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SMOKE AND TOXIC GASES FROM BURNING BUILDING MATERIALS

1. A TEST RIG FOR LARGE SCALE FIRES

by

G W V Stark and P Field

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SUMMARY

A test rig, consisting of a room communicating with a corridor, has been constructed for examining the products of combustion arising from fires in the compartment or corridor. Tests with wood fuel have shown that thermally reproducible fires are obtained from a given weight of fuel in the compartment and a given arrangement of ventilation.

Under the conditions of ventilation used, the smoke produced from relatively small loads of wood (14.5 to 29 kg/m^2) was sufficiently dense to impede escape, even when the smoke and fire gases were diluted with cool air to a temperature that could be borne for a short time during which an attempt to escape could be made.

The concentration of the principal toxic gas, carbon monoxide, in the fire gases is primarily dependent upon the weight of the fire load of wood. Dilution of the fire gases with cool air to a temperature that could be borne for a short time during escape produced atmospheres with fire gases from the greater weight of wood that were hazardous for short exposure, whereas those from the lesser weights were not so.

The production of carbon monoxide from the tests with the greatest degree of ventilation examined rose and fell simply during fires, whereas tests with the lesser degrees of ventilation resulted in periodic variations in concentration. The former test condition is more amenable to calculations concerning toxic gas evolution.

Department of the Environment and Fire Offices' Committee
Joint Fire Research Organization

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1. INTRODUCTION

The risk of fire in buildings created by the use of combustible materials in the structure or contents has long been recognised. While the use of traditional materials such as wood, cotton and wool has been accepted, with some safeguards as to the disposition of wood in the structure of a building[1], the introduction of other organic materials, in the main synthetic plastics, into a building may materially alter the risk to occupants and fire-fighters from the rate of development of the fire and the production of smoke and toxic gases during the fire [2,3].

Although small scale tests may be adequate to indicate the contribution to the fire by combustible materials[4], they may not always permit assessment of the production of smoke and toxic gases. Some tests in both large and small scale compartments suggested that the generation of the toxic gas, carbon monoxide, from wood fires could be correlated with a fair degree of accuracy for a wide range of dimensions up to full scale[5]. However, the evolution of other toxic gases from plastics could not be similarly correlated[6].

A large scale test rig was therefore constructed, which could be used to simulate many of the conditions under which a fire could occur, with appropriate instrumentation for the measurement of; the temperature of the fire gases, their composition, and the smoke produced during fires. The present note described the construction of the test rig and the instrumentation, and includes the results of a series of fire tests using wood fuel.

2. EXPERIMENTAL

2.1. <u>Test rig</u>

The test rig comprises a compartment and corridor, Figs 1 and 2; the compartment is of internal dimensions 3 m x 3 m x 2.4 m high. One side of the compartment communicates with a corridor 12.6 m long, 1.3 m wide and 2.4 m high. The compartment and corridor are constructed from panels of reinforced aerated concrete, 0.6 m wide, supported by an external steel frame. The panels of the compartment are 150 mm thick, and those of the corridor 100 mm thick. The use of an external support frame protects the steel as far as possible from fires within the structure.

The aerated concrete panels are protected from the effects of heat on their inner surfaces by originally a low density rendering of gypsum plaster and vermiculite, this has been replaced by a rendering of lime, cement and verniculite to avoid the production of sulphur containing gases from the dissociation of gypsum plaster at high temperatures. Although these gases did not interfere with measurements in the present tests, they could affect the analysis of gases arising from other combustible materials, particularly those containing sulphur.

The structure of the supporting frame is indicated in Fig.3. This form of construction of fire compartments is relatively cheap, and easy to maintain. Damaged panels can be replaced readily, and replacement and repair of the rendering present no difficulties.

The compartment can be ventilated in several ways, by partial or total removal of individual panels. For the tests reported in this note the sole means of ventilation of the compartment was an opening from floor to ceiling, of predetermined width, between the compartment and the corridor. Thus the ventilation air entered, and fire gases and smoke left, the compartment via the corridor. For the reported series of fire tests, the open end of the corridor was left unrestricted.

The test rig was built in a large open plan laboratory, of dimensions 40 m x 15 m x 12 m high, so that tests were unaffected by wind and weather. The laboratory could be ventilated to remove toxic gases and smoke through an openable section of the roof.

2.2. Gas Analysis

Samples of gas were drawn from two points, namely, at the opening between the compartment and corridor, and at a point 10 m from the compartment opening, close to the open end of the corridor. For this purpose, internally lacquered stainless steel tubes, 6 mm internal diameter were inserted through the roof panels and extended 150 mm below the ceiling level. Several tubes were installed at each site to allow more than one sample to be withdrawn. One tube at each sampling point was connected by silicone rubber tubing to a series of gas pipettes via a glass-wool filled filter tube and a water filled Drechsel bottle (to remove tars and highly soluble gases). Fire gases were drawn at a metered rate of 500 ml/min through this system by a pump, via a protective drying tube packed with granular anhydrous calcium chloride. Condensation on, and subsequent reaction with, the lacquered stainless steel tube was minimised by heating the tube resistively to about 150°. Individual gas pipettes were isolated at measured intervals during tests, the contents being analysed subsequently by gas-solid chromatography for the gases: oxygen, nitrogen, carbon dioxide and carbon monoxide.

The other tubes at each site were for the collection and analysis of samples of fire gases other than those mentioned above, as and when this might prove necessary.

2.3. Temperature Measurement

Thermocouples were installed through the ceiling of the compartment and corridor at the opening between the compartment and corridor, and at 2 m intervals along the corridor, with the thermocouple junctions 150 mm below the ceiling. For some tests further thermocouples were installed at the opening between compartment and corridor at different heights, to determine the position of the neutral plane between the fire gases and the air feeding the fire. Another thermocouple was installed at the open end of the corridor 150 mm above the floor to measure the temperature of air as it entered the corridor. The output from the thermocouples was registered during each test by a multipoint potentiometric recorder.

2.4. Smoke measurement

Smoke density was determined from measurements of the attenuation of light falling on a photocell after passing through the smoke. Two arrangements of light source and photocell were used during the tests. In the first, the light source was placed at ceiling level, and the photocell at floor level in the corridor, 10 m from the opening between compartment and corridor; in the second, the light source was placed on the roof of the corridor at the open end and the photocell fixed rigidly 5 m above the ground and 10 m from the open end of the corridor, as shown in Fig.4. Thus in each position the full depth of the issuing smoke was traversed by the light beam. The first method of measurement was replaced by the second because it was found that the light source was affected by the deposition of soot on the lens system, even when a purging stream of nitrogen was used.

A quartz-halogen lamp was used as the light source, because such lamps had been found to give a consistent output for long periods. A 75 mm thick matt metal honeycomb with approximately 6 mm orifices was placed in front of the photocell system to minimuse the entry of stray light from sources other than the quartz-halogen lamp. The output of the photocell was registered by a potentiometric chart recorder.

The attenuation of a beam of light by a particulate suspension (smoke) is given by

$$I = I_o e^{-knL} \qquad (1)$$

where I_o = unattenuated light flux at photocell (in absence of smoke)
I = attenuated light flux at photocell (in presence of smoke)
L = path length through smoke
n = number of particles in unit volume
k = an extinction coefficient

Optical density as used in this note is defined as the logarithm, base 10, of the ratio of incident to attenuated light flux, and is thus directly proportional to the path length L through the smoke, and the particle density n of the smoke. Because the complete depth of the smoke plume is traversed by the light beam, any expansion of the smoke plume along the axis of the light beam, as could occur in the corridor will not affect the product Ln, but expansion at right angles to the beam will proportionally reduce the value of n. Also, for smoke with a uniform particle density n, deviation of the beam from a direction normal to the plume by an angle ϕ will produce an apparent density of approximately $n/\cos\phi$. Tests in which optical densities measured vertically within the corridor were compared with those measured viz the arrangement in Fig.4, showed that this last effect was small and could be neglected, and only a linear correction was necessary for the lateral expansion of the smoke plume at the point of measurement. All optical densities in this note are expressed as the optical density within the corridor 10 m from the compartment opening making the above correction from measurements made on the emergent plume.

The optical density over unit path length permits comparisons to be made of the immediate obscuration of vision at given times, between different fire conditions and fire loads[3].

