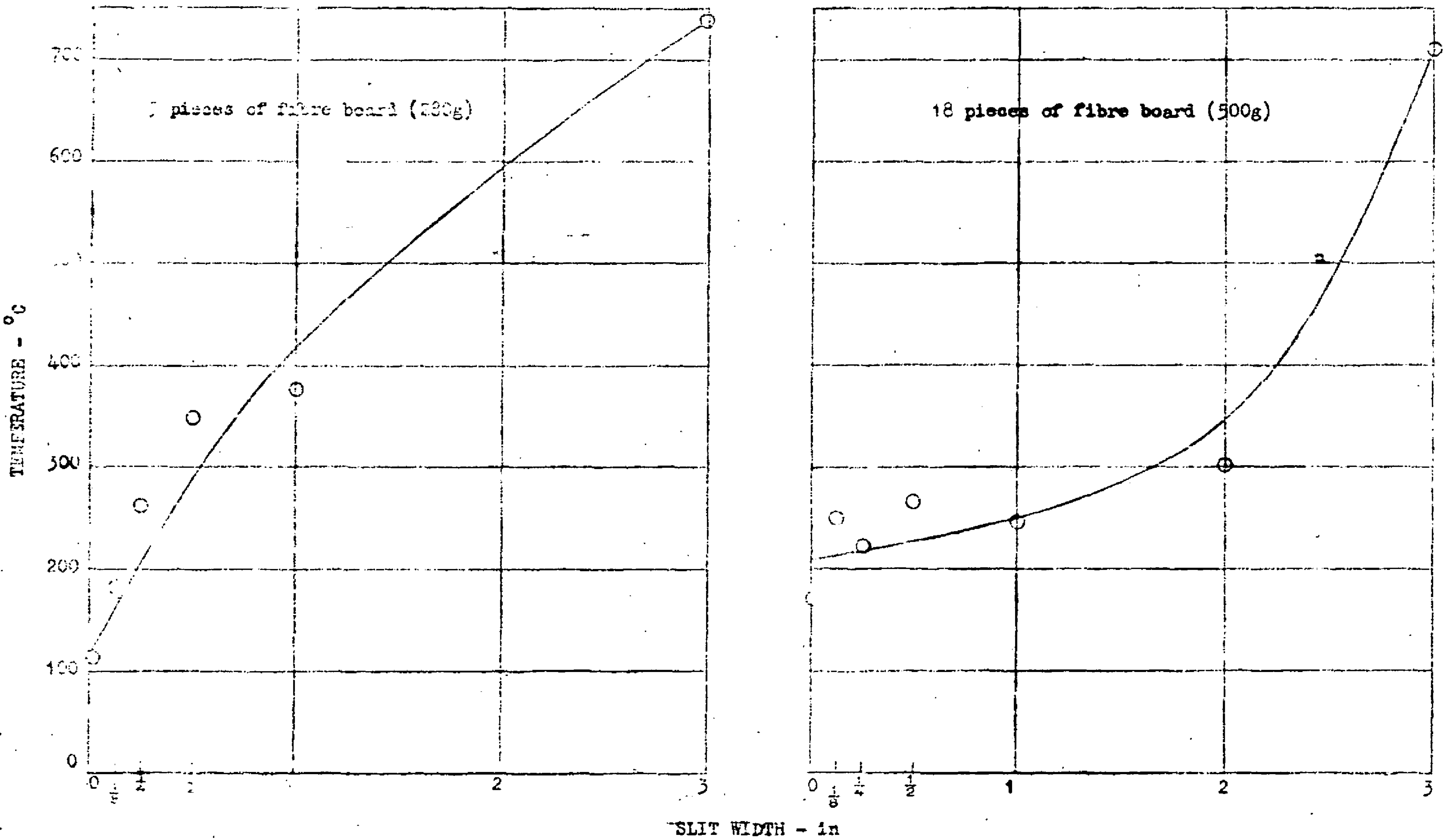

Fig. 2. MAXIMUM TEMPERATURE ATTAINED DURING COMBUSTION OF FIBRE BOARD IN A 1 FT CUBE WITH DIFFERENT DEGREES OF VENTILATION

