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Fire Research Note

No 614

THE GENERATION OF CARBON MONOXIDE BY FIRES IN COMPARTMENTS

by

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February 1966

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F.R. Note No. 614
February, 1966.

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SUMMARY

The composition of combustion gases, produced by burning cellulosic fuels in chambers with different degrees of ventilation, was measured. The results indicated that the maximum concentration of the toxic gas, carbon monoxide, was produced at the highest fire load when the amount of ventilation was small, but not the minimum possible. The time at which the maximum concentration of carbon monoxide was attained decreased as the mean density of the fuel load decreased.

The amount of air that could be contaminated to a dangerous level with carbon monoxide, in periods of time up to one hour after ignition, was a maximum when the amount of ventilation was between 6 and 18 per cent of the area of one wall of a cubical chamber. There was some evidence that the size of chamber, or of the fuel elements, or the degree of insulation could influence the production of carbon monoxide.

The design of ventilation systems for buildings to minimise the contamination of the atmosphere within them is discussed.

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DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES COMMITTEE

JOINT FIRE RESEARCH ORGANIZATION

THE GENERATION OF CARBON MONOXIDE BY FIRES IN COMPARTMENTS

by

D. J. Rasbash and G. W. V. Stark

INTRODUCTION

It is well known that the products of combustion at fires cause many fatalities. For example, in 1964 there were 681 fatalities at fires in the United Kingdom; of these 268 (39 per cent) were attributed to gases and smoke. With fires of cellulosic materials, such as wood and paper, carbon monoxide is probably the principal cause of toxification, although the production of carbon dioxide and other toxic materials, and the reduction of the oxygen content of the atmosphere increase the risk to human life. The effect of heat on the well-being of persons is of course another factor.

A number of full scale tests in the past have shown that following the start of a fire, dangerous concentrations of carbon monoxide can be produced in a short time and travel some distance from the fire[1,2]. It is therefore of interest to know the extent to which a fire can act as a generator of carbon monoxide, so that buildings can be designed to minimise the contamination of the atmosphere within them by the toxic products from a fire in perhaps one room or compartment.

This report describes some small scale tests designed to provide information on the effect of fire load and ventilation on the composition of the atmosphere within the compartment and on the rate of evolution of these gases from cellulosic fuels, and to estimate from this data the volume of air which could become dangerously contaminated by the combustion products from a fire. A few tests in a full sized compartment have also been made and are reported. Reports of tests made elsewhere were also examined to see if they could provide further information that could be incorporated in the data[3,4,5,6,7,8,9].

EXPERIMENTAL

The bulk of the work was carried out in a 0.91 m cube combustion chamber of 0.76 m^3 volume (Figs 1, 2 and 3). The chamber was made of 16 B.S.W. gauge sheet steel and was supported in an angle-iron frame. The front face of the chamber was mounted on a hinged frame and could be moved in a vertical direction so that an opening of predetermined depth could be formed at the top of the front face. This opening acted as a vent for the escape of combustion products and for the entry of air for the combustion taking place in the chamber. One side of the chamber was made of $\frac{1}{8}$ in thick asbestos millboard as an explosion relief in the event of an explosion in the chamber. Sampling points, Fig. 1, were installed in the back wall and the ceiling of the chamber for the insertion of gas sampling probes and thermocouples at different positions in the chamber. In most of the experiments, however, only one particular point, as indicated in Fig. 1, was used.

Another series of tests are in progress, using the same cubical chamber lined with $\frac{1}{2}$ in thick asbestos millboard on all surfaces exposed to the fire. This gave a compartment of 0.7 m^3 volume. Although it is the intention to take samples at several points of the compartment, the samples so far have been collected from the upper part of the ventilation slit and from the top of the chamber immediately over the fire.

A few experiments were also carried out on a full-sized room, 7.65 m long by 3.69 m wide by 2.95 m high (Fig. 4). A series of fire tests, which included extensive measurements of the temperatures in the room when different fire loads of wood were burnt with different ventilation openings, were being made in this room for a different research programme. Advantage was taken of this situation to make measurements of the composition of the combustion products as they approached the upper part of the ventilation opening in some of these tests.

The fire load used in a few preliminary tests with the 0.76 m^3 chamber was a crib of fibre board sticks, each measuring 30.5 cm by 2.54 cm by 1.27 cm. However, because difficulty was found in igniting these cribs reliably when the ventilation gap was small, the fuel was changed to wood-wool. The wood-wool was packed into a spherical cage of steel wire, of 15 cm, 30 cm or 60 cm diameter, which was suspended in the centre of the chamber. The wood-wool was then ignited by passing an electric current for 30 s through a small wire coil placed at the centre of the sphere. Tests were made in each spherical container at mean densities of wood-wool of 28.2 and 56.5 kg/m^3 corresponding to loads of 0.05 and 0.1 kg in the 15 cm sphere, 0.4 and 0.8 kg in the 30 cm sphere and 3.2 and 6.4 kg in the 60 cm sphere. In addition tests were carried out with 1.6 kg in the 60 cm sphere (mean density 14.1 kg/m^3) and with 12.8 kg of wood-wool spread in a layer about 30 cm deep on the floor of the chamber (mean density 42.7 kg/m^3). For most of these fire loads, tests were carried out with ventilation slit widths of 0, 0.32, 0.64, 1.27, 2.54, 5.08, 15.25, and 30.5 cm.

The fire load used in the tests in the 0.70 m^3 insulated chamber was a crib of 1.27 cm by 1.27 cm cross-section fibre board sticks on a 2 ft by 2 ft base. Two heights of crib were used of weights 6.4 and 12.8 kg at a mean density of 14.4 kg/m^3. A few grammes of wood-wool were placed in contact with the heating coil at the centre of the base of the crib to ensure ignition. The tests were carried out at ventilation slit widths of 5.08, 10.16 and 15.25 cm.

For the tests in the full-sized room, measurements of gas composition were made in a group of tests in which the ventilation openings were a quarter and half the area of the longer wall, and the fire load consisted of cribs of 2 in square sticks of mean density about 225 kg/m^3, at floor loadings of 7.3, 29.3 and 58.6 kg/m^2.

Method of analysis

The atmosphere from the combustion chamber was withdrawn through a stainless steel tube of 4 mm internal diameter, and passed through a liquid trap to a series of gas pipettes of about 50 ml capacity each. The pipettes could be disconnected from the gas stream by the operation of a four way tap. The atmosphere was drawn through the system at one litre a minute, and samples of the atmosphere were collected in the pipettes at intervals of time during a test. The gas samples were analysed in a gas chromatograph on columns of silica gel and molecular sieve operated at about 20°C, the relative proportions of each component being determined by peak integration. The response of the gas chromatograph was checked at frequent intervals by means of standard gas mixtures. All results are expressed as the composition of dry gas.

RESULTS

Sampling

The temperature and gas compositions were measured at six different points during one of the preliminary tests in which the fire load was 3 kg of fibre board sticks in the form of a crib. The oxygen content of the combustion gases measured at different times is given in Fig. 5, which indicates the positions of sampling. No consistent difference of either temperature or composition was observed, except for those sampling positions directly over the fire. Samples in subsequent tests were drawn from position C, as this position was not over the fire and was not in the angle formed by the sides of the chamber, where there could have been some stagnation.

Effect of ventilation on combustion

Some typical sets of gas analyses obtained with wood-wool as fuel are plotted in Figs 6, 7, 8 and 9. These show the concentrations of oxygen, carbon dioxide, carbon monoxide and methane in the dry gas as a function of time after ignition. The common feature of all the gas analyses was that a reduction in the concentration of oxygen was generally accompanied at about the same time by an increase in the concentration of the other three gases. Apart from this, however, there were three marked patterns of behaviour in the relationship between composition and time. In both Figs 6 and 7 (pattern A) there were rapid changes in gas composition shortly after ignition, resulting in a peak value of the concentration of the combustion products within a few minutes of ignition; thereafter there was a fairly rapid and smooth reduction in the concentration of these gases to zero. Two types of condition gave rise to this behaviour. Firstly, with a fire load of low bulk density and with low ventilation, the flaming which brought about the rapid changes in gas composition also resulted in the extinction of the fire. Thus at the end of the test only a small fraction of the fuel was consumed. The other condition occurred when there was a large ventilation opening; in this case the fuel was burnt rapidly so that only ash was left at the end of the test. Pattern B behaviour is illustrated in Fig. 8. In tests following this behaviour the concentration of combustion products increased to a peak value and thereafter diminished at a low rate. This was due to the establishment of smouldering combustion which could persist for several hours. In a number of tests the smouldering stopped after a time, leaving a high proportion of unburnt or partially burnt fuel. Finally, Pattern C behaviour usually occurred with high fire loads and moderate amounts of ventilation; fires behaving in this way showed a series of peak values of combustion products as combustion proceeded (Fig. 9).

It was observed during tests showing type C behaviour that the flames from the fire pulsed in a similar way to the gas composition. At the start of a test dense yellowish fumes issued from the vent; some time later there was a puff of flame which issued from the ventilation slit, the smoke at this stage becoming far less dense, and blue in colour. After this the flames would lift from the fuel bed and often decrease in size and go out. This stage was followed by emission of dense smoke which would then be followed by a further puff of flame from the vent and a repetition of the phenomena mentioned. These fluctuations were often more frequent than the intevals for sampling combustion gas for analysis.

Table 1 is a summary of the results of all tests using wood-wool as fuel in the 0.76 m^3 chamber. The results of tests made so far using fibre board sticks as fuel in the asbestos insulated chamber of 0.70 m^3 volume are given in Table 2. The tables show the minimum concentration of oxygen and the maximum concentrations of carbon dioxide, carbon monoxide and methane obtained in the tests, and also the maximum temperature reached in the chamber. The times at which these extreme values were reached are also included. The tables show that the maximum concentrations of carbon monoxide increased as the fire load increased and as the amount of ventilation decreased. However in the tests summarised in Table 1, there was no systematic increase in the carbon monoxide concentration for ventilation slits less than 1.27 cm wide. The maximum concentration of carbon monoxide measured in these experiments was 14 per cent, and occurred with the highest fire load tested. Temperatures are not recorded for the first two fire loads in Table 1 as the thermocouples then in use were faulty, but the temperature did not reach a high value, the walls of the chamber remaining fairly cool. Some tests were also made in a full scale chamber and these are recorded in Table 3.

The variation of composition of the atmosphere with time for the tests summarised in Tables 2 and 3 broadly followed type B behaviour; typical results are plotted in Figs 10 and 11.

The maximum concentration of carbon monoxide for all valid tests in Tables 1, 2, and 3 have been plotted against the parameter $F = AH^{\frac{1}{2}}W^{-1}$ in Fig. 12, where A is the area of the ventilation slit, H its height and W the fire load. The factor $AH^{\frac{1}{2}}$ is a measure of the rate at which air was supplied through the ventilation slit. The tests excluded are those where the ventilation slit was less than 1.27 cm wide and the test in which the cage containing the fuel fell from its support. The line drawn in the Figure shows the mean trend of the results. A similar curve may be drawn for the average carbon monoxide concentration for the first 30 min. of test plotted against the parameter F, as in Fig. 13.

Published papers [1-10] on the combustion of cellulosic fuels in chambers were consulted to see if they contained information on the production of carbon monoxide in a form permitting similar plots to be made. However the amount of data in a suitable form was small. Measurements of carbon monoxide in Ref. (1) were made in rooms communicating with the room on fire, but not of the discharging gases from the room on fire; however, the result is plotted in Fig. 12. The maximum response of the carbon monoxide meter in the tests reported in Ref. (2), was 1.5 per cent, lower than concentrations attained. In Ref. (3) the carbon monoxide concentrations given for the tests were estimated and not measured; however, the results are plotted in Figs 12 and 13. Of three tests in which carbon monoxide concentration was measured in Ref. (4), the vent area is not stated for two and in the third, water was applied to the fire before the carbon monoxide content reached a maximum. Average carbon monoxide content of the fire atmosphere is given in Ref. (5) for the period in which 20 to 70 per cent weight loss of fuel occurred. As this is the period during which the rate of combustion is highest, average carbon monoxide concentrations would also be expected to be higher than those measured from the time of ignition, and also the duration for this weight loss would differ from the first 30 min. of burning. However, the results obtained have been plotted in Fig. 13. The Refs (6) and (7) do not include any data on carbon monoxide content of the atmosphere. Ref. (8) contains some information on the carbon monoxide content in the tests reported but, allowing for scale, the ventilation area was below the limit set for the tests in Table 1; also the amount of combustible was small,

sufficient air being available in the buildings to allow combustion to proceed to completion. Ref. (9) reports tests in which the carbon monoxide concentration was measured at places remote from the room on fire; however the result of one test has been plotted in Fig. 12. The results for the tests reported in Ref. (10) of the combustion of fibre board or wood in a cubical chamber of 0.03 m^3 volume are in a suitable form and are plotted in Figs 12 and 13.

The results of tests reported in Refs (1), (3) and (5) do not fall about the drawn curves in Figs 12 and 13 but are grouped above the curves, indicating a higher content of carbon monoxide for a given value of parameter F. A possible contributory cause of this is indicated in Ref. (5), which reports comparative measurements of carbon monoxide concentration made with cooled and uncooled sampling probes. These show that the uncooled probe, which was the standard way of sampling, gave carbon monoxide concentrations about three times as great as those obtained with a cooled probe. The method of sampling used in the tests reported in this note allowed fairly rapid cooling of the gas stream, and would therefore be expected to give lower values of carbon monoxide concentration than those given in Ref. (5). Although precise details of the sampling system adopted for the tests reported in Ref. (3) are not given, it would appear that the sampling probe was exposed to the flames. A further contributory cause of this kind of discrepancy, apart from simple chemical equilibrium of the components of the sampled gases, could be the effect of the material of the sampling probes on the equilibrium. The tests reported in this note were made using stainless steel sampling tubes; those in Ref. (3) with iron tubes, and those in Ref. (5) with copper tubes. The last two metals and their oxides could interfere with the equilibrium of the component gases from the fire; any such effects would be much less with stainless steel.

After allowance is made for the possible difference in measured carbon monoxide concentration due to the probe, the values recorded in Ref. (5) are still substantially higher than those for tests made at the Fire Research Station, while those from Ref. (3) could fall about the mean curve drawn in the Figs 12 and 13. There are also departures from the mean curve in some of the Fire Research Station tests; for example, the carbon monoxide concentration for test 50, Table 1 was less than that indicated by the curve, and the results for the large scale tests may fall about a different mean curve. This is perhaps shown more clearly for plots of the minimum oxygen and maximum carbon dioxide concentrations, Figs 14 and 15, which indicate more rapid combustion for the full scale chamber, and less rapid combustion for the 0.03 m^3 chamber than for the 0.76 and 0.70 m^3 chambers used for most of the tests reported here.