Because the optical density is directly proportional to n, an estimate can be made of the amount of smoke P evolved during the time of burning of a fire, from

$$P = \int_0^t SD_m A\,dt \qquad (2)$$

where S = exit speed of smoke , m/min

D_m = optical density for unit path length of smoke, m

A = area of cross section of smoke plume, m^2

t = time of burning, min

The value of S can be calculated from the rate of entry of air into the corridor (see below) and the temperature of the fire gases at the point of measurement, 10 m from the opening between compartment and corridor. Because of the mass balance between emerging fire gases and entering air, the densities of which can be taken as the same, the volume rates of flow at a given temperature will be the same for entering air and emerging fire gases[5].

2.5. Rate of entry of air

The volume rate of entry of air into the corridor was calculated from the speed of entry of air, measured by a remote recording anemometer, and the area of cross section of the corridor from the floor to the neutral plane. Preliminary experiments had shown that the speed of entry was very uniform, except for positions close to the walls and floor and neutral plane, separating exiting fire gases and entering air. The anemometer was placed at the centre of the corridor and 500 mm above the floor.

2.6. Rate of evolution of fire gases

The rate of evolution of fire gases was determined at the opening between the compartment and corridor and at the open end of the corridor. Values for the compartment opening were calculated from the buoyancy of the fire gases and the size of the opening[4,7], whereas values for the open end of the corridor were calculated from the rate of flow of air into the corridor. Values were also calculated from the buoyancy of fire gases at that site to check the validity of measurement.

2.7. Ventilation of fire compartment

The main group of fire tests was carried out with two sizes of ventilation opening between the compartment and the corridor, one of width 240 mm and the other 700mm. These openings were chosen as representing a partially or fully opened door to a room in a dwelling. A test was also carried out with the width of the ventilation opening restricted to 80 mm, for comparison with earlier tests[4].

2.8. Fire Load

The main group of tests were made with wood fuel in the form of a crib, 1.5 m square section, built in the middle of the floor of the compartment, from 1.5 m long sticks of 50 mm square cross section, with a 1 : 4 spacing between the sticks (50 mm stick, 200 mm space) with alternating layers at right angles to each other. The spacing was chosen as representative of the combustible contents of a lightly furnished room[8]. One test was made at 1 : 1 spacing for comparison with a less readily combustible fuel load. Two further tests were made with the wood fuel present as a wall lining of matching together with a 1 : 4 spaced crib. For this test the crib was constructed against the angle between two walls to ensure rapid ignition of the wall cladding.

Two weights of crib were used, namely 120.5 and 241 kg, giving fire loads of 14.5 and 20 kg/m^2 (3 and 6 lb/ft^2) giving crib heights of 400 and 800 mm at 1 : 4 spacing. The tests with the walls lined with matching were made with the higher fire load, which consisted of 137.5 kg of matching and a 103.5 kg crib. The area of wall lining was 26 m^2 and the crib height, 350 mm. All fires were ignited by 1 kg of wood wool, laid on the floor in a narrow channel across the centre of the crib, in which was buried a stretched 1 kw spiral electrical element. Ignition was brought about by passing mains current through the element for one minute

Conditions of test precluded precise conditioning of the wood for these tests. However, the moisture content of the wood was reduced to 12 per cent or less by an electric fan-assisted convection heater prior to test. Care was taken to reduce the temperature in the compartment to less than 25^oC before igniting the fuel. The effect of moisture content of the wood on the development of the fire was examined in a few tests.

2.9. Observation

The development of the fire in the compartment could be observed through a protected port in the wall of the corridor opposite the opening between compartment and corridor. Additional observation was made from the open end of the corridor during tests. At the end of each test the corridor and compartment were entered to examine the amount and nature of any residues. These observations were used to augment the measurements made during tests.

2.10. Design of tests

The main programme consisted of tests of two fire loads at two dimensions of vent, and an alternative distribution of fire loads at two dimensions of vent. To these were added a test at closer spacing of one fire load of crib and a test at a more restricted vent of one fire load of crib. A randomised block arrangement of tests was not practicable because of the difficulties arising from the construction of different widths of vent, and the use of the apparatus for other test programmes. However, as the test rig was constructed in a large open plan heated compartment, external effects producing day to day variations were likely to have been small.

3. RESULTS

3.1. Effect of crib spacing

The Fire Survey Team of the Fire Research Station have investigated incidents in which modern lightly furnished rooms have become fully involved in fire within 5 min of ignition, and it was desired to reproduce these conditions of fire development. The temperature attained by the gases leaving the compartment for tests of 1 : 1 and 1 : 4 spaced wood cribs weighing 120.5 kg is plotted against time of burning in Fig.5. From the number of tests at 1 : 4 spacing two have been plotted in the figure, illustrating the reproducibility of burning when the moisture content of the wood was 12 per cent or less. The tests at 1 : 4 spacing gave the rapidity of combustion considered appropriate and this spacing was used for the main programme of tests.

3.2. Effect of moisture content of the wood

The moisture content of the wood cribs was estimated from the measurements made with a resistance probe moisture meter. Ignition of the crib was not always obtained at wood moisture contents of 15 per cent or more, and was delayed at values between 13 and 15 per cent. The temperature of the fire gases at the opening between compartment and corridor for tests with cribs of wood at moisture contents of less than 12 per cent and more than 13 per cent are plotted in Fig.6, from which it can be seen that the principal effect of the higher moisture content was to reduce the rate of rise of temperature.

3.3. Main test programme

The results obtained in the main programme are summarised in Table 1. The effect of fire load and of fire load distribution, and of vent width on individual parameters is described below. Where more than one test was made for a given set of conditions, the range of values and

Table 1
Summarised results of fire tests

Test No		1	2	3	4	5	6	7
Wood kg	Crib	120.5	120.5	241	103.5	241	103.5	241
	Wall				137.5		137.5	
Vent width, mm		240	700	240	240	700	700	80
Max. fire Gas Temp. °C +	Vent	835–870(852)	880–930(909)	940–960(950)	960	1080–1100(1090)	1070	860
	Corr	300	400–435(418)	380–420(400)	570	550–635(592)	680	190
Time of burning min.		30	20	40	40	30	30	75*
Min. O_2, % Vent		2.3	2.8	8.2	6.8	5.0	7.2	4.3
Max CO_2, % Vent		18.8	17.7	14.2	12.9	13.7	12.1	16.5
Max CO, % Vent		0.2	1.1	3.5	4.8	6.0	2.4	3.5
Total CO kg Vent		1.9	4.4	12.2	19.6	50.6	16.2	8.1
Min O_2, % Corr.		14.5	12.2	11.9	9.2	7.0	7.1	14.7
Max CO_2, % Corr.		7.0	9.1	8.2	11.4	14.1	13.1	5.8
Max CO, % Corr.		0.8	0.3	2.7	1.1	1.6	1.3	1.7
Smoke	Max Opt.D.	2	2.5	4.0	2.5	3.2	4.7	1.2
	P	41	77	106	217	243	274	47

Abbreviations:

- Vent = opening from compartment to corridor
- Corr = open end of corridor (10 m from compartment opening)
- Max = maximum recorded value
- Min = minimum recorded value
- O_2 = oxygen content of fire gases
- CO_2 = carbon dioxide content of fire gases
- CO = carbon monoxide content of fire gases
- Opt.D = optical density
- P = total particulate matter, Eqn.1
- Total CO = amount of carbon monoxide released during test
- * = Burning continued for more than 120 min
- + = Mean values in parenthesis

their mean is given in the Table.

3.3.1. Temperature of fire gases

The maximum value of the temperatures of the fire gases measured at the opening between the compartment and corridor, and at the end of the corridor, 10 m from the compartment opening, are given in Table 1. When more than one test was made, the range and mean values are given in the Table. A simple analysis of variance summarised in the Appendix on the individual tests indicated that the difference between test conditions was highly significant when compared with the difference within test conditions. Typical records from individualtests are given in Fig 7 for the temperatures at different heights in the opening between compartment and corridor (the hightemperatures registered by the lowest thermocouples were due to radiation from the fire), and in Fig 8 for temperatures at 2 m intervals along the corridor. Curves of the maximum values of temperature measured at the vent are plotted in Fig 9. Fig 7 and 9 indicate that the neutral plane between the inflowing air and the outflowing fire gases occurred at about 1400 mm below the ceiling of the test rig for both vent widths of 240 and 700 mm; this was confirmed by observations of the smokey fire gases from the open end of the corridor. Curves of the maximum temperatures recorded down the corridor are plotted in Fig.10; these indicate that the fall in fire gas temperature was fairly steady from 2 m from the compartment vent to the open end of the corridor, but that between the compartment vent and 2 m from it along the corridor, the rate of fall of temperature was much greater, and had some dependence on the width of the compartment opening tests 3,5 and 7, and on the fire load, tests 2 and 5. Circulation of flame and gases in vortices could be seen over this distance, but such disturbances were not apparent further from the compartment opening. The vortices appeared to be generated by the change in the direction of flow of the fire gases through a right angle on passing from the compartment into the corridor.