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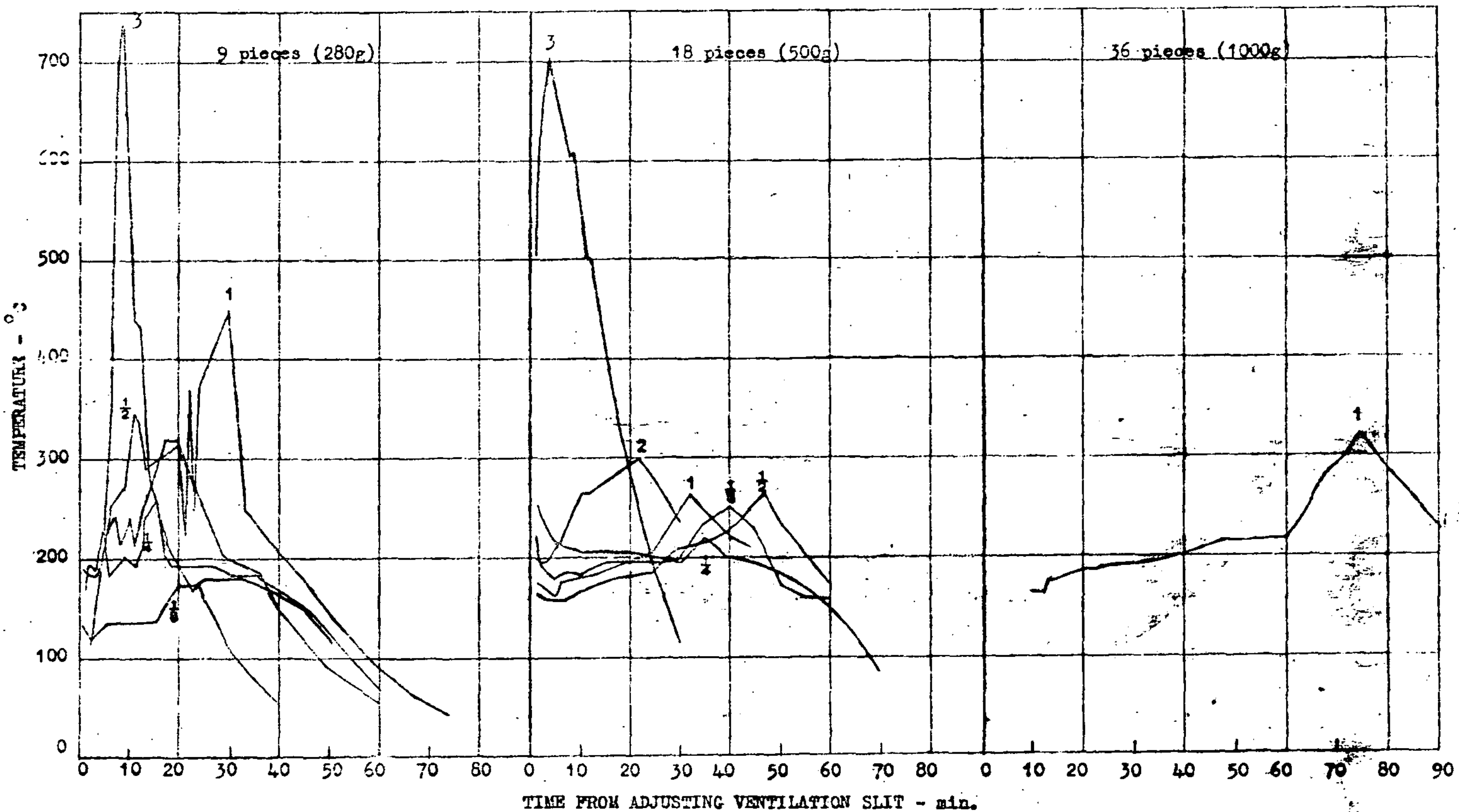

FIG. 3. TEMPERATURE OF ATMOSPHERE IN A 1 FT CUBE DURING COMBUSTION OF FIBRE BOARD
(numbers on graphs refer to slit widths in inches)