Such differences may be due to the better insulation and hence the higher temperatures attained during combustion in the larger chambers, or to other scale differences such as the size of the fuel elements, and the distribution of these elements in the chamber. Another possible cause is the position from which the samples of gas were withdrawn from the chamber. The carbon monoxide contents measured for tests reported in Ref. (5) were collected by a long probe inserted through the vent to a position above the fire, which might account for the high values obtained. However, the carbon monoxide content measured in Ref. (9) falls on the curve, Fig. 12, while that measured in Ref. (1) lies well above the curve. The difference between these two results, which were both from tests in full scale dwellings in which samples were collected in a room remote from the fire, could perhaps be attributed to the distribution of the fuel. The fuel in Ref. (9) was furniture only, whereas in Ref. (1) the fuel included fibre board on the walls. A few tests with fibre board wall linings in the 0.70 m chamber, have given maximum carbon monoxide contents substantially higher than in tests with the same fire load in the form of cribs only.

Rate of evolution of carbon monoxide

It is important for practical purposes to obtain an estimate of the rate at which carbon monoxide was evolved from the fires. This was obtained by combining data on the concentration of carbon monoxide with data on rates of ventilation through the ventilation slit, and calculating the intake of air from the simplified relation obtained from equations presented by Kawagoe[3]:

$$\frac{M}{\rho_o} = AH^{\frac{1}{2}}.G$$

where M = mass flow of air

ρ_o = density of inflowing air

A = area of ventilation opening

H = height of ventilation opening

G = term dependent on temperature (Fig. 16)

The derivation of the simplified equation is given in the Appendix. It can be seen from Fig. 16 that for values greater than 100°C of Δ T, (the difference between the temperature of the emerging combustion gases and the ambient atmosphere), the value of G does not vary much for quite large variations of ΔT. For values of ΔT up to 100°C, G is approximately proportional to $\Delta T^{\frac{1}{2}}$. In experiments with the 0.76 m^3 chamber, the maximum values of Δ T in the tests varied from 50° to 800°C, which corresponds to a variation of G of 1.8, whereas the factor $AH^{\frac{1}{2}}$ varied by a factor of more than 1000. Thus in calculating the ventilation rates through the ventilation slit, the size of the slit is a far more significant factor than the temperature reached by the combustion gases and the simplification to equation (1) is therefore of minor importance.

Knowing the carbon monoxide concentration C, in the combustion gases, and the ventilation rate r, it is possible to calculate the rate at which the atmosphere outside the chamber on fire might be dangerously contaminated with carbon monoxide. It is necessary to assume a threshold value of carbon monoxide concentration, C_{crit}, which would be dangerous under the circumstances envisaged, and to calculate the volume of air which would be needed to dilute the combustion gases to give this value. Thus if in a given time interval, ∂t, the carbon monoxide concentration is C_t, and the rate of ventilation is r_t, then as the volume of combustion gases discharged through the vent is the same as the volume of air entering the vent, the total volume of carbon monoxide discharged, reduced to atmospheric temperature, will be $C_t r_t \partial t$. As long as C_t is not less than C_{crit}, the volume V_o of air that would be contaminated to the threshold level within a time interval Δt, would be given by

$$V_o = \frac{C_t}{C_{crit}} . r_t \, \partial t \qquad (2)$$

By summing equation (2) over a series of consecutive time intervals, the potential accumulation of contaminated air which could result from the vented combustion gases may be calculated; this will be referred to as the toxic potential of the fire. This calculation was made for the tests in Table 1 for the first 15, 30 and 60 min. of combustion. The critical value of carbon monoxide concentration taken for these calculations was 0.3 per cent, which is a value at which there is great danger resulting from a short period of exposure[11].

The results of these computations are shown in Figs 17, 18 and 19. It can be seen that for all fire loads there was a condition of ventilation at which the toxic potential was a maximum. Although this ventilation condition changed to some extent with the fire load and time of burning, for all conditions of test it lay between vent openings of 0.05 and 0.15 m^2 corresponding to between 6 and 18 per cent of the area of one wall of the cubical chamber.

Figure 20 shows the maximum toxic potential as a function of fire load. Broadly, the toxic potential increased with fire load. However, there were some exceptions which were probably the consequence of the different packing densities of wood-wool used in the experiments. The main deviation was between the results of the 60 cm sphere containing 1.6, 3.2 and 6.4 kg of fuel. The maximum toxic potential was obtained with the 3.2 kg fire load. The toxic potential of the 1.6 kg fire load was substantially less, and was even slightly less than the toxic potential of the 0.8 kg fire load at a higher mean density. However, it cannot be concluded from this that fuel of low mean density is safer than fuel of high mean density, since the build-up of carbon monoxide is much more rapid at low mean density. This is illustrated in Fig. 21 which shows the mean time that elapsed for the maximum production of carbon monoxide to be attained during tests as a function of the mean density of the fuel.

DISCUSSION

The tests reported in this note form part of a series of tests being undertaken to examine the potential toxicity of the atmospheres resulting from fires. The tests are continuing, but sufficient results are available to indicate the extent of the risk to human life resulting from the evolution of carbon monoxide from fires of cellulosic fuels. The effect of other toxic constituents of the combustion products, such as the acidic and aldehydic products produced by restricted burning, or the possible augmentation of the effect of carbon monoxide by other products such as carbon dioxide, are not dealt with in this note.

The tests do not indicate any marked effect due to the type of cellulosic fuel on the composition of the combustion gases, but at this stage of the research programme it is not possible to indicate the extent of the effect of scale on the composition of combustion gases. It would seem however that, at high fire loads and moderate vent sizes, under which conditions the highest toxic potentials are obtained, the effect of scale is minimal; these are conditions that could often be present in actual fire incidents.

The tests in the insulated and uninsulated cubical chambers do not show any large differences in composition of combustion gases due to the degree of insulation. The higher gas phase temperatures attainable with higher insulation would be expected to favour the production of carbon monoxide at the expense of carbon dioxide. The results, (Figs 12 and 13) indicate some increase of carbon monoxide content as the size of the chamber and its degree of insulation increases.

Application of the results to building design problems

The results obtained for appropriately sized compartments may be applied directly to fires in buildings for an assessment of the risk to human life arising from carbon monoxide from fires, and to provide a basis for the design of safety measures to protect human life.

As a fire can generate quantities of gas dangerous to human life in times that are similar to those between ignition and discovery, special attention should be given in the design of a building to the protection of occupants during this period.

The problem divides into two main parts. Firstly, the design of compartments so that the escape of toxic gases from the fire into the building is prevented or minimised, and secondly to design escape routes so that they do not become filled with such a large amount of toxic gas that they constitute a danger to the people using them.

The escape of toxic gases from a compartment on fire is best prevented by the fitting of doors of sufficient fire resistance to withstand the fire throughout its course, and which seal well enough to stop the escape of hazardous quantities of combustion gases. Such a door should be self-closing. However, experiments have indicated that it is not generally possible to make a door sufficiently well-sealed, or a room so air-tight, that a fire is reliably extinguished. Many fires could extinguish themselves rapidly when the amount of ventilation is limited; in particular those which burn rapidly in the early stages, and so deplete the oxygen supply rapidly, probably before any deep-seated smouldering can become established. However if the nature of the fuel and its ignition are such as to allow deep-seated smouldering to become established, then the fire can continue to burn and produce substantial concentrations of carbon monoxide at very low levels of ventilation. Thus in tests Nos. 32 and 56 in Table 1, the ventilation rate was nominally zero, but burning continued for a long time and the maximum concentrations of carbon monoxide occurred 40 min. and 1 hour after ignition. In these tests the wood-wool fuel was at the highest packing density used, and this kind of combustion could occur with fuels in a similar condition. However, when slow smouldering combustion is established, the temperatures reached in the compartment are considerably less than for continuous flaming combustion, and the fire resistance required for doors to resist smouldering combustion would be much less than that required for flaming combustion. In general, if a room is tightly sealed, and, for example, windows cannot fail quickly, the rate of combustion of a fire in the room will be controlled by the restricted entry of air, and the temperatures attained in the room will not be high.

As the area of any openings from a compartment involved in fire into the rest of the building is increased, then the quantity of combustion products that can pass into the building is increased. If there is no other form of ventilation for the compartment, the quantity of combustion products passing into the building will be approximately proportional to the area of the opening times the square root of its height. Where openings at different heights are present, the factor is the total area of the openings times the square root of the vertical distance between the bottom of the lowest and the top of the highest opening. It is therefore better to provide horizontal ventilation slits, which should be at a common level where more than one vent is provided, and to keep the area of the vents to the minimum practical size. The temperature in the compartments has little effect on the amount of gas and smoke escaping as long as this temperature is 100°C or more. However, as the ventilation increases above a small optimum value, the toxic potential arising from a given fire load decreases. Thus the most dangerous condition for the contamination of communicating parts of the building occurs at this optimum vent area. The experiments in the 0.76 m^3 chamber suggest that this optimum size is about 6 to 18 per cent of the area of one wall of the compartment, but there is some evidence that the area increases as the fire load increases (Figs 17-19). This area approximates to that of an open door in the average dwelling room, and so emphasises the desirability of fitting self-closing doors.

The protection of the occupants of a multi-occupancy building, against the toxic effects of the combustion products from a compartment on fire, could be obtained by providing a system of through-ventilation of a sufficient rate to dilute to a safe level the gases entering the communicating parts of the building. The air stream would need to be sufficient to reduce the carbon monoxide concentration to a value well below 0.3 per cent which was taken as being dangerous for exposures of a quarter-hour or so. The information in this report goes some way to allow such a dilution system of ventilation to be specified. Normally, a ventilation flow is established through the corridors and staircases. The ventilation rate through and the size of openings on to such routes should be such that the toxic products of any fire in a communicating compartment escaping into the route would be safely diluted. As the acceptable level of air movement is fairly closely defined at a low rate, the main control would be through restricting the sizes of the communicating vents.

The design of escape routes poses a rather different problem; in general, conditions should be such that escapees are not exposed to a concentration of toxic gas that might be dangerous for the time of exposure while the escapees are passing through the escape route. It has been reported that 1 to 2 per cent of carbon monoxide can bring about unconsciousness after two or three breaths, and may cause death in a minute or so[11]. Concentrations in excess of this value were commonly found in the tests reported here for both smouldering and flaming combustion. Thus any escape route enclosed by smoke doors and less or comparable in volume to that of a compartment opening on to it, could become a dangerous toxic hazard if gases from a fire which had become accumulated in the compartment were allowed to discharge into the escape route.

There are two ways in which an escape route is kept clear: either an exhaust system draws ventilation air through the route, or a pressure system pushes the ventilation air through the route. The first system could give rise to hazardous conditions by drawing the combustion products into the escape route, the worst condition arising if the door of the burning compartment were opened and the atmosphere in the room were transferred rapidly into the escape route. Under these conditions the combustion gases could move as a plug for a considerable distance along the route, which could serve more than one accommodation unit. The second system would be freer from this kind of risk, but unless the flow of ventilation air could reach high rates when the door to the escape route was opened, transfer of combustion products to the route could occur, and the dilution might not be sufficient to render the escape route safe.

Therefore the use of self-closing doors to compartments would not only restrict burning but would also increase safety along the escape route; and a pressurised ventilation system would in principle be better than a suction system, provided the rates of flow of ventilation air were able to cope with possible contamination of the escape routes with combustion products during escape.

The information provided in Figs 12 and 17 to 19 can be used, as a first approximation, to calculate flows of ventilation air needed to reduce the carbon monoxide concentration from a burning compartment to a safe level. From the expected fire load in a compartment and the size of ventilation openings, the maximum carbon monoxide concentration which would occur can be obtained from Fig. 12. The concentration and rate of flow of carbon monoxide through those ventilation openings into the escape routes and the rest of the building can be calculated from equation (1) entering the appropriate dimensions for these openings; the value of G may be taken as 2.5 - 3 for smouldering combustion, and 4 for flaming combustion. The type of combustion can be deduced from the

expected nature of the contents and the degree of ventilation; bulky flammable materials would tend to flame freely, but less bulky materials would tend to smoulder; and small ventilation openings would favour smouldering but large ventilation openings would favour flaming.

Errors that might be envisaged from this approach arise from the possibility that the size of the compartment and the size and distribution of the fuel elements and their mean density have some effect on the carbon monoxide content. Figure 12 shows that the tests in the full scale room gave a lower maximum carbon monoxide content at higher ventilation rates and lower fire loads than the small scale tests, but that the maximum concentration was possibly higher with the large scale chamber than with the small scale chambers, and was reached at lower values of the factor F. This difference might be due in part to the distribution and size of the fuel elements.

In general, the use of maximum values of carbon monoxide content will overestimate the amount of dilution required, but as can be seen from Figs 12 and 13, the average concentration for the first 30 min. is about half the maximum value, and some individual maximum values are at least twice the value given by the appropriate point on the curve in Fig. 12. Other reasons for the suggested calculation giving an over-estimate of the ventilation rate are:

(a) The opening of an escape door from a compartment will increase the ventilation and therefore reduce the carbon monoxide concentration in the combustion products by improving the efficiency of combustion.

(b) The opening or breaking of windows communicating with open air will not only increase the ventilation of the fire but will also provide an alternative path for the escape of combustion products in probably a safe manner. Indeed, if external windows could be designed to shatter in the early stages of a fire, they would play a part in reducing the amounts of carbon monoxide within a building.

The toxic hazard in a compartment

A large number of persons are incapacitated or killed by the release of toxic gases in an occupied room. Aged persons are prone to this kind of accident, for example as the result of smouldering fires caused by smoking in bed. The results of the tests in the 0.76 m^3 chamber suggest that concentrations of carbon monoxide hazardous to life can be attained from the combustion of 1.9 kg (4.2 lb) in an average sized room of 28 m^3 volume. Where the ventilation was small, the carbon monoxide concentration remained steady for 30 min. or more, the duration depending on the fire load. Thus, under conditions of low ventilation - conditions aged persons would be expected to favour - the burning of a small amount of combustible could readily produce lethal atmospheres for periods long enough to put the occupant at risk, the risk of death perhaps being increased by the lower resistance of an aged person to that of an adult of working age.

CONCLUSIONS

The combustion of cellulosic fuels in a compartment with restricted ventilation results not only in the generation of highly toxic concentrations of carbon monoxide within the compartment, but also in the emission of quantities of this toxic gas sufficient to contaminate large volumes of air in compartments and routes adjacent to the compartment.

The risk to persons in compartments with low ventilation in which a fire occurs is very high, even when only small fires are present. Their escape and that of their neighbours in a multi-occupancy building would depend on the dilution of the gases, passing from the burning compartment into the escape routes, to safe levels.

The transfer of toxic gases from a burning compartment into another part of the building may be minimised by the fitting of self-closing doors, and by the use of a pressure system of ventilation through the communicating routes in the building. The dilution of toxic gases escaping through the open door of a compartment on fire would require the ventilation rate under these conditions to be high. Methods of calculating ventilation rates are presented, which should assist in the design of ventilation systems.

The comments given here are made for carbon monoxide as the toxic gas. Similar approaches can be made to the assessment and reduction of the risk due to other toxic gases, for example, those that are formed in the early stages of a fire before flash over.