3.3.2. Time of burning

Wood in a fire in a compartment burns in three stages as indicated in Figs 7 and 8. (A) firstly there is a short period between ignition and fully established burning; this is followed by (B) steady burning with bright yellow flames, which then changes to (C) burning with bluish transparent flames when the bulk of the wood has been converted to carbonaceous residues. The first stage occurs over the time for the complete involvement of the crib in flaming combustion; the second or main stage occurs when flaming combustion is fully established i.e. when volatiles are produced freely from all surfaces by the pyrolysis of wood, and the third stage occurs over the period when the carbonaceous residues are converted to carbon monoxide which then burns. The times of burning given in Table 1 approximate to the first two stages of burning, and were taken as the times from ignition to the time when the initial sharp fall in temperature gave place to a lower rate of decrease in temperature, similar to that observed in cooling. Although combustion continued after the recorded time of burning, the thermal output from the carbonaceous residue was small.

The time of burning increased with increasing fire load, and with decreasing vent width. At the smallest vent width examined, 80 mm, more of the wood appeared to be left as carbonaceous residues, and the third stage of burning continued for a longer time than for tests at the larger widths of vent.

3.3.3. Production of fire gases

Minimum concentrations of oxygen and maximum concentrations of carbon dioxide and carbon monoxide measured in the fire gases in tests are given in Figs 11-16. Figs,11,13 and 15 present results for the fire gases at the opening between compartment and corridor, and Figs 12, 14 and 16 for the fire gases at the open end of the corridor.

Broadly speaking, corresponding curves for oxygen and carbon dioxide concentrations at the two measuring sites, Figs 11 and 12, and 13 and 14, have the same shape, but the concentrations measured at the open end of the corridor show a lesser variation with time than those measured at the opening between compartment and corridor. Earlier small scale tests had shown that fire gases escaping from a compartment vent were uniform in composition over the area of vent they occupied[9]. This uniformity of composition has been assumed to apply in the present tests. However, measurements made at the open end of the corridor in connection with other tests conducted in the test rig indicated a gradient in fire gas composition at the open end of the corridor, the oxygen content increasing, and the carbon dioxide and carbon monoxide contents decreasing, as the distance of the sampling point below the ceiling approached the neutral plane between incoming air and outgoing fire gases. Entrainment of air into the outgoing fire gases as they passed through the corridor would be expected, but the gradient in gas composition and in temperature at the sampling point in the corridor will reduce the accuracy of measurements at this side but a similar significance is shown for 'between test' variation as is shown by the temperatures at the compartment opening.

Certain general conclusion can be drawn.

a) smaller vent openings, Tests 1,3,4 and 7 produce fluctuations of gas composition indicative of periodic burning. Only slight indications were given of such variations in the records of temperature with time, see for example Fig 8.

b) the widest opening, tests 2,5 & 6 didn't show such fluctuations of gas composition.

c) the lowest concentration of carbon monoxide recorded at the opening between compartment and corridor was given by the smaller fire load, tests 1 and 2.

d) the highest concentration of carbon dioxide at the opening between compartment and corridor was also recorded for the smaller fire load, tests 1 and 2.

e) the highest concentration of carbon monoxide at the opening between compartment and corridor was given in test 5, for which the rate of burning was the highest. This test also gave the highest total emission of carbon monoxide.

Broadly similar behaviour was found at the open end of the corridor. Some of the differences in the order of values between this site and the opening between compartment and corridor arose because of the continued combustion of gases from the compartment in the corridor.

The single test at the smallest vent width, 80 mm (test 7), exhibited behaviour differing from the remaining tests. Although the extremes of values of fire gas composition were recorded during the 75 min of regular sampling, combustion continued for more than 120 min, when the oxygen content had increased to

16.8 per cent, the carbon dioxide content had decreased to 3.2 per cent, and the carbon monoxide content to 0.16 per cent (Fig 14). The value for the total emission of carbon monoxide, entered in Table 1 is therefore a minimum value.

3.3.4. <u>Rate of production of fire gases. Air speed</u>

Values of the rate of flow of fire gases at the opening between the compartment and corridor for the three widths of vent, 80 mm, 240 mm and 700 mm, calculated from the buoyancy of the fire gases[5], are plotted in Fig 17, curves 1,2 and 3. Curve 4 is plotted in the same way for the open end of the corridor, and curve 5, also for the open end of the corridor, is plotted from the speed of entry of air into the corridor during tests. A common curve of air speed against temperature of fire gases, used for this calculation, was drawn by eye from many individual points of velocity against temperature of fire gases taken from the results for each test. This curve is reproduced in Fig 18, with individual points from one test, selected at random, plotted in the Figure. The area occupied by entering air under the neutral plane, multiplied by the air speed at the temperature of interest, is the rate of entry of air at that temperature. As the position of the neutral plane remained virtually constant, at 1 m below the ceiling, for all tests except No 7, when it was about 700 - 800 mm below the ceiling, and during the first minute or so of each test, curve 5 was drawn assuming a constant position of the neutral plane 1 m below the ceiling.

The product of the rate of flow of fire gases and the concentration of carbon monoxide, integrated over the time of test, approximates to the total yield of carbon monoxide during the test. This quantity is given as the total CO in Table 1. A wide range of values for total carbon monoxide were obtained, the highest value being given by test 5 with the larger load of wood and the largest vent, and the smallest with the smaller fire load and the smaller vent width. The rates of combustion in these tests were the highest and lowest respectively for the main programme of tests. The apportioning of some of the fire load of wood on the walls reduced the concentration and total yield of carbon monoxide for tests at the larger vent size, but increased it somewhat at the smaller vent size (compare tests 5 and 6, and 3 and 4).

Although luminous flaming combustion in test 7 (larger fire load at 80 mm vent width) stopped after about 75 min, combustion with non-luminous flames and the production of carbon monoxide continued for more than 120 min when the last gas samples were withdrawn. However, the total amount of carbon monoxide was lower than the amounts found for the fires of shorter duration at the larger vent widths of the main test programme.

No calculations have been attempted for the total amounts of carbon monoxide for the sampling site at the open end of the corridor, because of the observed concentration gradient of the combustion gases, referred to previously.

3.3.5. Smoke

Because the whole depth of the smoke plume was used for the measurement of the optical density of smoke, and the optical density is dependent primarily upon the number of smoke particles intercepted by the light beam, and not their distribution, gradients in the plume do not affect the measurement.

The calculated maximum optical densities per metre path length are given in Table 1. These values correspond to smoke in the corridor, 10 m from the opening between compartment and corridor, at which the depth of the smoke plume for all tests except No 7 was about 1 m. The optical density was greater for the greater fire load, but the effect of fire load on optical density was not consistent. The difference in optical density between tests at vent widths of 240 and 700 mm was small. The values of total amounts of smoke, P, show a strong dependence on ventilation, values being higher for the larger degrees of ventilation, at a given load and on the fire load, values being higher for the higher fire load. The presence of part of the fire load as a wall lining increased the total amount of smoke, but the maximum values showed no consistent variations for the two distributions of fire load.

4. DISCUSSION

4.1. Temperature, thermal balance

The thermal conductivity of the walls of the test rig is about 0.16 W/m$^{\circ}$C, and hence U values for the walls of the compartment and corridor are about 0.9 and 1.3 W/m^2 °C. The thermal outputs of the wood fires in the reported tests are dependent upon the fire load and the heat of combustion of the wood, and the time of burning. Assuming that only about 70 per cent of the fuel load was consumed to allow for free moisture in the fuel and the carbonaceous residues left at the end of the recorded time of burning, the thermal outputs calculated from the heat of combustion of wood lie between 0.7 and 1.4 MW. Thus the thermal losses through the walls of the compartment, 36 kW, taking 1000°C as the temperature of the fire gases, lie between 2 and 5 per cent, assuming no losses through the floor. Thermal losses from the thermal capacity of the walls and ceiling of the compartment, taking the specific heat of the structure as 0.16, are less than 1/1000 of the thermal output. Because of the small proportion of heat loss through the walls from the thermal output for the fires, and the constant rate of flow of fire gases from the compartment, the temperature of the fire gases leaving the compartment will depend upon the rate of heat release during combustion. Thus integration of fire gas temperature at the compartment over the time of burning would give an estimate of the total heat release from the fuel consumed.