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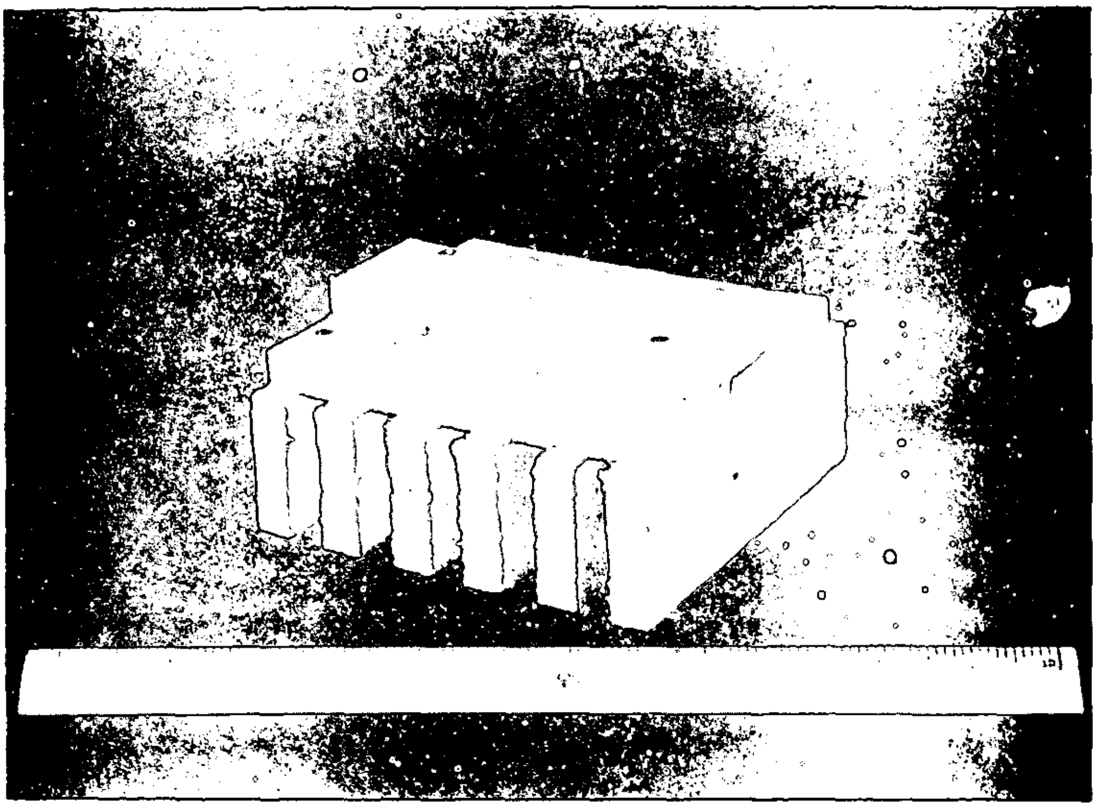
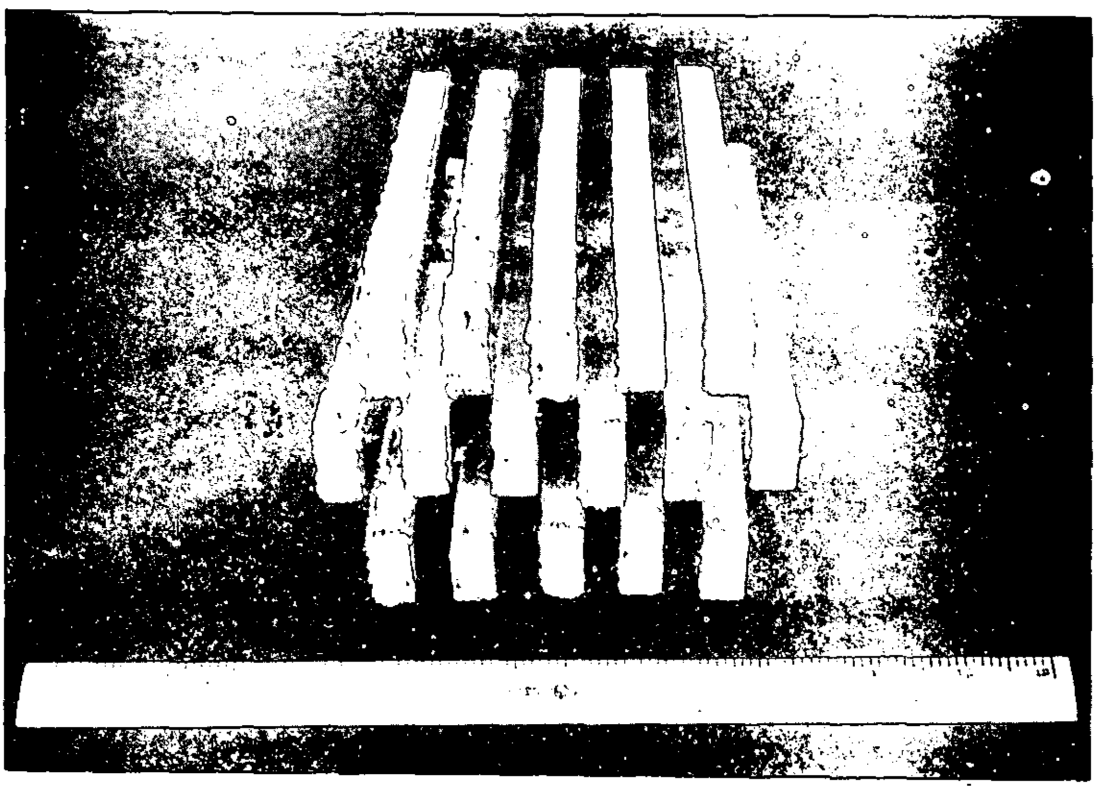


FIBREBOARD CRIB (SQUARE TYPE)
PLATE 1



FIBREBOARD CRIB (LONG TYPE)
PLATE 2