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TABLE 1

EXTREME VALUES OF COMBUSTION PRODUCTS

SUMMARY OF TEST RESULTS

0.76 m^3 STEEL CHAMBER FUEL - WOOD WOOL

Test No.	Vent area m^2	Fire load kg	Oxygen		Carbon dioxide		Carbon monoxide		Methane		Temperature	
			Min. % vol.	Time to reach min. min.	Max. % vol.	Time to reach max. min.	Max. % vol.	Time to reach max. min.	Max. % vol.	Time to reach max. min.	Max. °K	Time to reach max. min.
1	0.0000	0.050	14.4	≯ 2	6.3	≯ 2	0.70	4	NM	NM	NR	NR
2	0.0058		15.0	4	5.4	2	0.38	2	NM	NM	NR	NR
3	0.0116		15.3	6	4.8	3	0.42	3	NM	NM	NR	NR
4	0.0232		17.6	6	3.1	6	0.33	8	NM	NM	NR	NR
5	0.0464		16.4	2	4.1	2	0.08	2	NM	NM	NR	NR
15	0.0000	0.100	14.5	20	4.6	20	1.32	30	0.10	30	NR	NR
14	0.0029		13.6	10	6.3	10	0.60	25	0.08	30	NR	NR
13	0.0058		15.3	15	4.2	15	0.99	15	0.08	20	NR	NR
12	0.0116		16.2	15	3.6	8	0.90	15	0.09	15	NR	NR
11	0.0232		17.8	8	2.1	8	0.34	15	NM	NM	NR	NR
10	0.0464		17.0	8	3.2	8	0.15	15	NM	NM	NR	NR
23	0.0000	0.400	10.1	60	9.4	60	2.26	60	0.24	8	369	2.5
22	0.0029		13.1	10	6.7	10	1.89	10	0.17	10	359	2
21	0.0058		11.1	10	8.0	10	2.33	20	0.25	20	393	4
20	0.0116		8.3	6	11.4	6	3.34	6	0.43	6	388	2
19	0.0232		12.3	10	7.3	8	2.14	8	0.24	10	398	3
18	0.0464		15.5	2	8.4	2	1.30	8	0.24	10	393	2
17	0.1395		19.3	2	0.9	2	0.10	2	NM	NM	338	3
16	0.2789		19.6	15	0.14	6	NM	NM	NM	NM	321	5
32	0.0000	0.800	6.4	40	13.0	40	6.40	40	0.47	40	343	5
31	0.0029		8.0	60	11.5	40	5.90	40	0.37	40	328	5.5
30	0.0058		9.0	50	11.7	40	5.20	30	0.40	30	334	3
29	0.0116		10.0	40	9.6	50	4.90	50	0.31	50	355	6
27	0.0232		11.9	20	7.6	20	3.10	20	0.21	20	NR	NR
26	0.0464		13.2	4	7.1	4	2.10	20	0.20	20	NR	NR
25	0.1395		19.3	6	0.4	6	NM	NM	NM	NM	336	16
24	0.2789		19.5	8	0.24	8	NM	NM	NM	NM	323	9

NR = Not recorded.

NM = Not measurable.

TABLE 1 (Cont'd)

Test No.	Vent area m^2	Fire load kg	Oxygen		Carbon dioxide		Carbon monoxide		Methane		Temperature	
			Min. % vol.	Time to reach min. min.	Max. % vol.	Time to reach max. min.	Max. % vol.	Time to reach max. min.	Max. % vol.	Time to reach max. min.	Max. °K	Time to reach max. min.
40	0.0000	1.600	8.3	2	12.6	2	5.30	2	0.50	4	452	2
39	0.0029		10.0	2	9.8	2	3.00	2	0.20	2	436	2
38	0.0058		10.7	4	10.3	4	3.80	4	0.30	4	486	2
37	0.0116		10.0	2	12.2	2	4.40	2	0.40	2	459	1
36	0.0232		9.2	2	10.6	2	4.20	2	0.40	3	486	1
35	0.0464		9.0	2	10.6	2	3.80	2	0.30	2	452	1
34	0.1395		10.7	4	11.0	4	1.00	4	0.08	2	657	4.5
33	0.2789		18.5	4	3.0	2	0.30	2	0.03	2	NR	NR
48	0.0000	3.200	4.4	10	15.8	10	5.90	15	0.43	8	396	2
47	0.0029		2.7	10	16.9	11	7.80	10	0.77	10	455	3
46	0.0058		5.9	4	14.9	4	6.70	4	0.90	4	415	2
45	0.0116		5.5	8	14.4	8	7.70	100	0.49	30	413	2
44	0.0232		4.4	2	13.6	2	7.40	90	0.48	4	443	2
43	0.0464		7.0	2	14.1	2	6.00	20	0.60	20	390	2
42	0.1395		8.4	8	12.9	8	0.80	8	0.07	4	776	12.5
*41	0.2789		9.1	6	13.4	6	2.00	6	0.30	6	926	6
56	0.0000	6.400	8.8	60	10.8	10	4.50	60	0.23	20	343	6
55	0.0029		3.8	60	14.5	60	8.20	60	0.62	60	347	2
54	0.0058		5.2	15	14.2	15	6.30	15	0.56	15	338	6
53	0.0116		3.1	60	17.0	60	10.80	60	1.20	60	357	2
52	0.0232		5.9	100	13.8	60	8.30	60	0.79	60	357	>60
51	0.0464		9.3	30	11.4	100	5.60	100	0.61	100	394	38
50	0.1395		16.4	4	3.6	4	0.49	60	0.02	4	622	40
49	0.2789		17.4	4	2.7	4	0.65	4	0.08	4	595	8
61	0.0000	12.800	4.2	60	16.3	60	7.90	30	0.62	60	408	3
60	0.0116		3.0	2	16.5	2	6.60	2	0.52	2	408	2
59	0.0232		1.5	15	19.6	15	14.10	15	1.52	15	427	49
58	0.0464		6.9	90	13.8	30	6.60	15	0.79	30	441	>60
57	0.1395		2.4	20	19.7	20	1.70	3	0.19	60	830	17

*Fuel cage fell. Result affected.

NR = Not recorded.

TABLE 2

Extreme values of constituents of combustion gases

Summary of tests. 0.7 m^3 chamber. Fibre board as fuel

Test No.	Vent area m^2	Fire load kg	Oxygen		Carbon dioxide		Carbon monoxide		Methane		Temp.	
			Min. % vol.	Time to reach min. min.	Max. % vol.	Time to reach max. min.	Max. % vol.	Time to reach max. min.	Max. % vol.	Time to reach max. min.	Max. °K	Time to reach max. min.
1	0.134	6.4	3.5	10	18.2	10	2.7	10	0.5	5	943	13
2	0.091	6.4	6.1	10	15.3	15	2.8	10	0.15	10	918	20
3	0.045	6.4	7.5	50	12.5	50	4.9	15	0.9	15	727	6
4	0.045	12.8	>10.9	<120	< 9.7	<120	3.8	100	0.7	15	503	105
5	0.091	12.8	8.1	15	13.8	15	3.7	30	0.7	45	913	20
6	0.134	12.8	9.5	15	11.6	15	3.3	25	0.3	5	1003	15

TABLE 3

Extreme values of combustion products

Summary of tests. Full scale room.

Test No.	Vent area m^2	Fire load kg	Oxygen Min. % vol.	Oxygen Time to reach min. min.	Carbon dioxide Max. % vol.	Carbon dioxide Time to reach max. min.	Carbon monoxide Max. % vol.	Carbon monoxide Time to reach max. min.	Methane Max. % vol.	Methane Time to reach max. min.	Temp. Max. °K	Temp. Time to reach max. min.
1	5.57	210	16.4	20	4.5	5	NM	NM	NM	NM	$<$592	$>$5
2	5.57	1700	2.0	20	17.7	20	4.4	30	1.02	30	1108	20
3	11.14	1700	4.5	10	17.6	10	0.33	10	0.06	10	1128	30
4	5.57	850	6.3	15	14.2	15	0.48	15	0.03	10	1173	15
5	5.57	850	3.3	10	15.5	10	0.85	15	0.16	10	1143	15
6	5.57	1700	1.4	25	19.9	20	5.2	20	0.70	20	1378	30

NM = Not measurable

APPENDIX

The effect of temperature on the flow of gas through a vent

The following equation relating mass flow of air into a compartment containing a fire, and the size of the vent through which hot gases are discharging and air entering is given by Kawagoe [3]

$$\frac{M}{\rho_o} = \frac{2^{3/2} a \cdot A \cdot H^{\frac{1}{2}} \cdot g^{\frac{1}{2}} \left(1 - \frac{\rho_1}{\rho_o}\right)^{\frac{1}{2}}}{3\left\{1 + \left(\frac{\rho_o}{\rho_1}\right)^{\frac{1}{3}} \cdot \left(1 + \frac{R}{M}\right)^{\frac{2}{3}}\right\}^{3/2}} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

where

M = mass flow of air into the compartment

a = discharge coefficient

A = area of ventilation slit

H = height of ventilation slit

ρ_1 = density of gas in compartment

ρ_o = density of air entering compartment

R = rate of burning

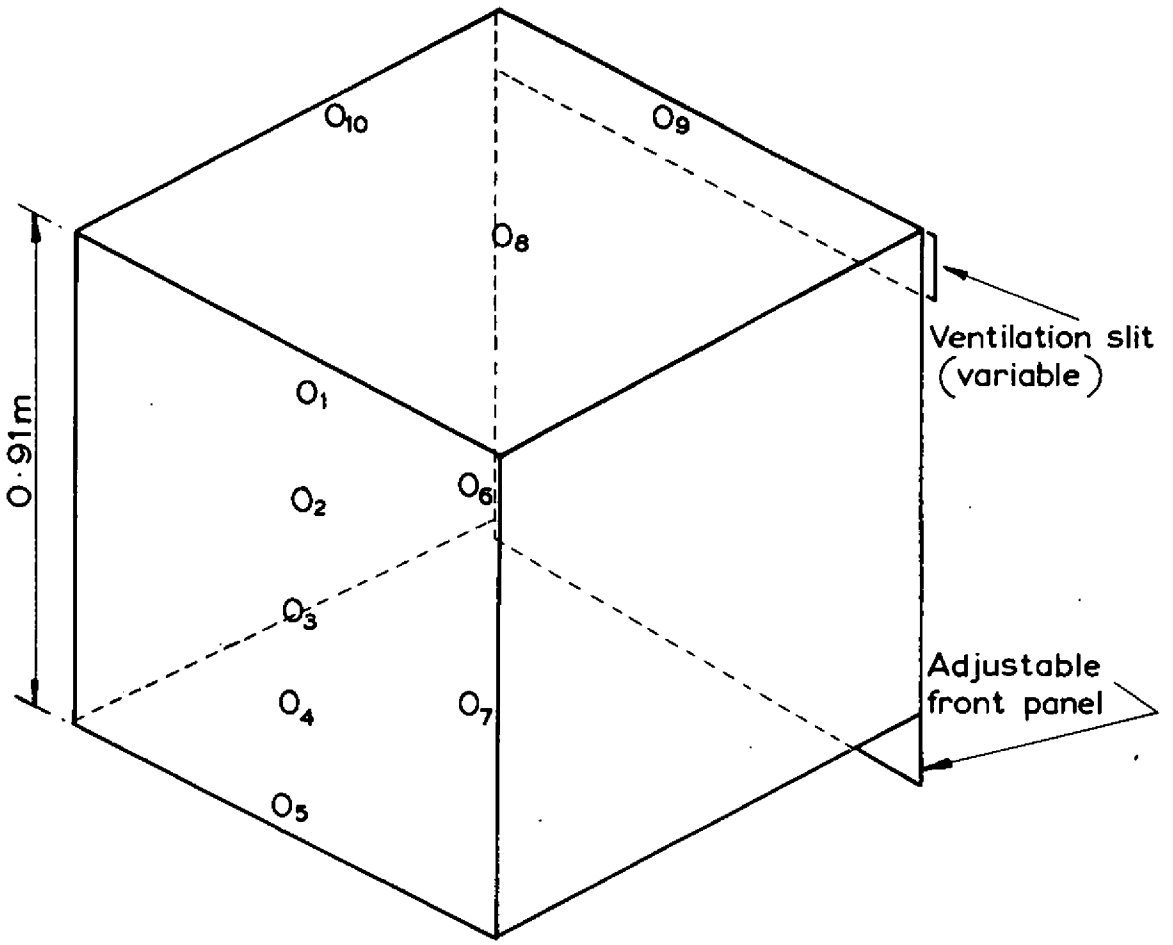
Making the assumptions that the gases obey perfect gas laws, that the mean molecular weight of the combustion products (including nitrogen) does not differ from that of air and using values of 0.7 for a, and 0.2 for R/M gives the relation:

$$\frac{M}{\rho_o} = \frac{20.6 \left(\frac{\Delta T}{\Delta T + 283}\right)^{\frac{1}{2}}}{\left\{1 + 1.13 \left(\frac{\Delta T + 283}{283}\right)^{\frac{1}{3}}\right\}^{\frac{2}{3}}} \cdot A \cdot H^{\frac{1}{2}}$$

or

$$\frac{M}{\rho_o} = G \cdot A \cdot H^{\frac{1}{2}}$$

where G is the variable term dependent upon ΔT, the temperature difference between the hot gases in the compartment and the temperature of the air entering the compartment, 283°K



Note :

O_1 - O_{10} = Sampling points

O_2 = Sampling point used in main group of tests

FIG. 1. CUBICAL COMBUSTION CHAMBER

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FIG. 2. 0·76m³ CUBICAL BOX, OPEN, SHOWING CAGE FOR FUEL