Integration of the fire gas temperature from the time of ignition to the time when the temperature of the fire gases had fallen to 300°C supported the above conclusion. Duplicate runs of test 1 gave values of 8840 and 8905 in arbitrary units and the test of the same weight of wood crib at 1 : 1 crib spacing have a value of 8740, while test 3 at the same ventilation and twice the fire load, gave a value of 15630.

The thermal output for the smaller fire load, 0.7 MW, although based upon 70 per cent of the thermal output for dry wood, makes no allowance for incomplete combustion. The calculated removal of heat, by the fire gases of specific heat 0.25 leaving the compartment at about 20 Sm^3/min, at a mean temperature of 600°C for 35 min (Test 1), and through the compartment walls and ceiling at a U value of 0.9 W/m^2 °C, is about 0.3 MW. The calculated value of heat removal by the fire gases is thus of the same order as the estimate of heat output by the fuel.

The above calculations, together with the evidence of reproducibility of fire gas temperature and time of burning show that the test rig, erected as it is in a large draught-free enclosure, can provide the reproducible conditions needed for the study of the behaviour and products of combustion from combustible materials in fires in buildings.

The method used for ignition, in which a small amount of priming material consistent with those likely to be found in practice, allows the initial rate of development of a fire to be determined. As ignition of the priming fuel takes place only a few seconds after initiating the heating of the resistance wire, the initial rate of development of the fire (Section A in Figs 6 and 7) is therefore typical of that of the fuel in a fire incident when flaming combustion first occurs following ignition from a small flaming source or from the conversion of smouldering to flaming combustion of a priming fuel such as cellulosic material.

4.2. Carbon monoxide

Because of the thermally reproducible behaviour of the test rig, it might be expected that the release of products of combustion from a fire in the test rig would be consistently reproduced in tests under identical conditions of ventilation and fire load. Earlier small scale tests had provided a relation Fig 19 between the maximum concentration of carbon monoxide in fire gases and the rate of flow of fire gases and the fire load represented by the parameter $AH^{\frac{1}{2}}W^{-1}$, where A is the area of the ventilation opening and H its height, and W is the weight of fuel[4]. An earlier examination of results for large scale tests had shown reasonable agreement for values of $AH^{\frac{1}{2}}W^{-1}$ of less than about 5×10^{-3}.[5] The present test results, plotted as points in Fig. 19 show appreciable scatter at values of $AH^{\frac{1}{2}}W^{-1}$ above 4×10^{-3}. It is therefore concluded that the relationship does not apply to the condition of test examined here.

The results given in Table 1 indicate that the generation of fire gases with a high content of carbon monoxide was favoured by high temperatures in the fire compartment, by higher fire loads and by a lower degree of ventilation. Too few results are available for a statistical analysis of variance, but the indications are that the fire load was the most important factor. The variable nature of wood, and its hygroscopic properties would be expected to contribute to some variation in combustion products.

The mixing of some of the air with the fire gases on their counter-current passage through the corridor would be expected to lead to some vertical variation in gas composition as has been mentioned. This effect, together with combustion outside the fire compartment because flames were often seen for some distance down the corridor, will result in the composition of the fire gases at the open end of the corridor showing differences in measured composition from that of fires gases leaving the compartment. Dilution of the fire gases with cool air to a temperature that could be borne during escape (120°C) would produce hazardous atmospheres for all tests except Nos 1, 2 and 6, from one or other the fire gases from compartment opening or from the open end of the corridor. Thus except for test 6, all tests at the higher fire load would produce cooled atmospheres hazardous for short term exposure.

4.3. Smoke

The results presented in Table 1 show no simple relationship between the fire load, ventilation, or the distribution of fuel, on the maximum optical density of the smoke. The reason for this is not understood, but may be associated with factors such as the moisture content of the wood, (because water vapour is known to reduce the density of some smokes[12]), or the turbulence of combustion products in the fire compartment, (because recirculation of smoke through the flame zone could result in its partial or complete consumption).

The effect of test conditions on the total amount of smoke P is, however, well indicated. The amount of smoke increased with fire load and also with increased ventilation, and was greater when part of the fire load was present as a wall lining. If the area of the exposed surface of wood were the sole controlling factor, then the smoke from the higher fire load in crib form would be about twice that of the lower fire load, and that from the higher fire load as crib and wall lining would be 2½ times that of the lower fire load. However, although the values of P increased in the expected order for the three fire loads, the increase was greater than that predicted, indicating that other factors were also affecting the production of smoke.

It is however evident from the tests that wood fuel can produce very dense smoke for a large part of the period of flaming combustion. If, for example, the fire gases leaving the corridor were diluted with air to about 150°, a temperature which could be borne for a short period during escape[10], the maxima of optical densities per metre path length would range from 0.6 to 1.4, with an average value of 0.9. Under these conditions, visibility would be restricted to from 1 to 2 m, presenting a handicap to escape over a distance of 5 m, regarded as presenting a maxima safe distance for escape[11].

5. CONCLUSIONS

5.1. The test rig

The test rig provides a reproducible thermal environment from a fire at a given condition of ventilation and fire load.

5.2. Wood fuel in the test rig

Conditioning of timber for fire loads needs to be consistent. Moisture contents in excess of 12 per cent may lead to difficulties in ignition, and delay the development of burning. Further tests are needed to examine the effects of moisture content on the production of smoke and toxic gases.

A greater number of tests than those reported are needed for statistical analyses of the effects of ventilation and fire load on the production of smoke and toxic gases, and on fire development as indicated by the temperature of the fire gases. (A combined analysis of these and other tests with additional PVC fuel will be presented in a later paper).

5.3. Fire gases

The test rig and sampling systems are effective for the measurement of the properties of fire gases issuing from the compartment. For the open end of the corridor rates of flow of fire gases calculated from their buoyancy agreed well with rates calculated from anemometric velocity measurements. The rates calculated from buoyancy for the opening between compartment and corridor are therefore considered reasonable.

Variations in the composition of fire gases between different weights of wood fuel and its distribution and different degrees of ventilation are complex.

These may be resolved by experiemnts with more consistent wood fuels of known moisture content and by choice of suitable experimental conditions. For example, conditions resulting in periodic fluctuations (tests 1, 3 and 4) should be avoided if possible in favour of conditions resulting in simple variations during burning.

5.4. Smoke

The amount and density of the smoke produced increase with the amount of fuel burned and the degree of ventilation. The variation in optical density between tests indicates that factors other than these may also operate. The amount of smoke produced, P, showed a more consistent relationships with fire load and ventilation than did the maximum optical density.

The amount of smoke produced in these tests, which were of relatively light fire load densities, were sufficient to hinder escape even when diluted to temperatures making them bearable during escape.

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APPENDIX

Simple analysis of variance. Temperature of fire gases

Temperature at compartment opening

Data

Test	Fuel kg	Vent width mm	Temperature
1	121	240	835, 870
2	121	700	900, 925, 930, 880
3	241	240	960, 940
4	241	240	960
5	241	700	1080, 1100
6	241	700	1070
7	241	80	860

Source of Variance	Sum of squares	D.F.	Mean square	Variance Ratio
Between tests	87495.7	6	14582.6	27.7
Within tests	2631.3	6	438.6	
Total	90126.9	12		

The between test variation is highly significant (0.001 level) compared with the within test variation.

Temperature at open end of corridor

Test	Fuel kg	Vent width mm	Temperature
1	121	240	300
2	121	700	400, 435, 420
3	241	240	420, 380
4	241	240	570
5	241	700	550, 635
6	241	700	680
7	241	80	190

Source of variance	Sum of squares	D.F.	Mean square	Variance Ratio
Between tests	205939	6	34323.2	27.3
Within tests	5029.2	4	1257.3	
Total	210968.2	10		

The between test variation is highly significant (less than 0.01 level) compared with the within test variation.

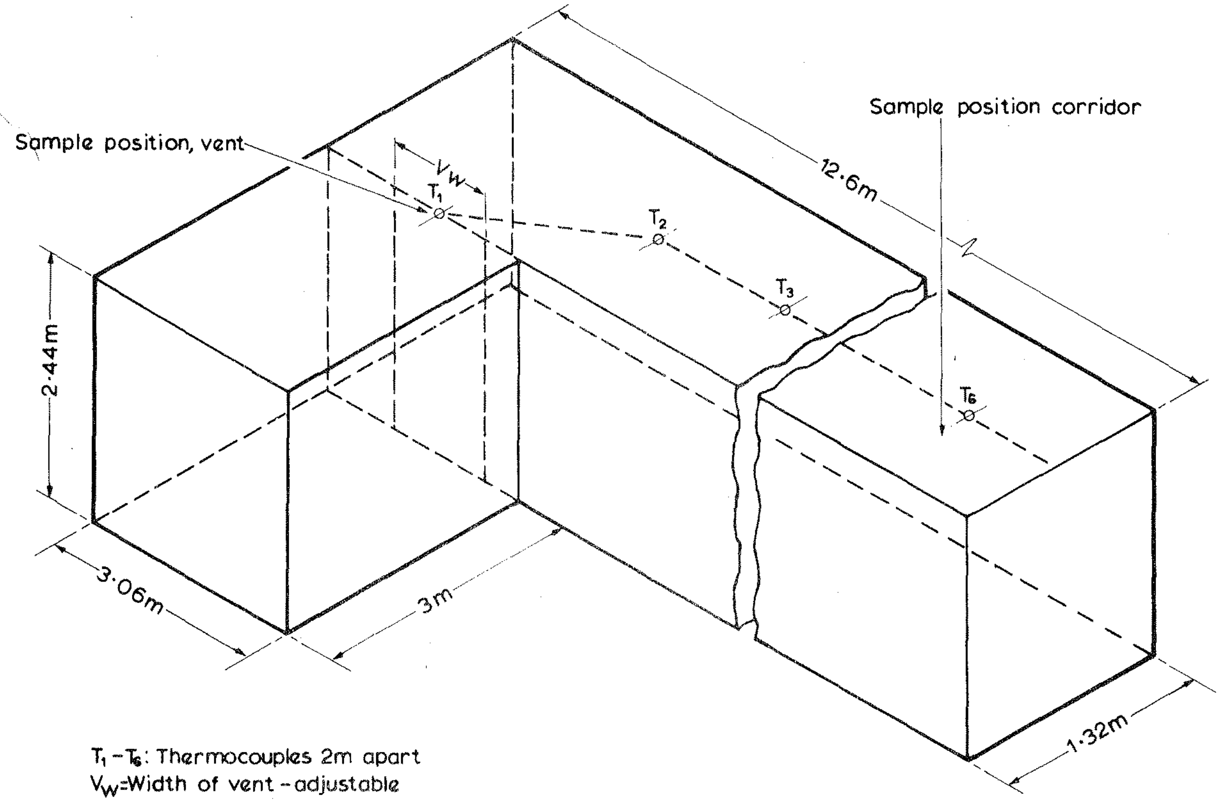


Figure 1 Compartment and corridor

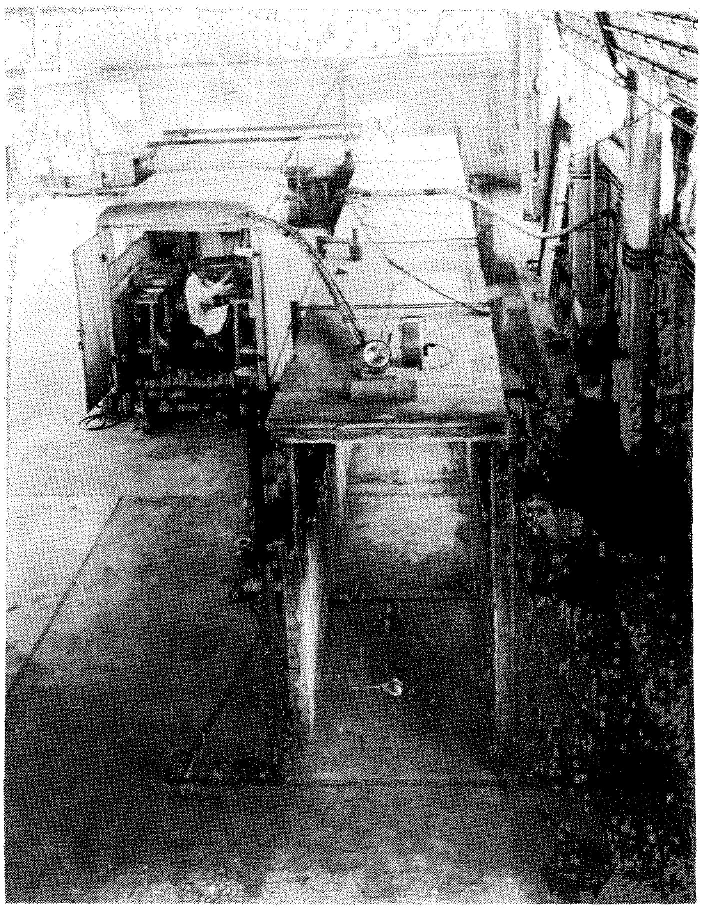
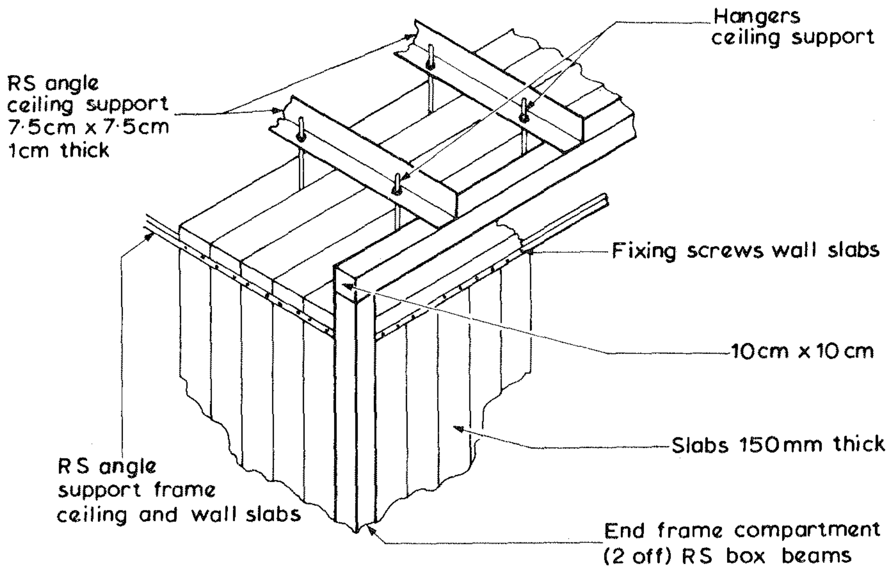
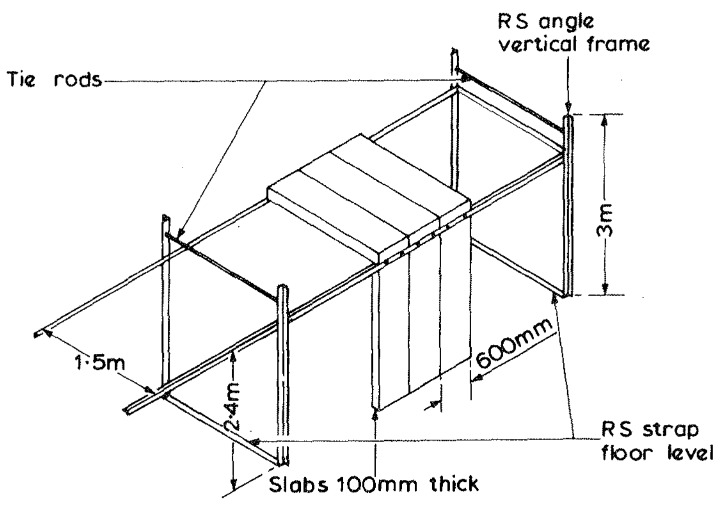