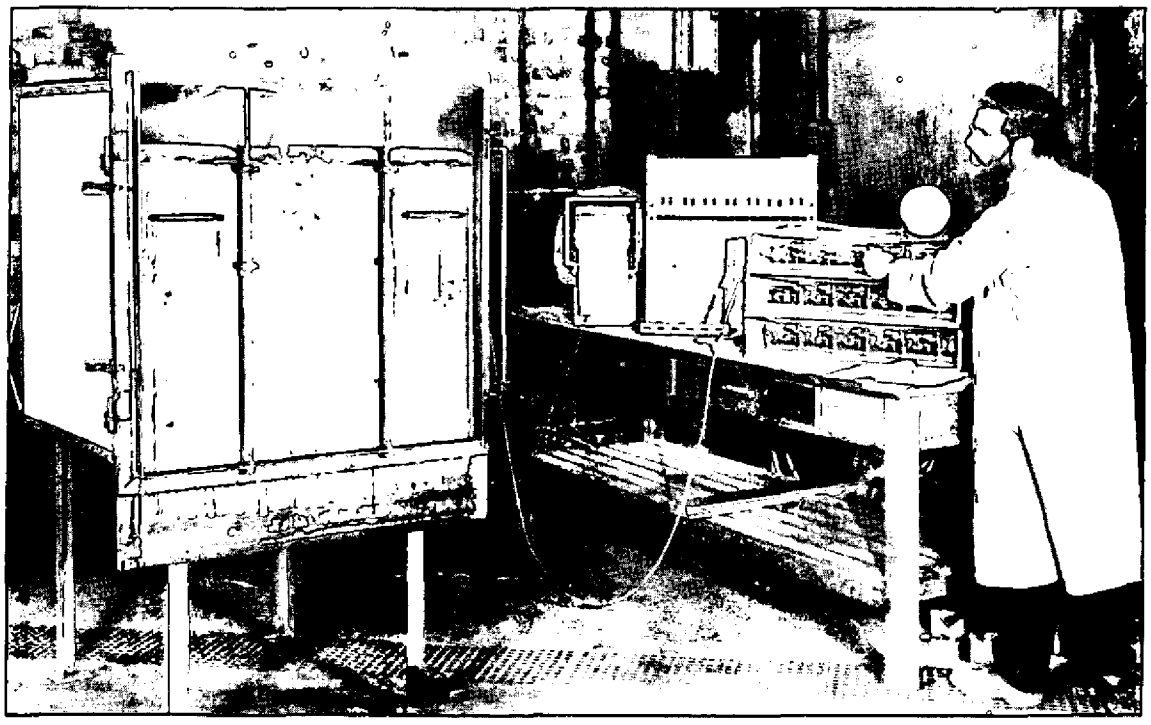
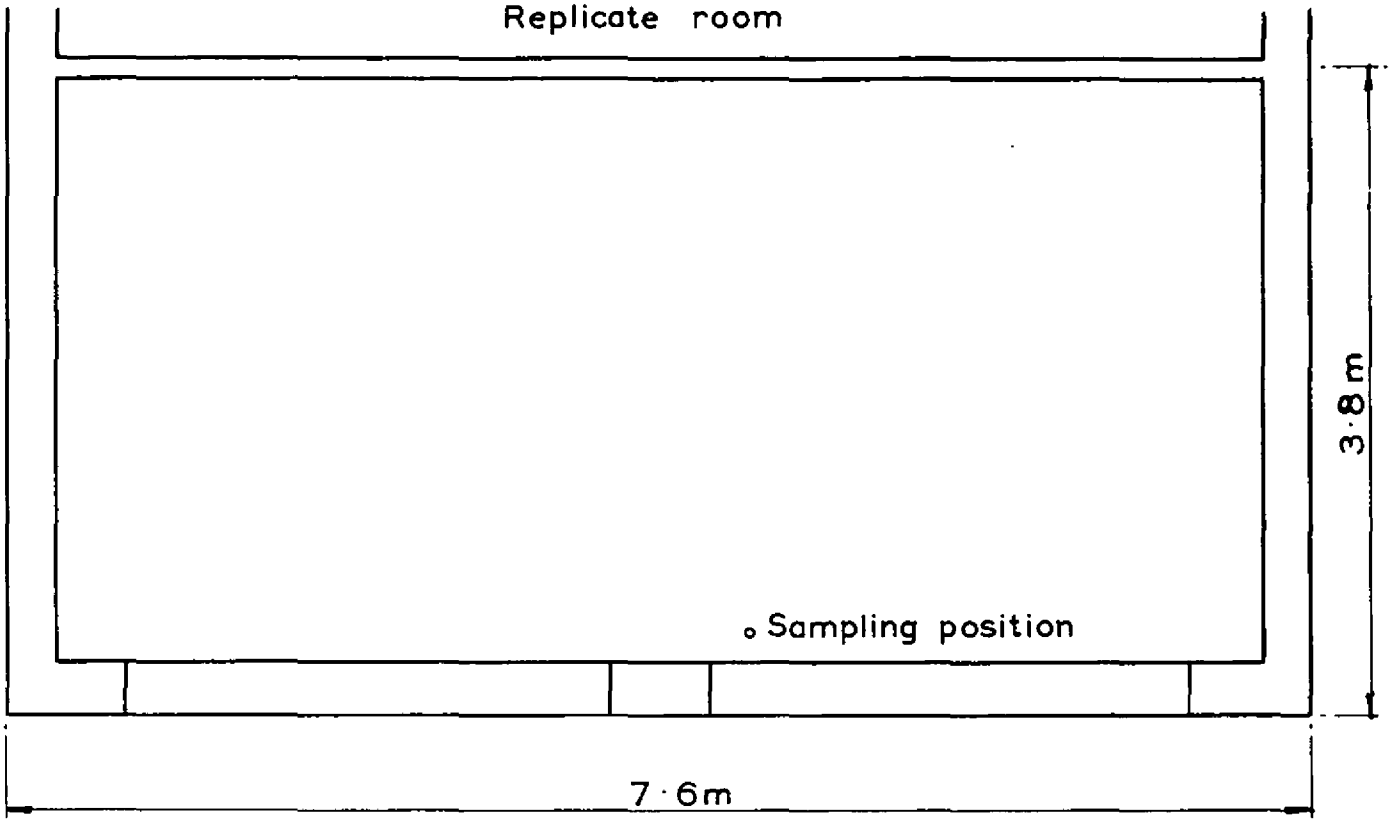
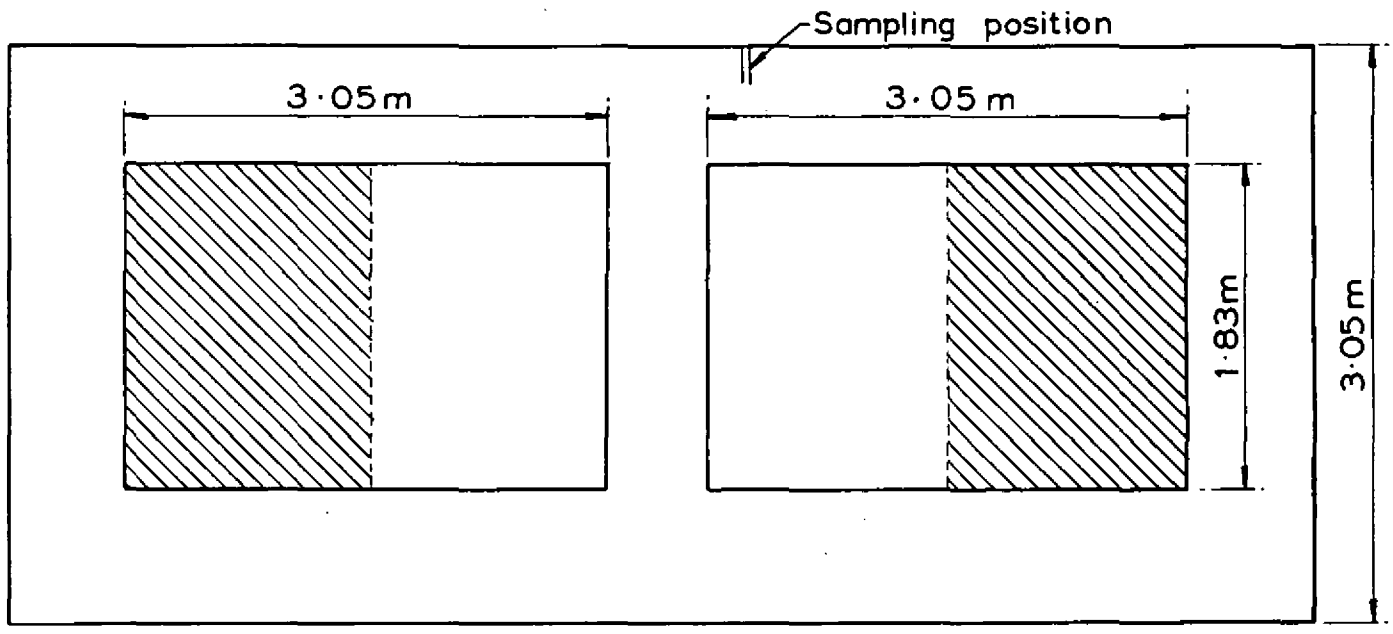


FIG. 3. 0·76m³ CUBICAL BOX 15cm VENTILATION SLIT DURING TEST



PLAN



ELEVATION

Note:

Ventilation:- Hatched areas of windows sealed for lower level of ventilation.

FIG. 4. SKETCH OF FULL SIZE ROOM

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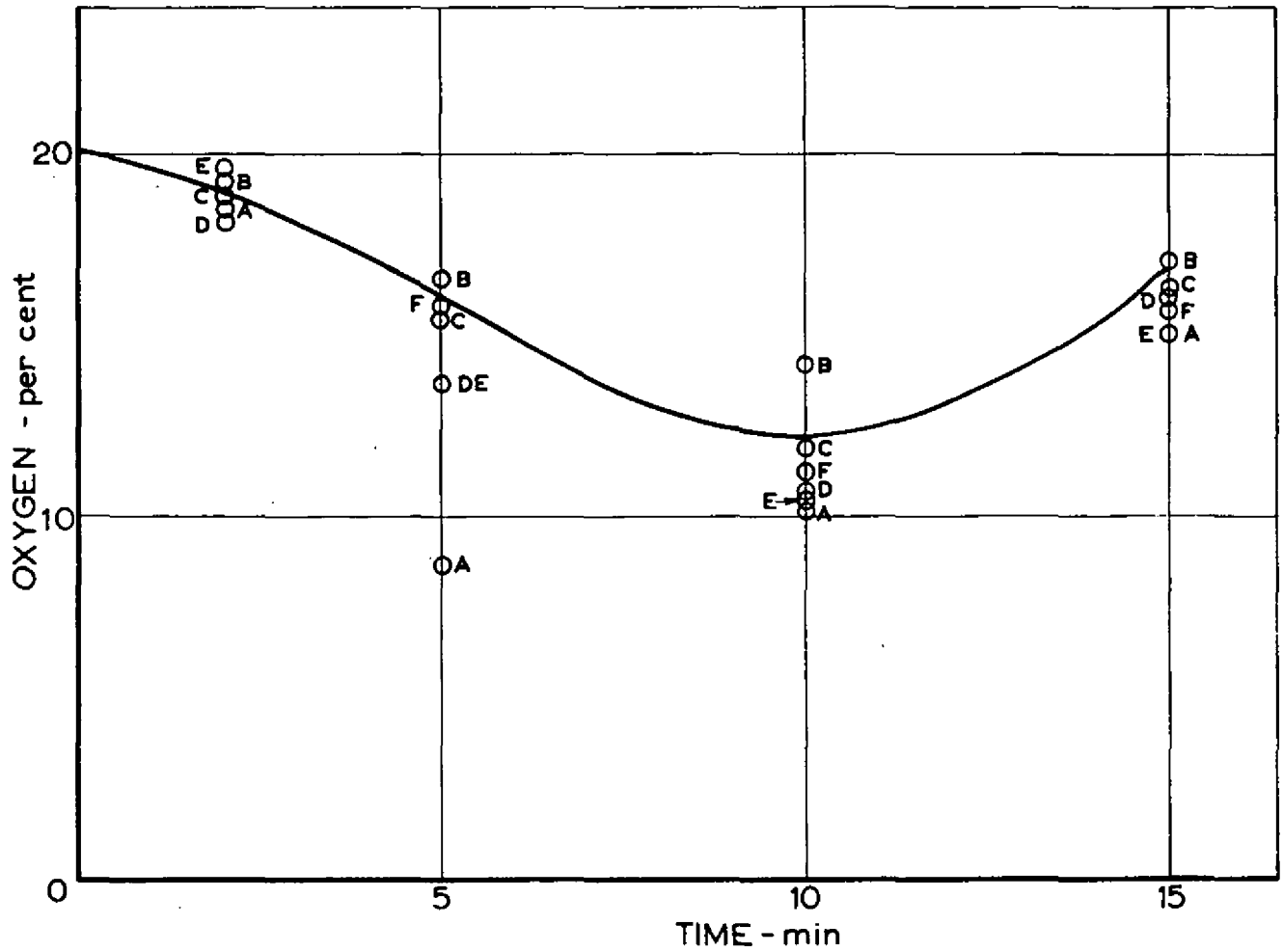
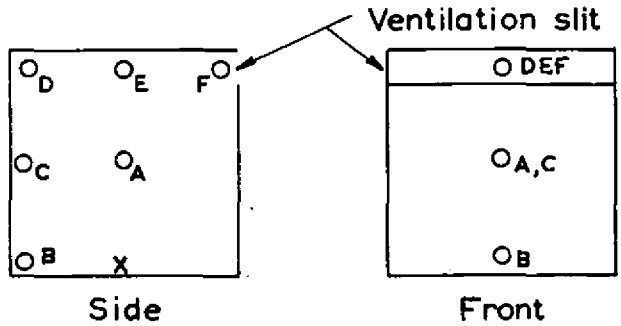


POSITION OF SAMPLING POINTS



ELEVATION

Conditions of test

$O_A - O_F$ = Sampling points used
X = Igniter
Fire load = 3 kg Fibre board crib
Vent area = 0·1395 m^2