Figure 2 View of compartment and corridor showing mobile control laboratory



a) Detail of compartment steel frame and aerated concrete slabs



b) Detail of corridor

Figure 3 Large scale test rig constructional detail

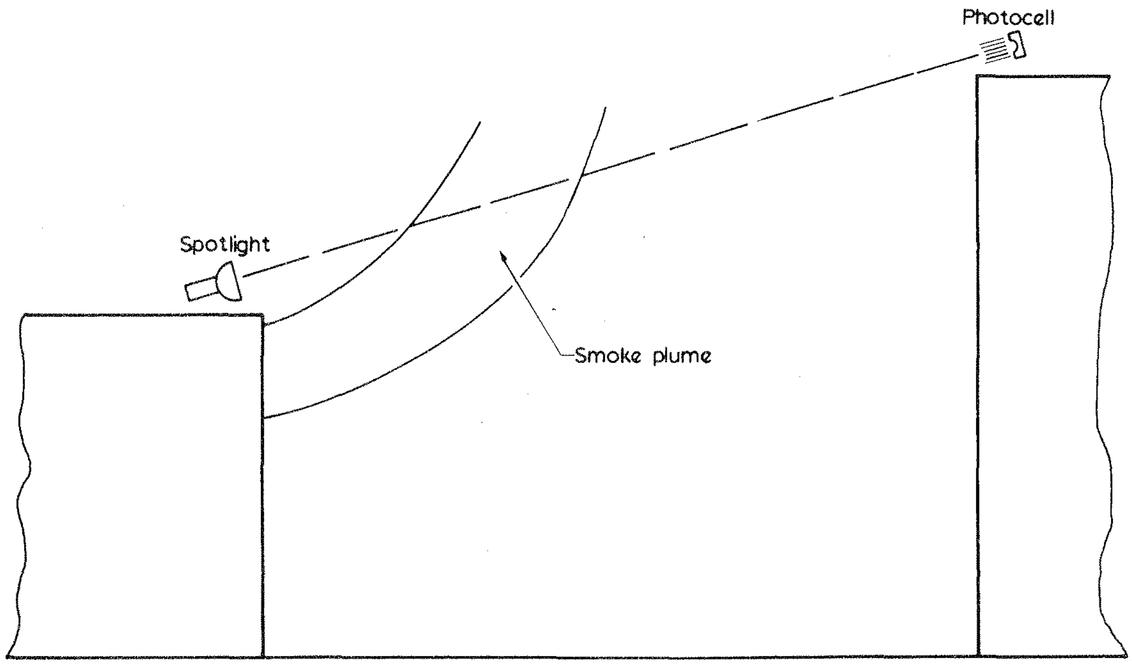


Figure 4 Smoke measurement-arrangement of spotlight and photocell

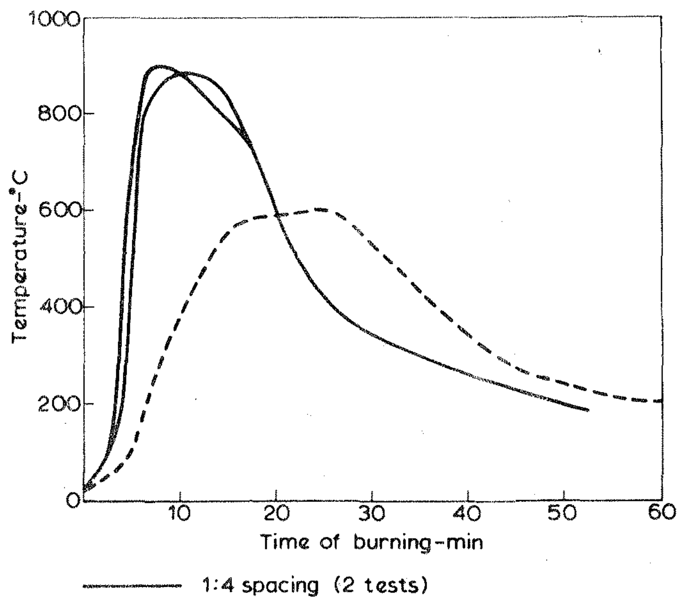
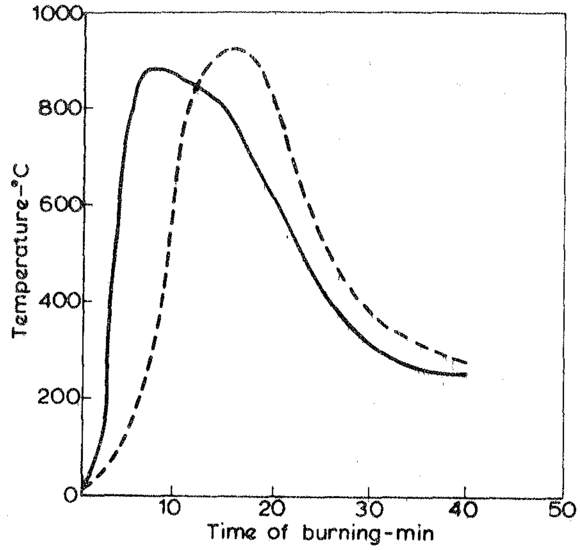


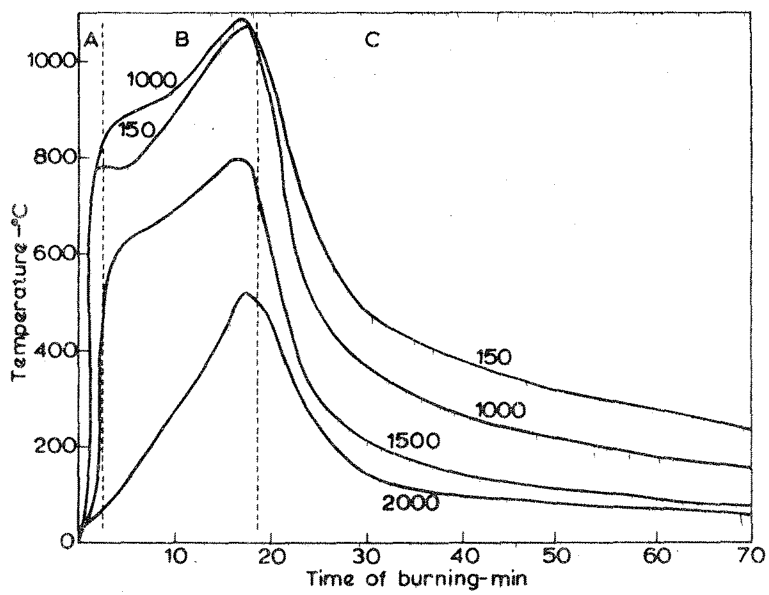
Figure 5 Temperature of fire gases from compartment, effect of crib spacing 120·5kg wood, 700mm vent



——— Moisture content ≤ 12 per cent

- - - - - Moisture content > 13 per cent

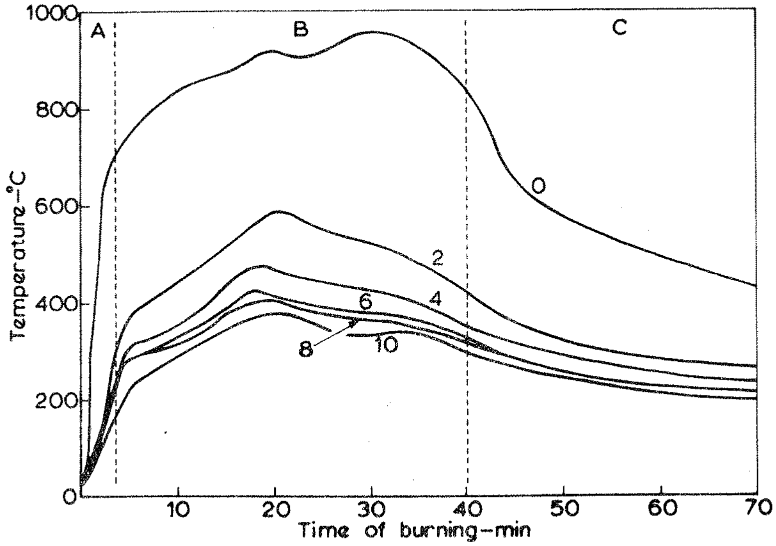
Figure 6 Temperature of fire gases from compartment, effect of moisture in wood, 120 5kg crib, 700mm vent



Figs: Distance below ceiling-mm

A—First stage of burning
B—Second stage of burning
C—Third stage of burning

Figure 7 Temperature at compartment vent, test 5, 241kg crib, 700mm vent



Figs: Distance along corridor-m

A–First stage of burning
B–Second stage of burning
C–Third stage of burning

Figure 8 Fire gas temperatures along corridor, test 3, 241kg crib, 240mm vent

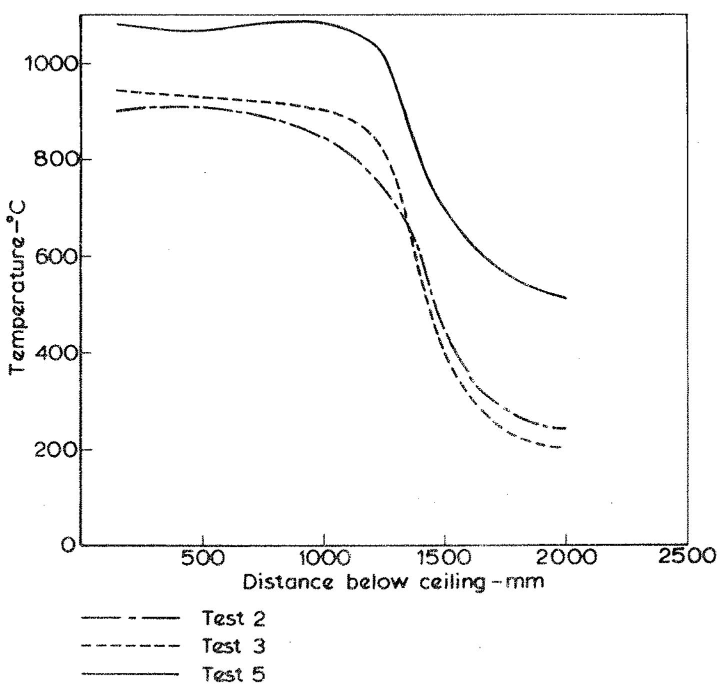


Figure 9 Position of neutral plane compartment vent

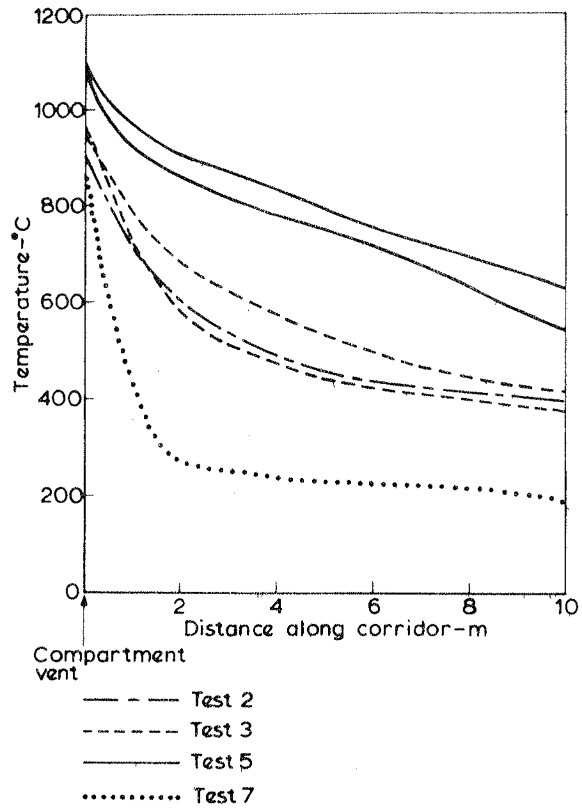


Figure 10 Temperature of fire gases in corridor

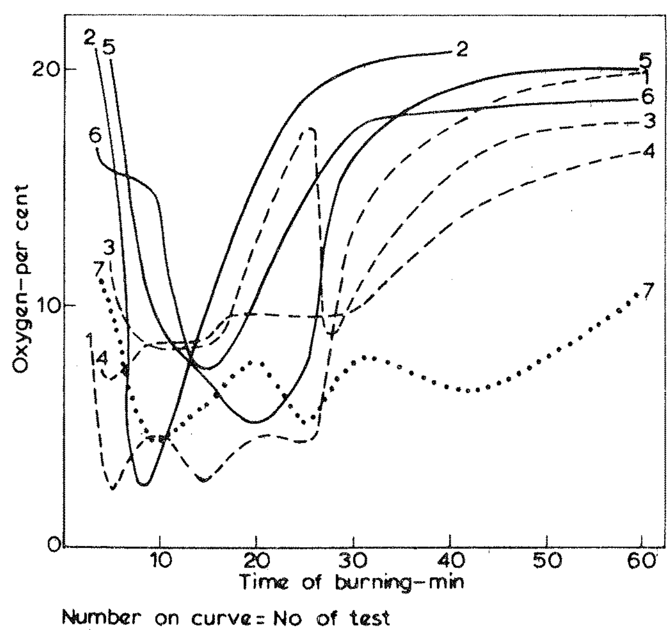


Figure 11 Oxygen in fire gases from compartment

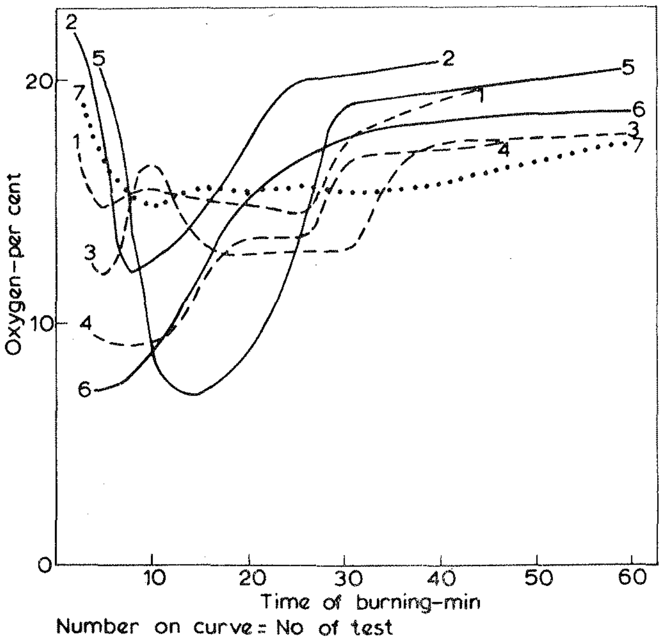


Figure 12 Oxygen in fire gases from corridor

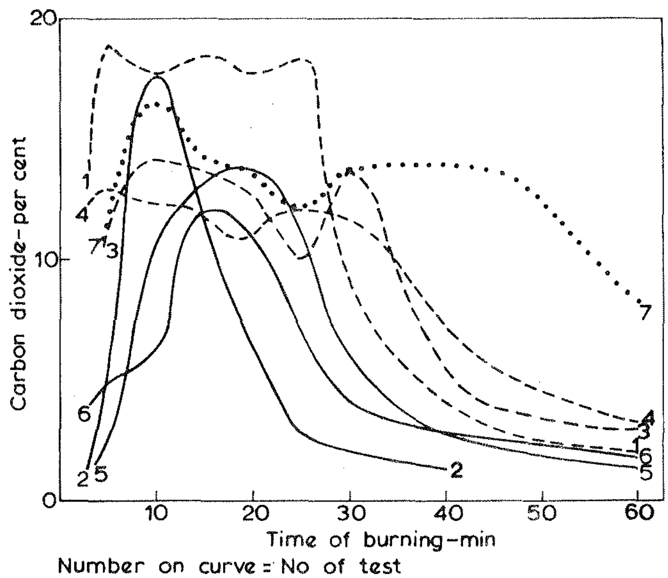
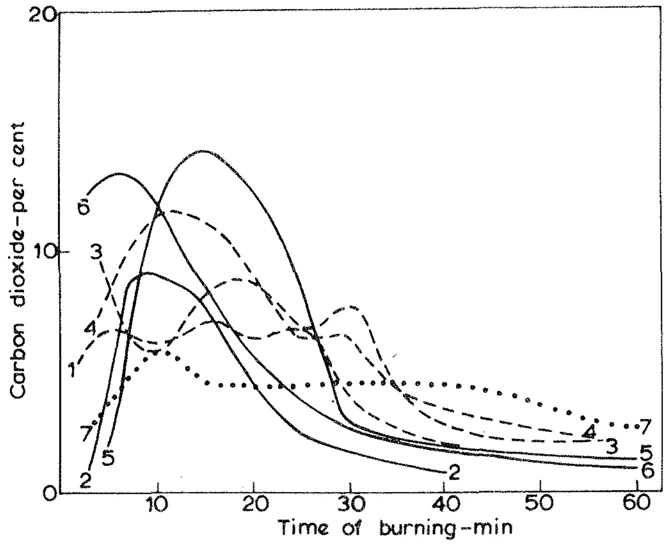
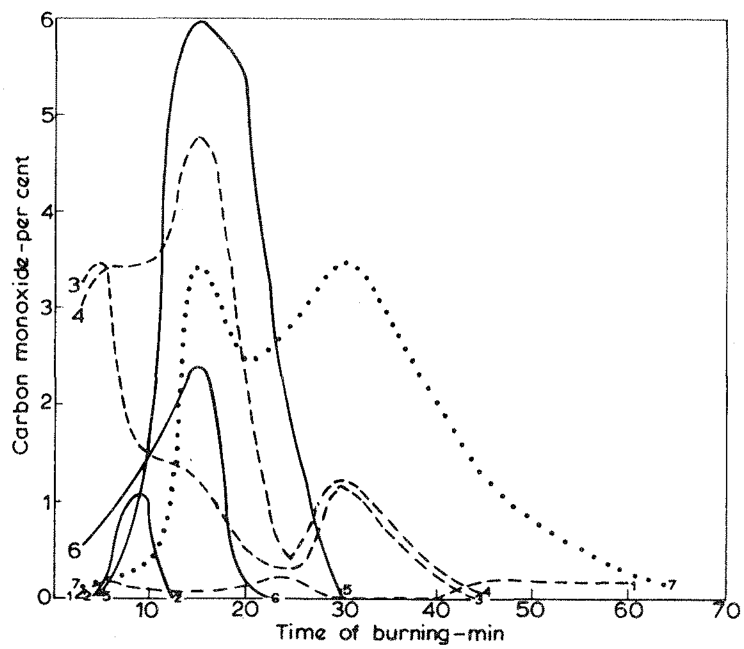