FIG. 5. OXYGEN CONTENT OF ATMOSPHERE DURING TEST IN 0·76 m^3 CHAMBER

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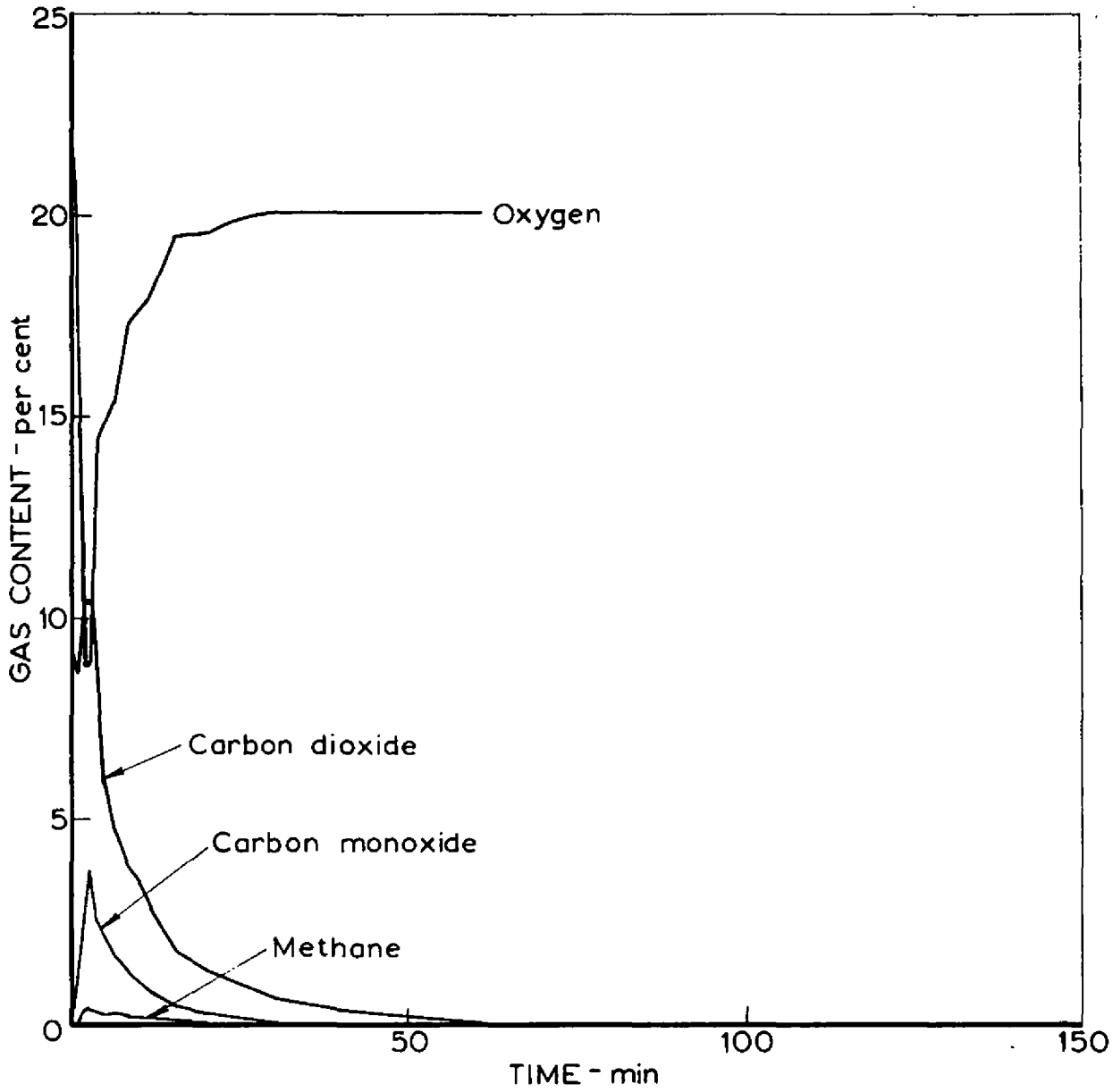
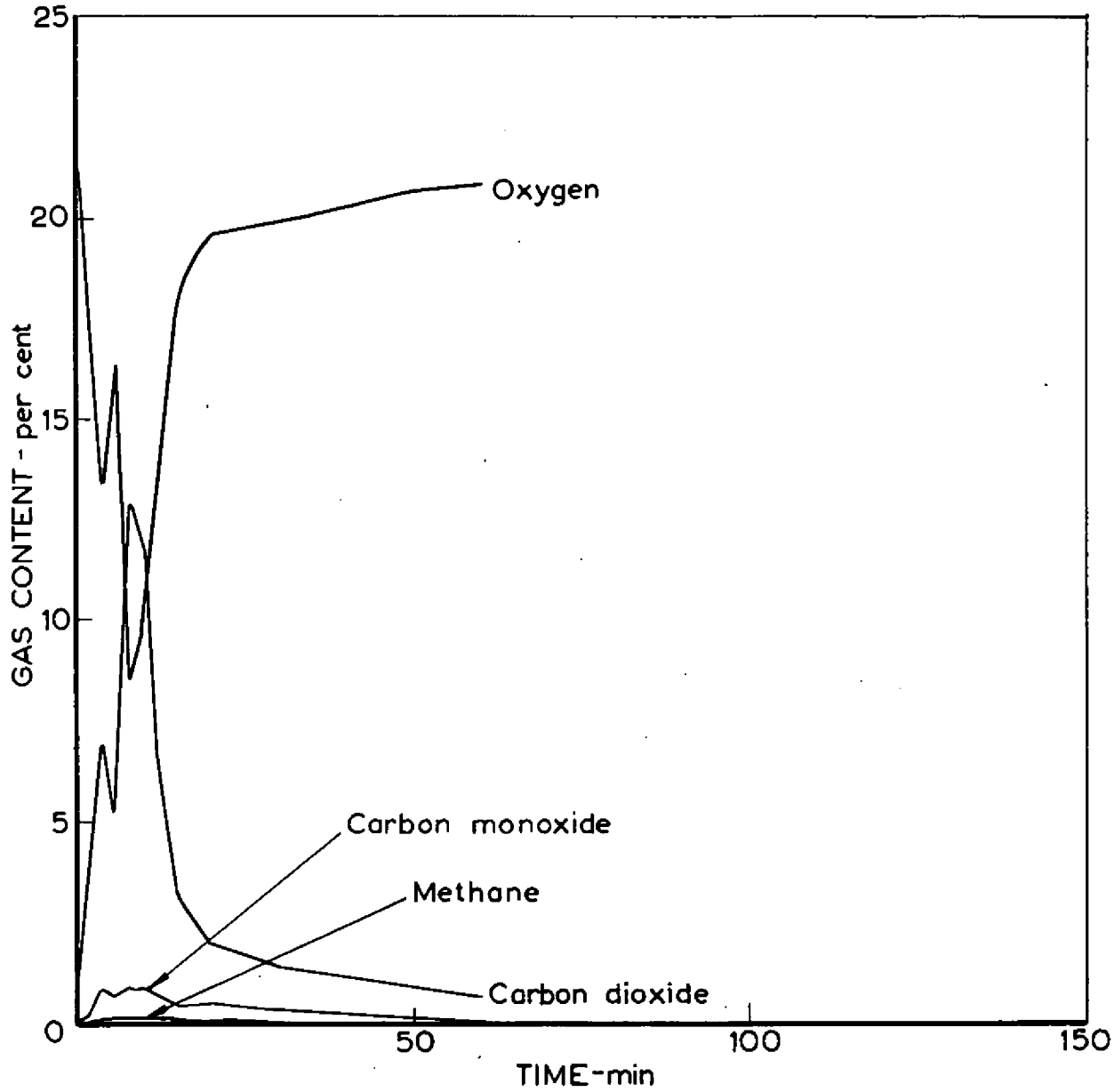


Behaviour - pattern A

Vent area	=	0·0464 m^2
Fuel	=	Wood wool
Load	=	1·6 kg
Mean density	=	14·1 kg/m^3

FIG. 6. COMPOSITION OF COMBUSTION GASES DURING TEST IN 0·76 m^3 CHAMBER



Behaviour - pattern A

Vent area	=	0·1390 m^2
Fuel	=	Wood wool
Load	=	3·2 kg
Mean density	=	28·2 kg/m^3

FIG. 7. COMPOSITION OF COMBUSTION GASES DURING TEST IN 0·76 m^3 CHAMBER

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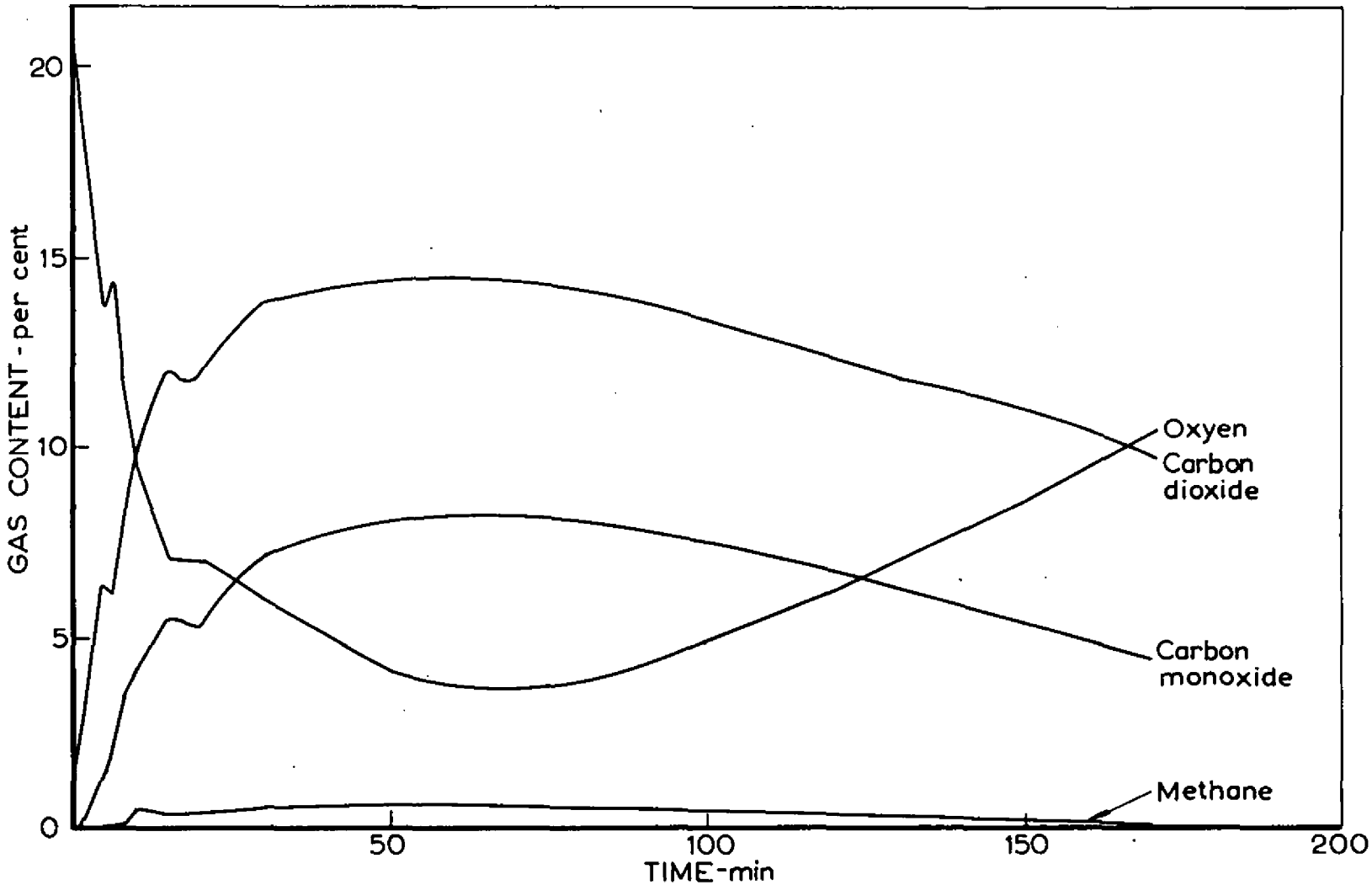
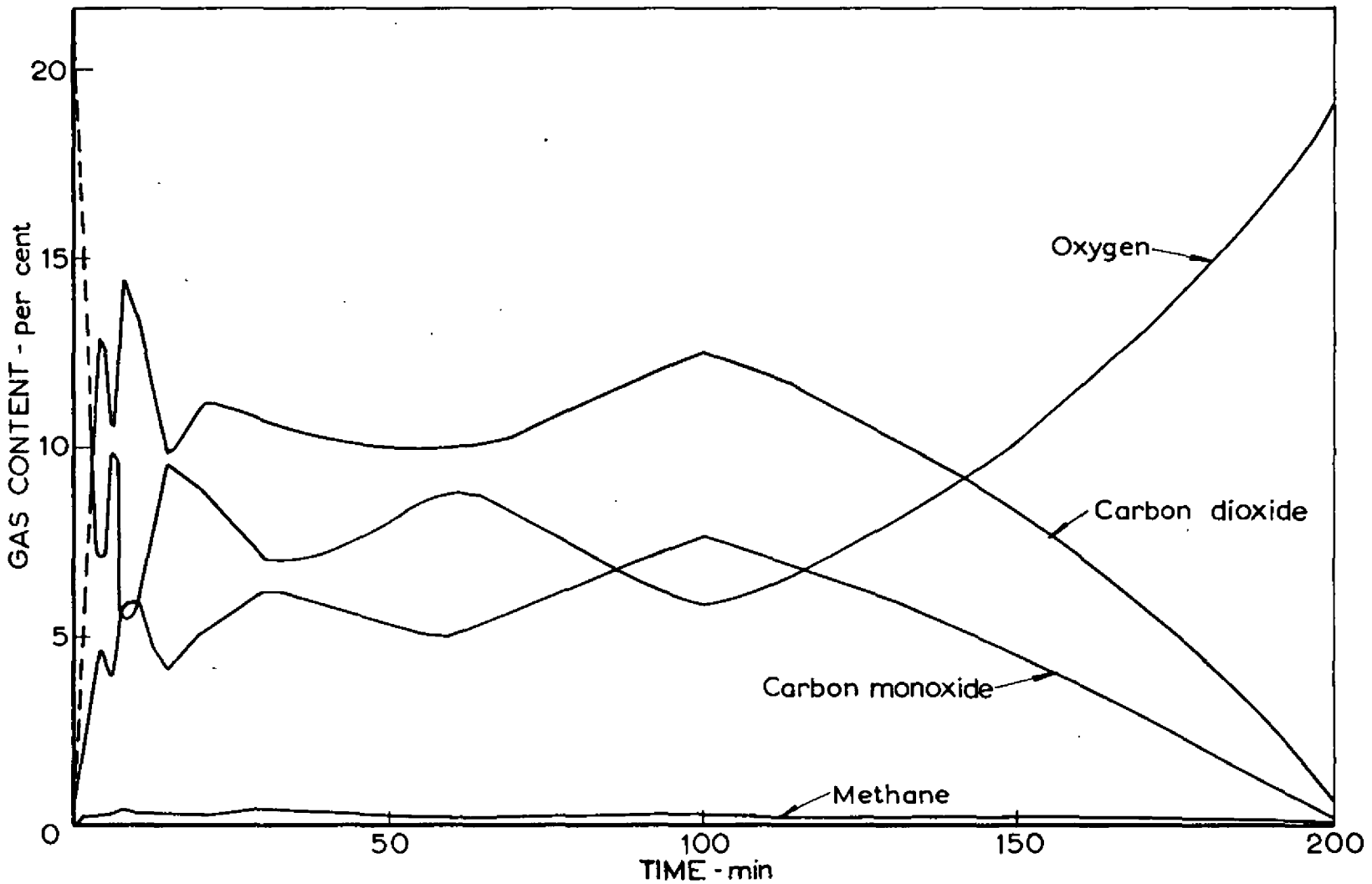


Behaviour - pattern B

Vent area	=	0·0029 m^2
Fuel	=	Wood wool
Load	=	6·4 kg
Mean density	=	56·4 kg/m^3

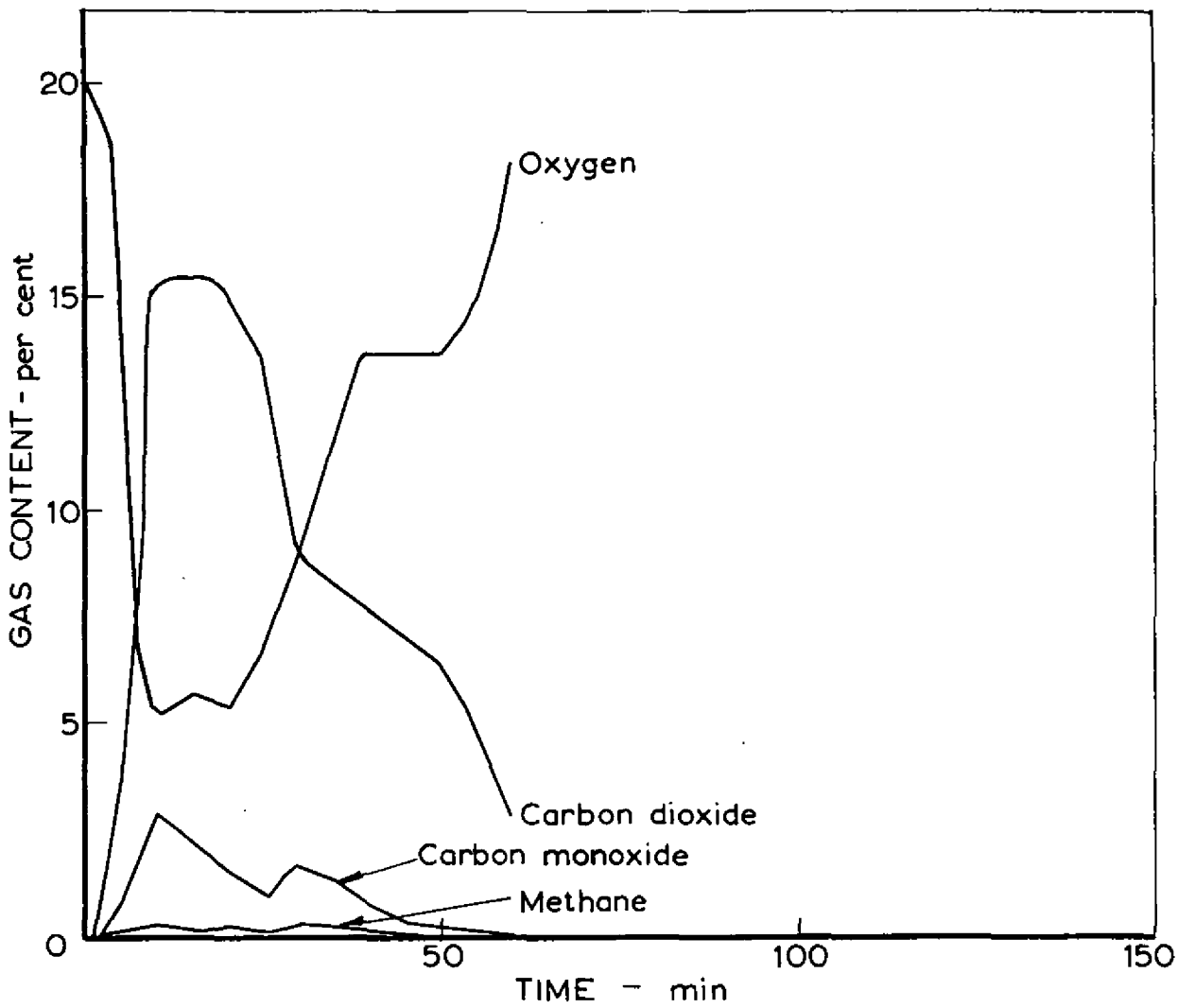
FIG. 8. COMPOSITION OF COMBUSTION GASES DURING TEST IN 0·76 m^3 CHAMBER



Behaviour - pattern C

Vent area	=	0·0116 m^2
Fuel	=	Wood wool
Load	=	3·2 kg
Mean density	=	28·1 kg/m^3

FIG. 9. COMPOSITION OF COMBUSTION GASES DURING TEST IN 0·76 m^3 CHAMBER



Behaviour - pattern B

Vent area	=	0·0928 m^2
Fuel	=	Fibre board crib
Load	=	6·4 kg
Mean density	=	140 kg / m^3

FIG. 10. COMPOSITION OF COMBUSTION GASES DURING TEST IN 0·70 m^3 INSULATED CHAMBER

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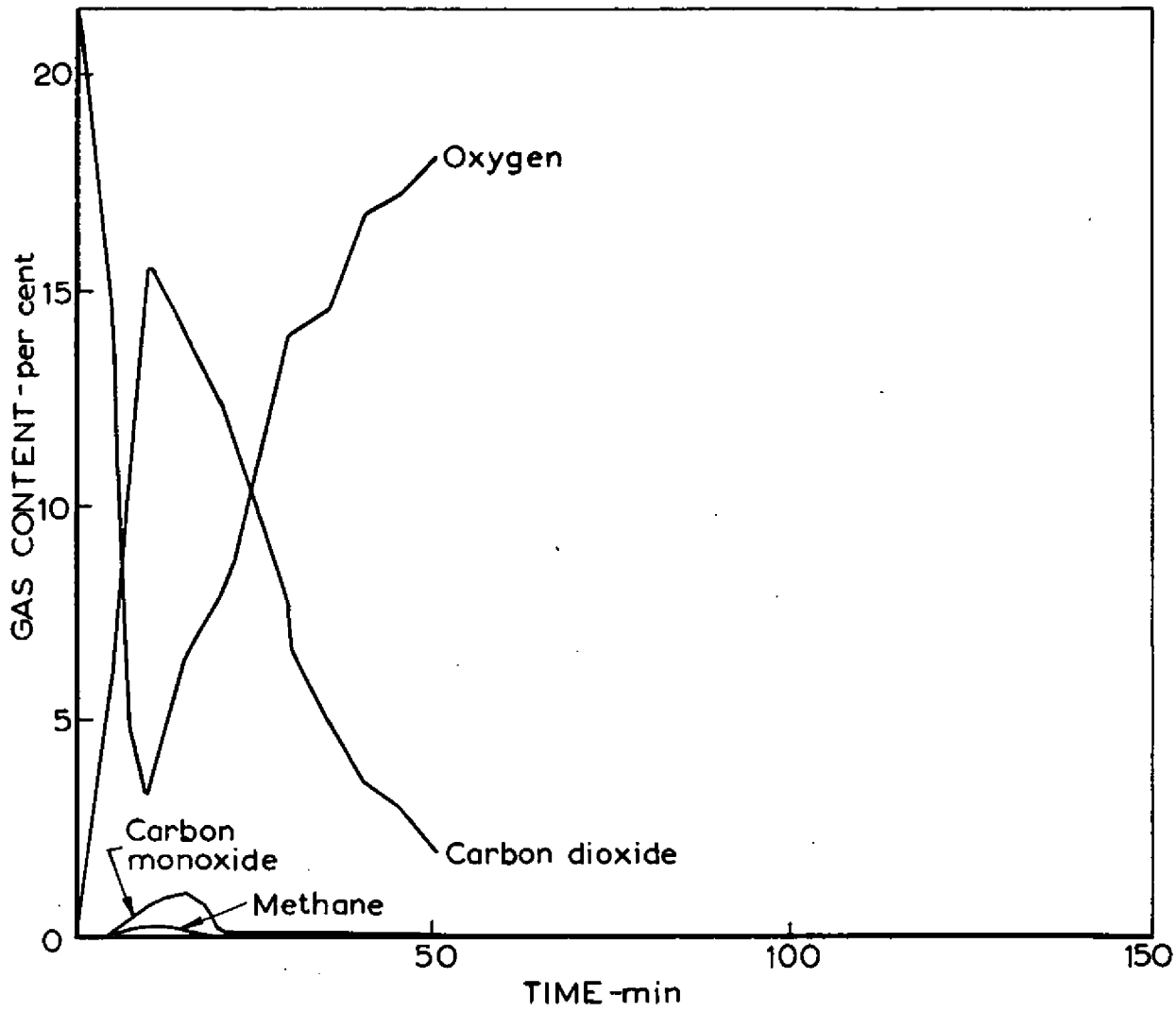

Behaviour - pattern B

Vent area	=	18·3 m²
Fuel	=	Wood 2in x 2in section
Load	=	850 kg
Mean density	=	225 kg/m³

FIG. 11. COMPOSITION OF COMBUSTION GASES DURING TEST IN FULL SCALE ROOM

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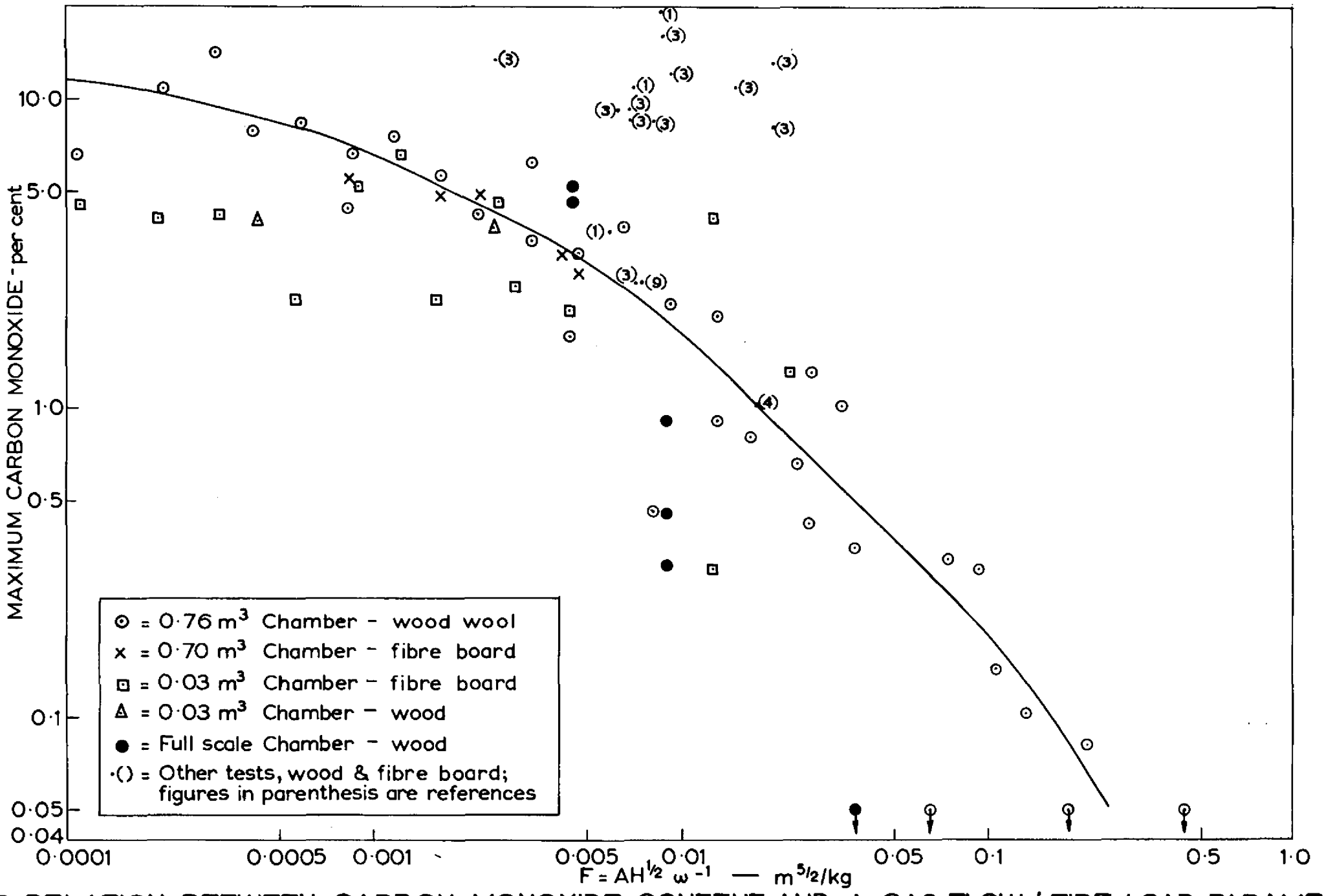