Figure 13 Carbon dioxide in fire gases



Number on curve = No of test

Figure 14 Carbon dioxide in fire gases



Number on curve = No of test

Figure 15 Carbon monoxide in fire gases

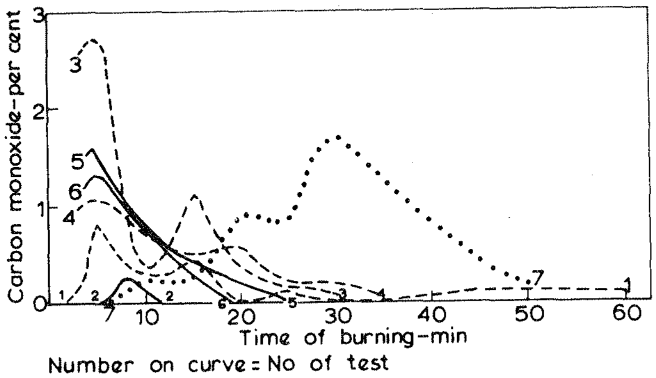


Figure 16 Carbon monoxide in fire gases

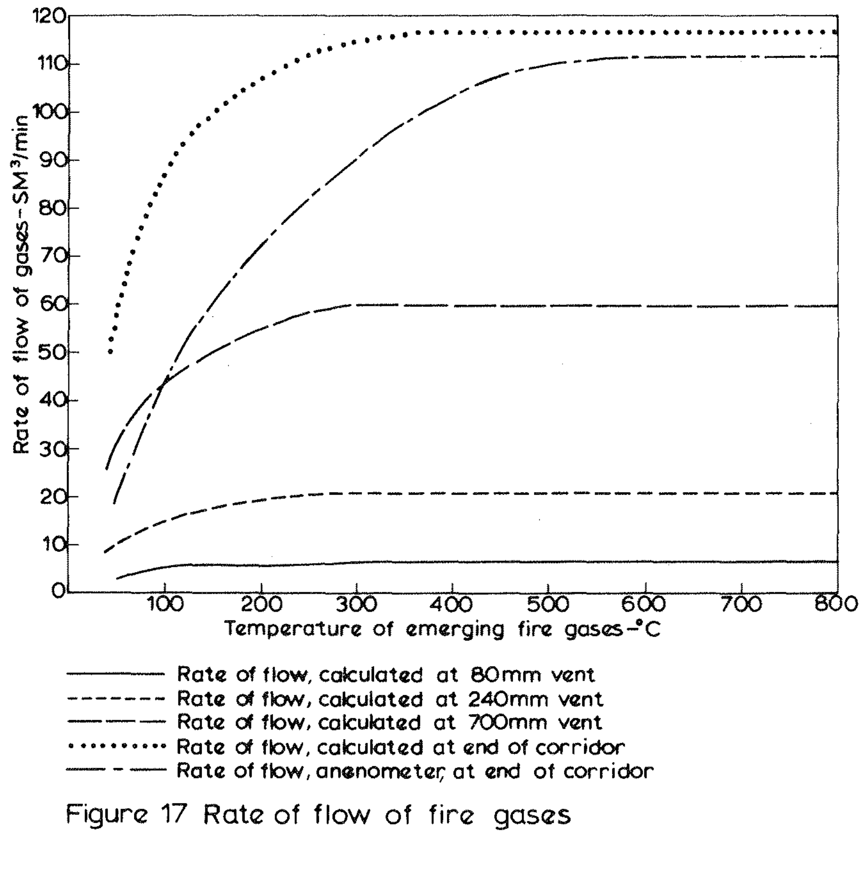


Figure 17 Rate of flow of fire gases

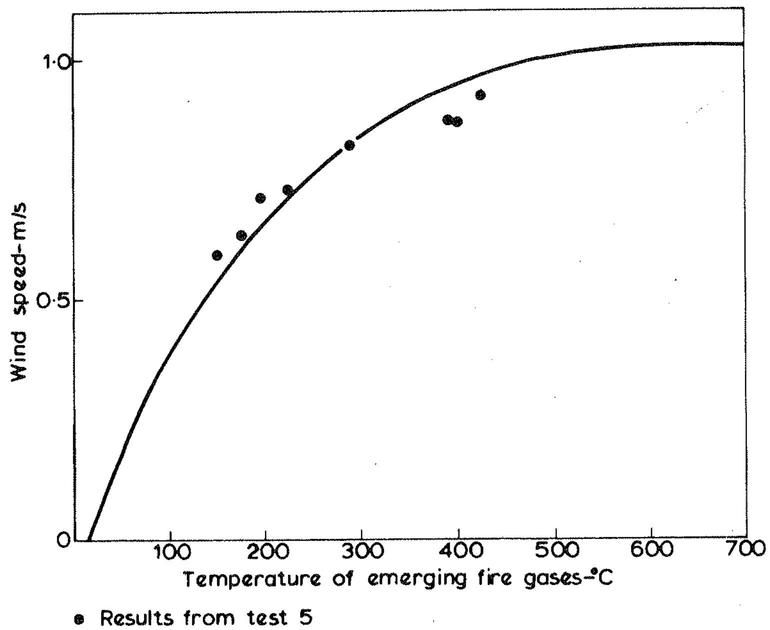


Figure 18 Speed of air entering corridor

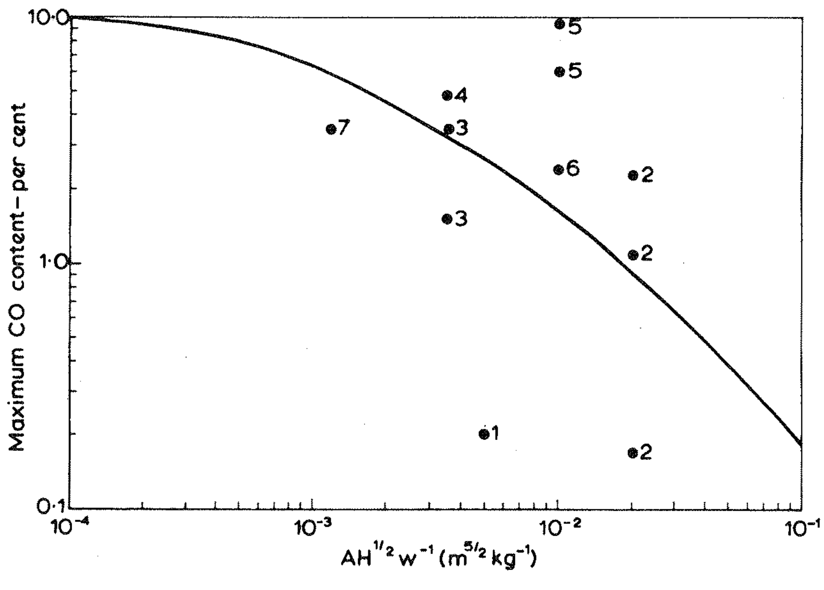


Figure 19 Effect of ventilation and fire load on maximum content of carbon monoxide