FIG. 12. RELATION BETWEEN CARBON MONOXIDE CONTENT AND A GAS FLOW / FIRE LOAD PARAMETER

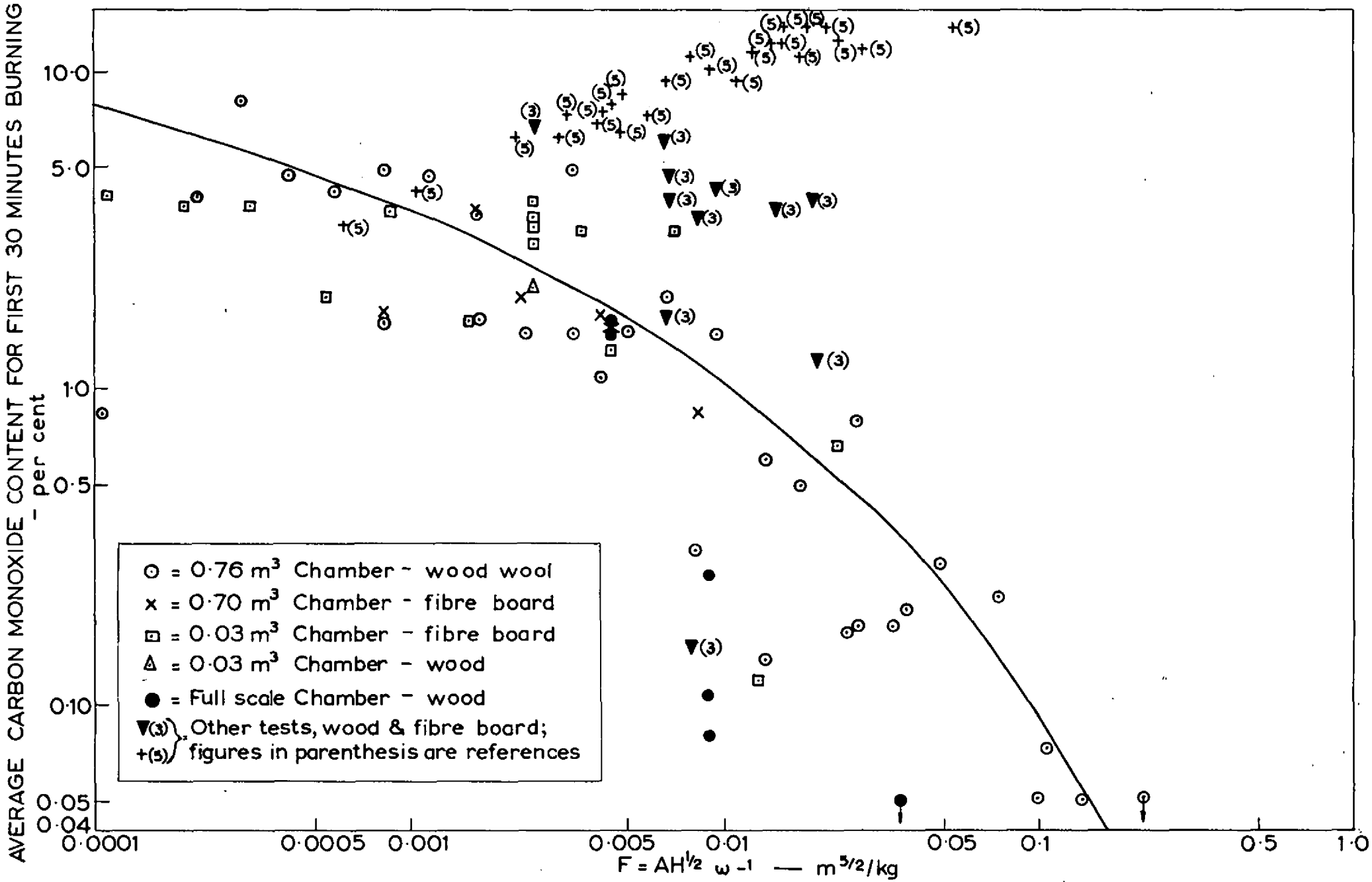


FIG. 13. RELATION BETWEEN AVERAGE CARBON MONOXIDE CONTENT FOR 30 MINUTES BURNING, AND GAS FLOW / FIRE LOAD PARAMETER

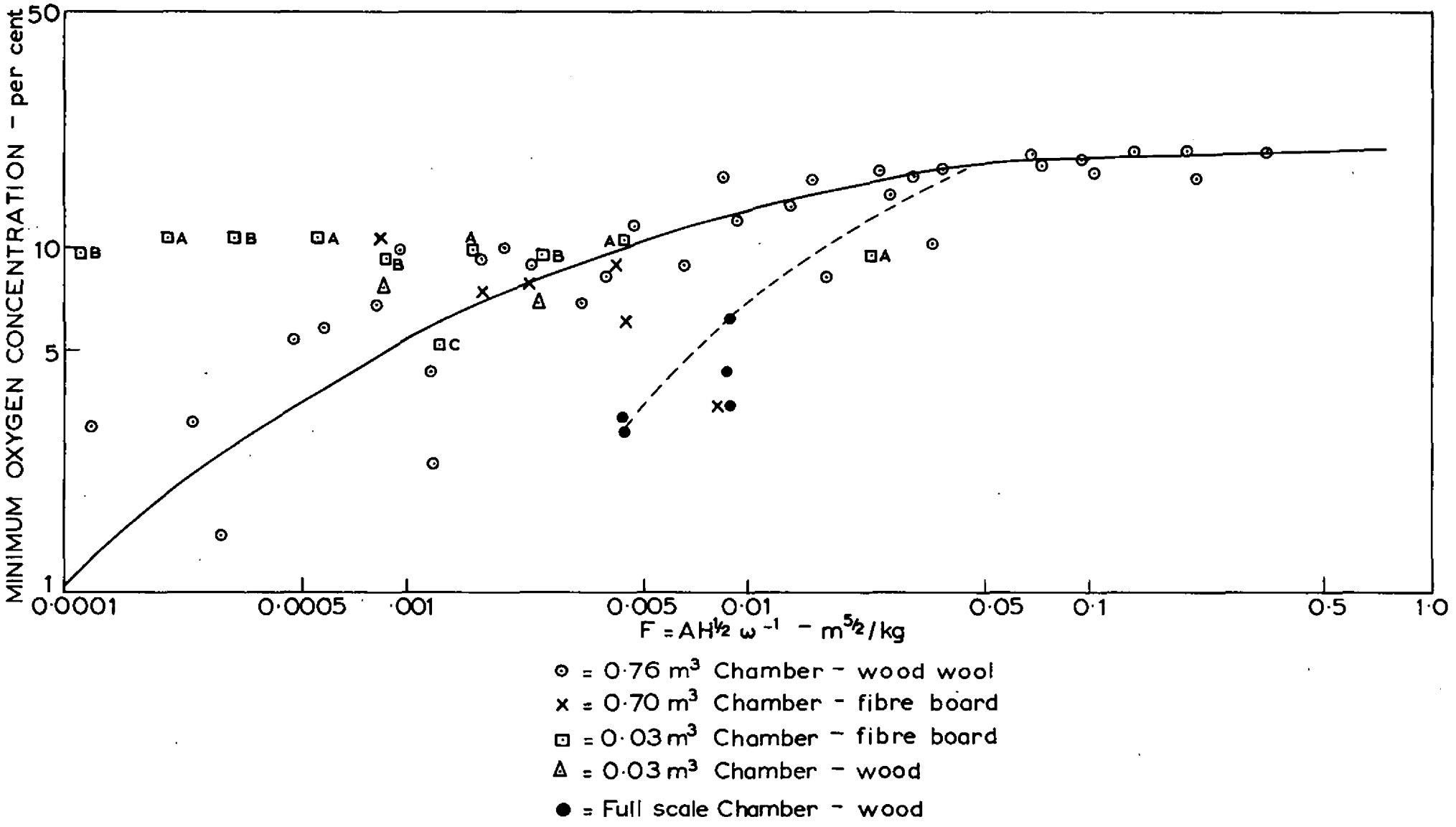


FIG. 14. RELATION BETWEEN OXYGEN CONTENT AND GAS FLOW / FIRE LOAD PARAMETER

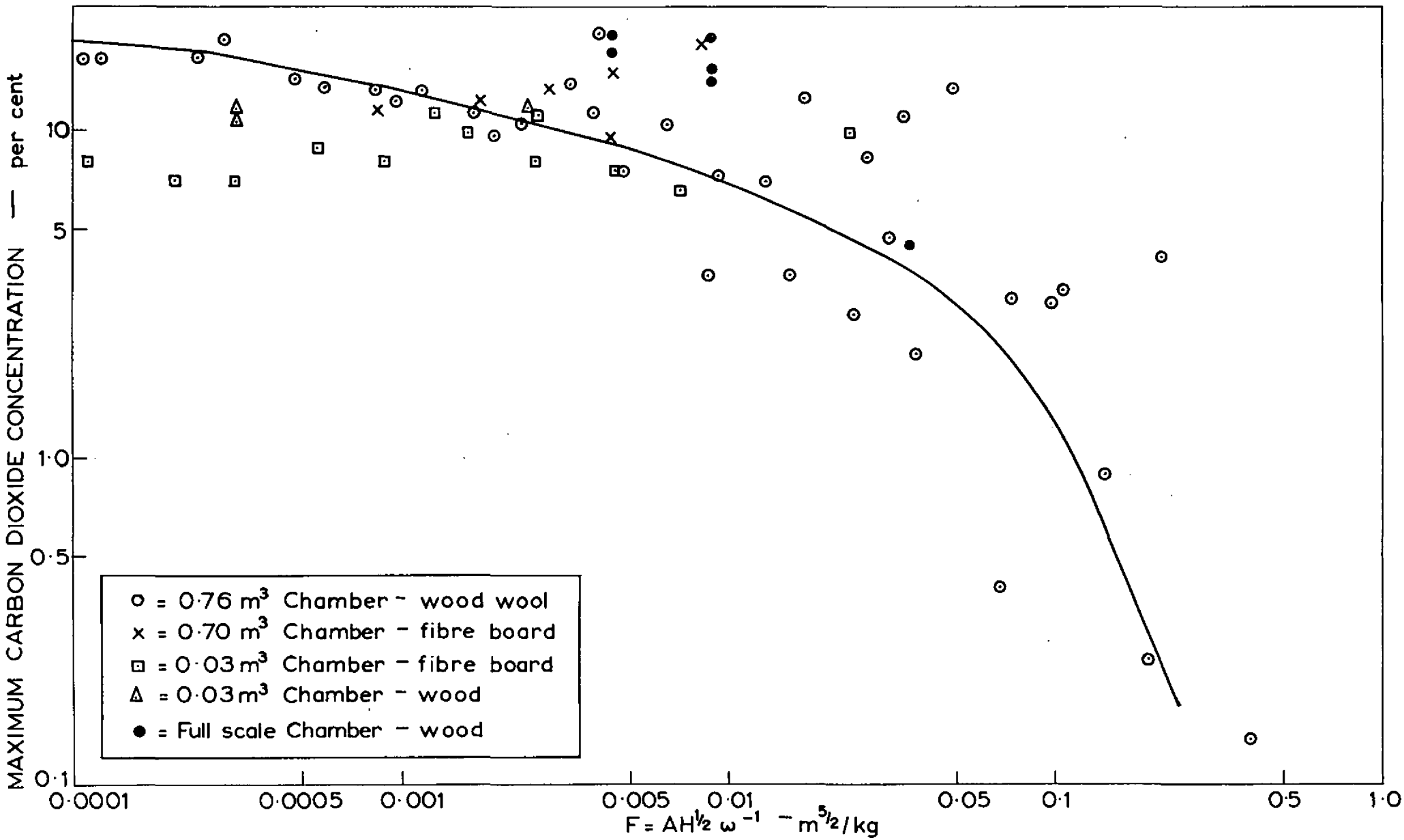


FIG. 15 RELATION BETWEEN CARBON DIOXIDE CONTENT AND GAS FLOW/FIRE LOAD PARAMETER

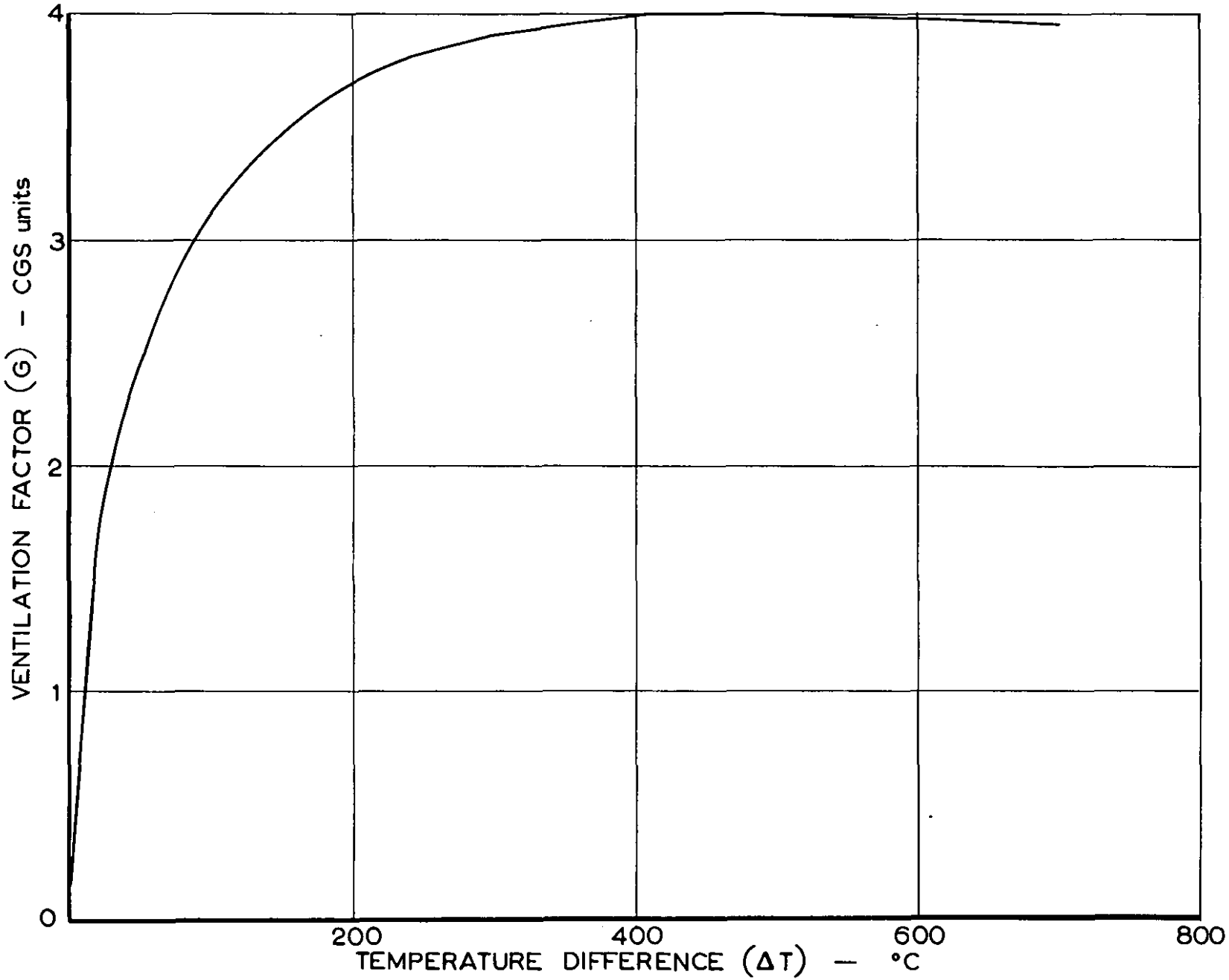


FIG. 16 EFFECT OF TEMPERATURE ON PARAMETER (G) FOR GAS FLOW CALCULATION

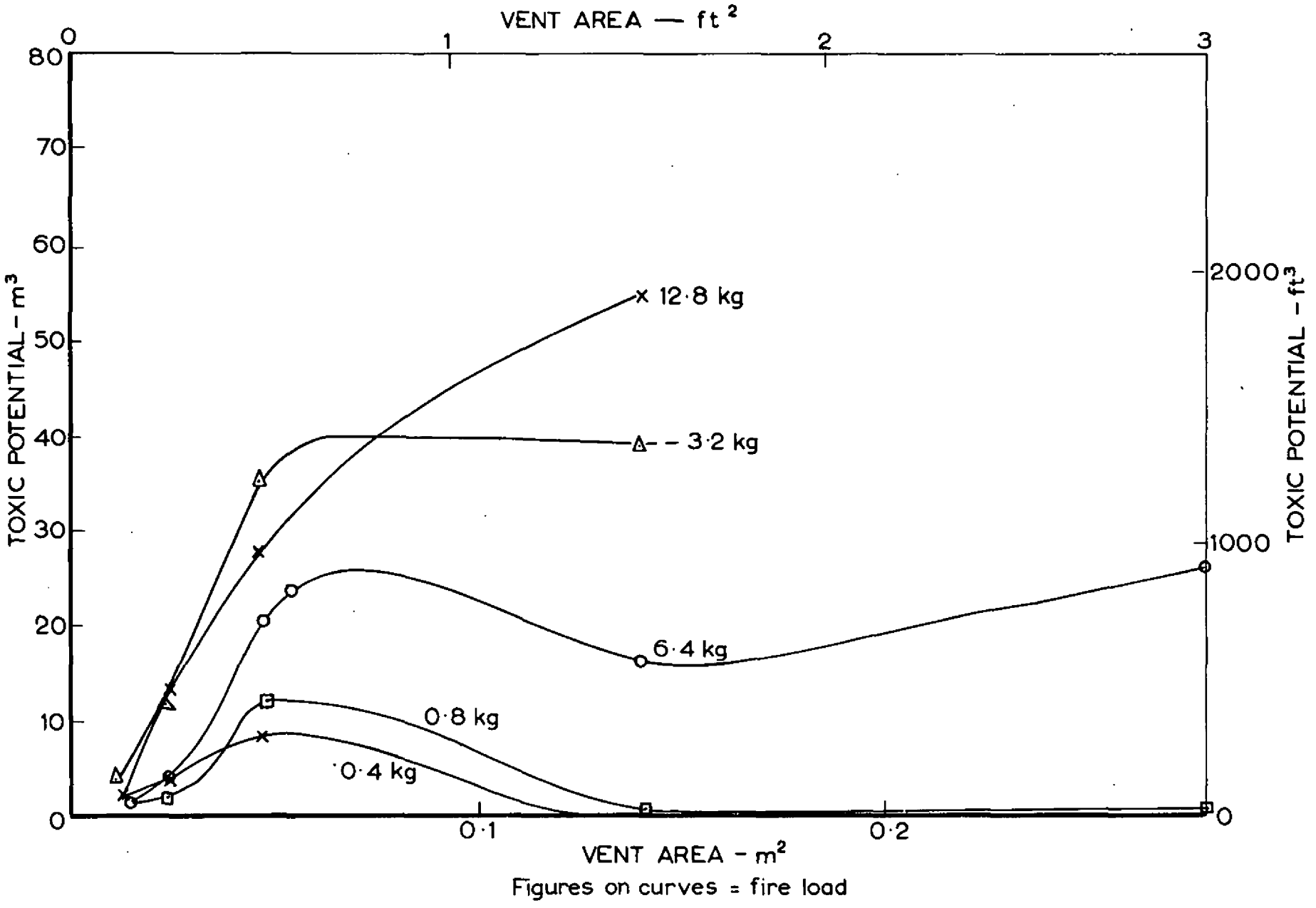


FIG. 17. TOXIC POTENTIAL, 15 MINUTES BURNING TIME

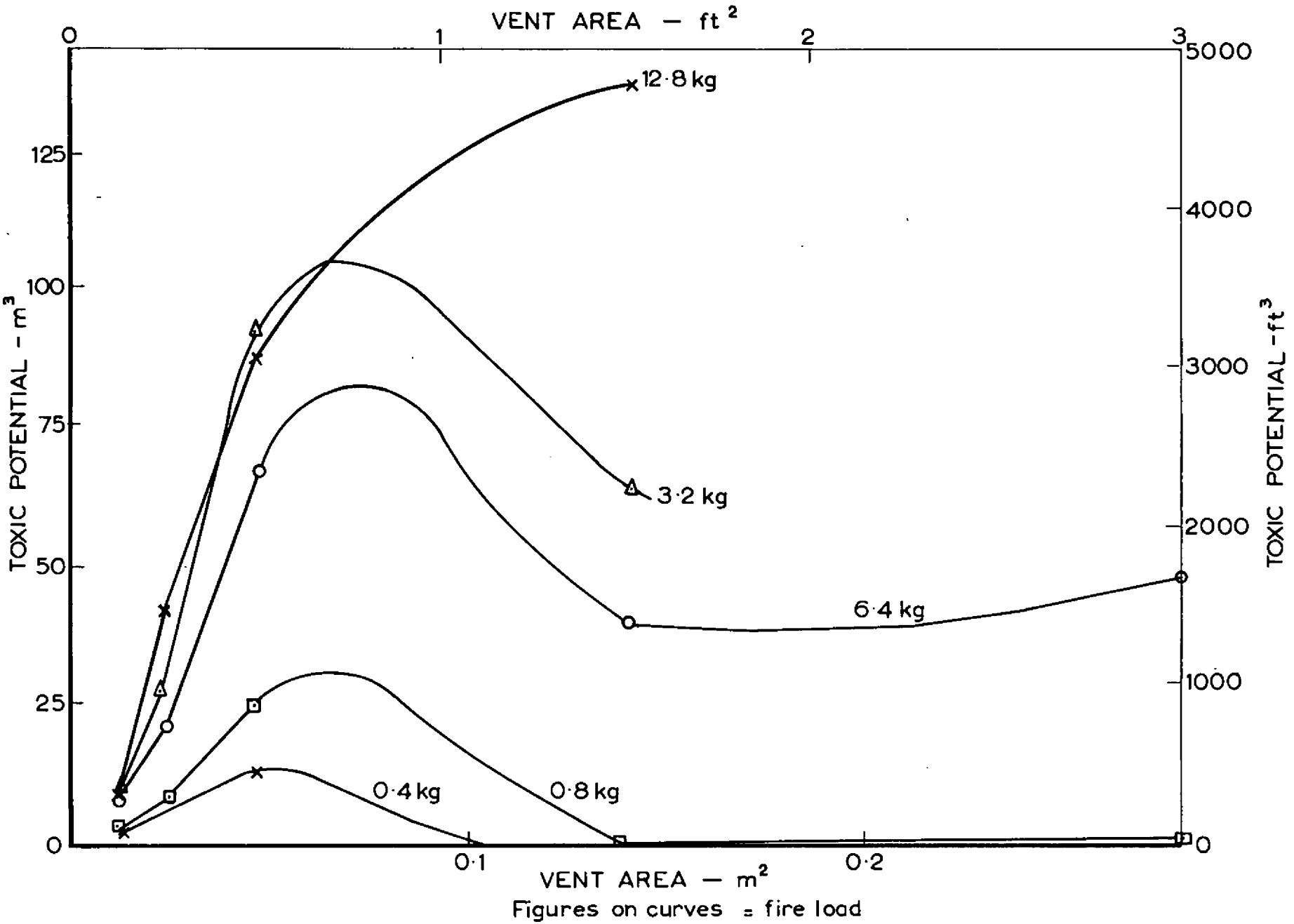
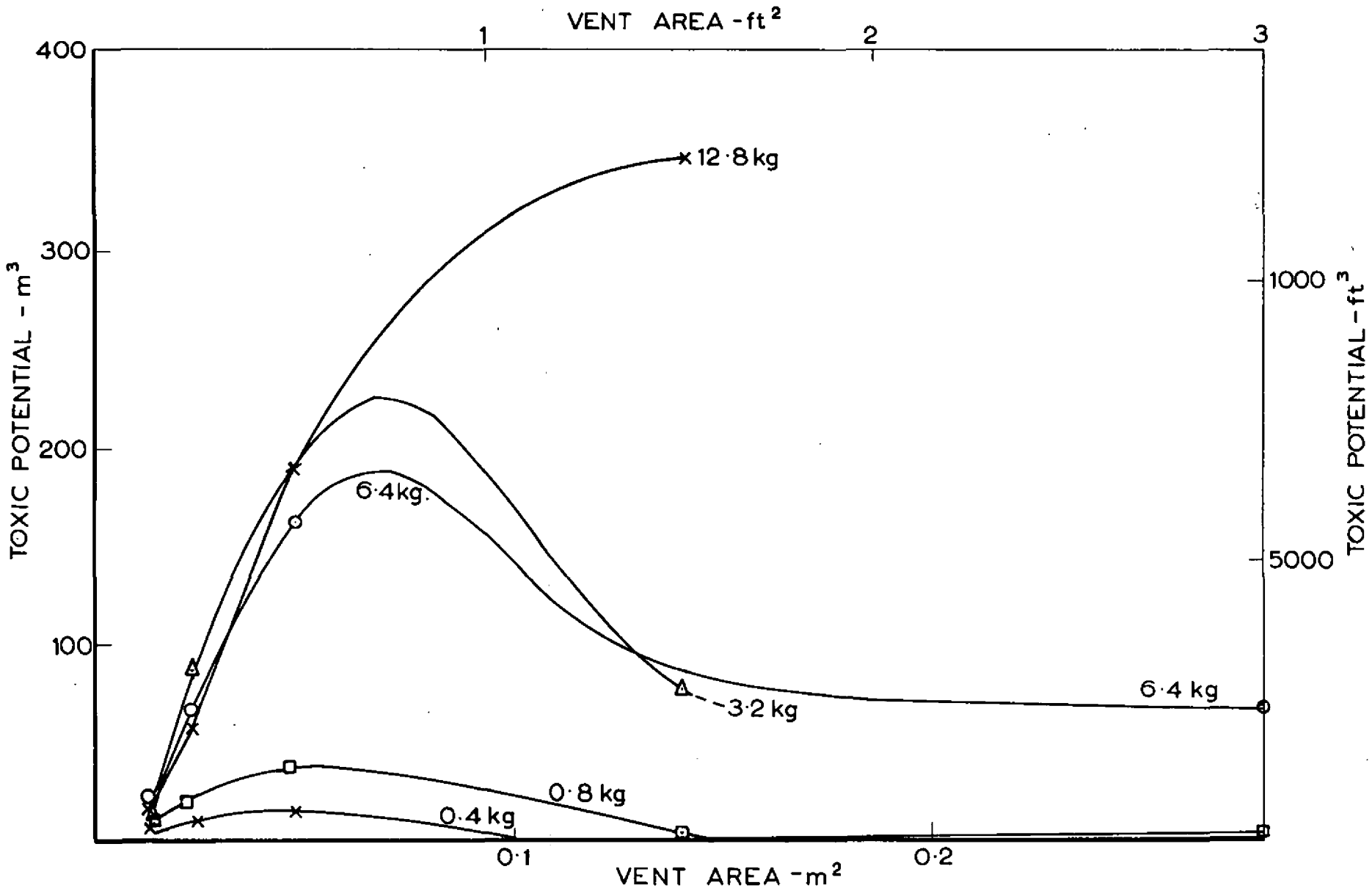


FIG. 18. TOXIC POTENTIAL, 30 MINUTES BURNING



Figures on curves = fire load

FIG. 19. TOXIC POTENTIAL, 60 MINUTES BURNING

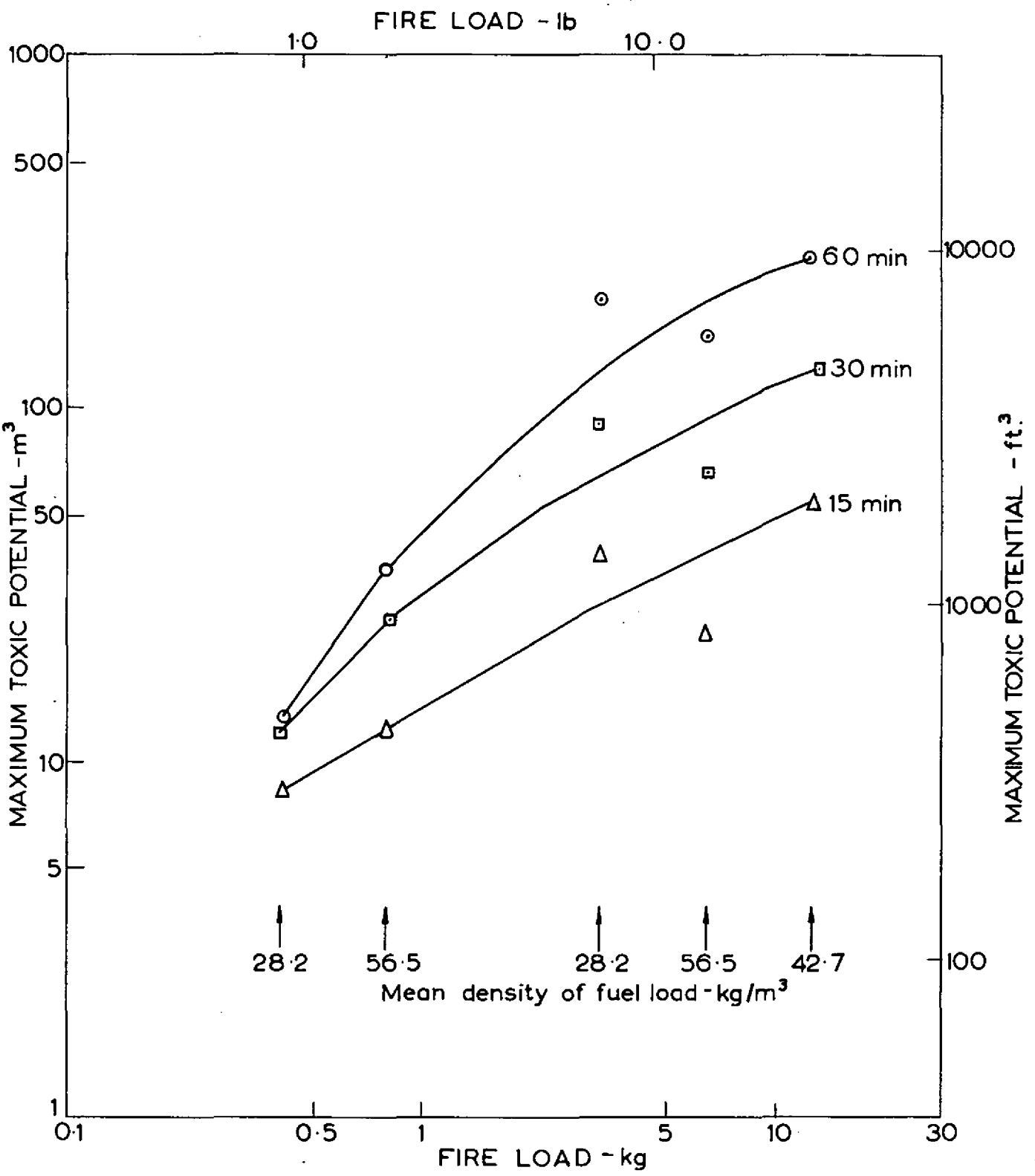


FIG. 20. EFFECT OF FIRE LOAD ON MAXIMUM TOXIC POTENTIAL

1/6804 F.R. 614

1/6805 F.R.614

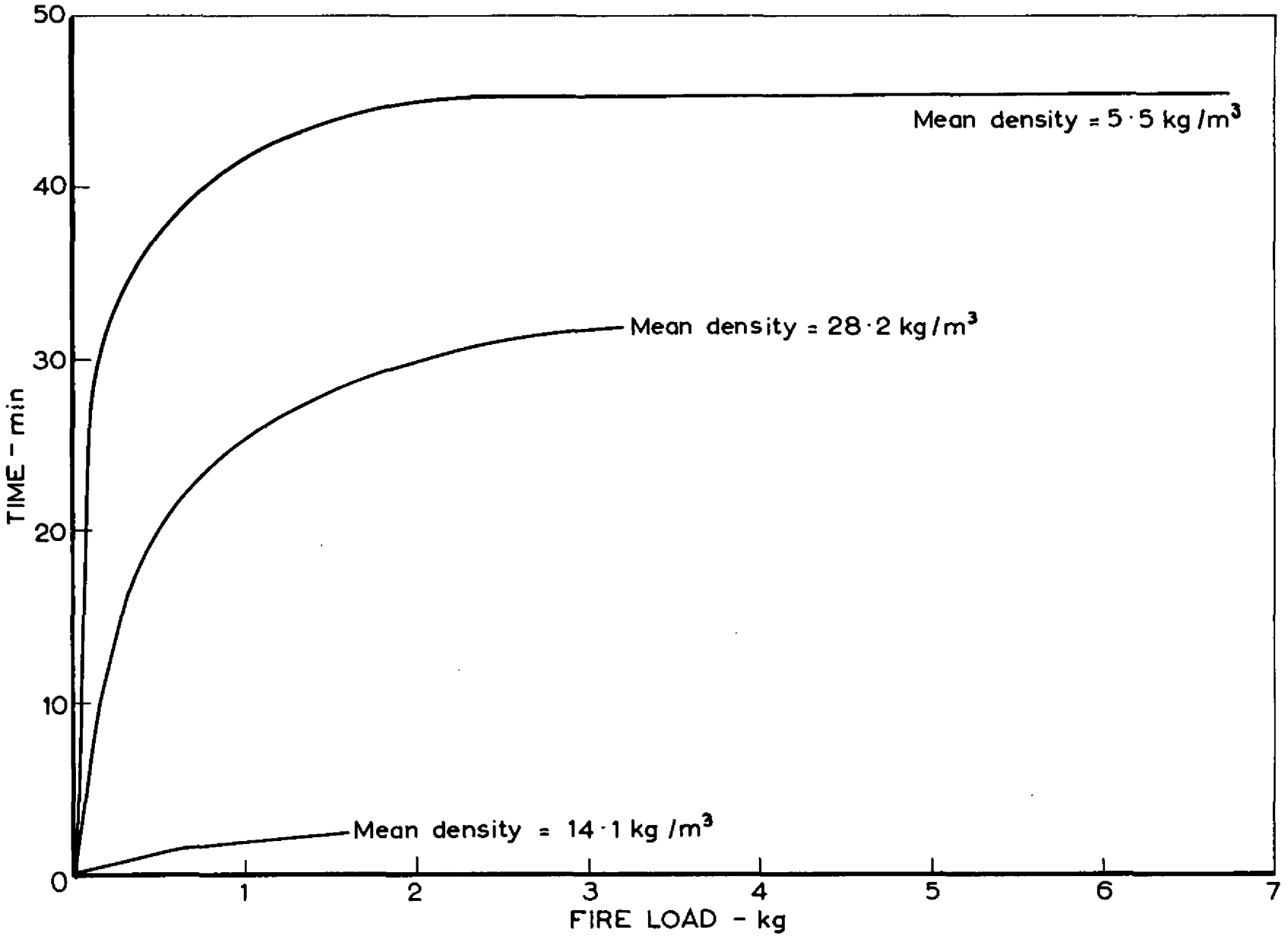


FIG. 21. EFFECT OF MEAN DENSITY OF FUEL LOAD ON TIME TO REACH MAXIMUM CONCENTRATION OF CARBON MONOXIDE OF FIRE GASES