



Fire Research Note

No 1030

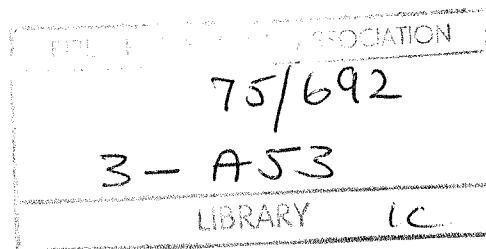
TOXIC GASES AND SMOKE FROM POLYVINYL CHLORIDE
IN FIRES IN THE FRS FULL-SCALE TEST RIG

by

G W V STARK and P FIELD

April 1975

FIRE
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SUMMARY

Tests in which the contribution of wall linings of PVC to the fire hazards presented by traditional combustible material (wood) are reported.

PVC linings in a compartment did not significantly change maximum fire gas temperatures, or smoke density, but increased the overall outputs of heat and smoke. Their main contribution was to the toxic gases by the addition of hydrogen chloride to the carbon monoxide from the combustion of wood.

PVC wall paper and cloth did not contribute much to the hazard from a wood fire in a compartment. However PVC in a corridor could lead to the discharge of larger concentrations of hydrogen chloride.

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1. INTRODUCTION

The major part of the combustible material in the structure and contents of buildings, in particular, dwellings, is cellulosic in origin, for example, wood, paper, cellulosic building boards and cotton. However, in the past decade or so synthetic plastics have been increasingly used, augmenting and replacing traditional materials.

The presence of plastics in buildings may alter the amount and composition of the products of combustion, smoke and toxic gases, produced in a fire. Any such changes can be measured directly, by using a test rig containing the appropriate fire load of combustibles, in which the conditions arising in a typical fire incident can be simulated in a realistic and reproducible way. Such measurements also require apparatus for the collection and quantitative estimation of the smoke and gases produced.

The results of laboratory pyrolyses and small scale fire tests conducted at the Fire Research Station, which allow identification of expected products of combustion have already been reported^{1,2,3}, as also have some tests in the open air⁴. Quantitative prediction of the products of combustion likely to occur in a full-scale fire, however, is not possible because, firstly, of the possible absence of product-consuming flames in small-scale pyrolyses, secondly, of the larger thermal losses occurring in small-scale structures as compared with large-scale structures and thirdly, of the uncontrolled influence of wind in outdoor tests.

For these reasons, a large-scale test rig, consisting of a compartment and a communicating corridor, has been constructed at the Fire Research Station in the Moels Laboratory, a large barn-like building, so as to ensure freedom from the effects of wind and weather. Some tests in which wood was the only fuel burned in the compartment of the rig have been reported⁵. These tests have shown that the rig provides a means of conducting fire tests in a thermally reproducible manner.

A simple analysis of variance on results from a series of fire tests indicated that differences in fire load and ventilation had significant effects on the products of combustion⁵. However, as it is customary to report maximum or extreme values of temperature, smoke and toxic gases, the validity of simple analyses of variance on these quantities is in doubt. For this reason, extreme value statistics have been applied to data from some of the tests reported here, and form the subject matter of a separate Fire Research Note⁶.

The tests reported here examine the burning of mixed fire loads of wood and PVC (polyvinyl chloride) wall linings, (PVC is one of the commonest plastics used in buildings) and a comparison is made between the results from these tests and the previous tests of wood alone. The wall linings tested were a rigid, unplasticised, sheet PVC, 3 mm thick, a decorative wall-cloth and a decorative wall-paper. The purpose of the tests was to determine the contribution of such wall linings to the smoke and toxic gases from a supporting wood fire, and to examine the feasibility of predicting the production of toxic gases from basic data gained from laboratory studies of the thermal decomposition of PVC^{3,7}, and of predicting the production of smoke from the characteristics of fire load and ventilation.

2. EXPERIMENTAL

The test rig consisted of a compartment and corridor, illustrated in Figs 1 and 2, in which the only opening in the compartment communicated with the corridor; a detailed description is given elsewhere⁵. The compartment, measuring approximately 3 m square and 2.4 m high, was constructed from 150 mm thick slabs of reinforced aerated concrete, and the corridor, approximately 12 m long and 1.3 m wide was constructed from similar slabs of 100 mm thickness. All internal surfaces were rendered with a heat-resisting low-density rendering supported on wire mesh or expanded metal lathing. The end of the corridor close to the compartment was sealed with a wall of lightweight concrete blocks, and the other end of the corridor was left unrestricted.

2.1. Compartment ventilation

Because the sole opening to the compartment was from the corridor, air to support combustion passed through the corridor, entering the compartment through the lower part of this opening, which extended to ceiling level, while the fire gases passed through the upper part of the corridor into the open space of the Models Laboratory. Two widths of compartment opening, 240 mm and 700 mm, were used

in these tests. Such conditions make calculations of gas flows relatively simple, and at the same time represent conditions that could occur in a fire incident, resulting in the maximum accumulation of combustion products within a building.

2.2. Fire load

The basic fire loads of wood consisted of cribs of sticks 1.5 m long and 50 mm square section, laid with a space of approximately 200 mm between sticks, with alternate layers at right angles with each other, to form a stack of 1.5 m square base and weights of 120.5 and 241 kg⁵. These weights produce fire loads of 13.5 and 27 kg/m² (approximately 3 and 6 lb/ft²). Fires were started in all tests by first igniting, by means of an electrically heated wire, a narrow band of 1 kg of wood wool laid at the base of the crib.

The 3 mm thick rigid PVC sheet was fixed to the walls by mushroom headed nails; the PVC coated wall-paper and wall-cloth were stuck to the wall with a water based cellulosic adhesive. The content of PVC polymer, required for quantitative data on the chlorine content, was determined in separate experiments. The rigid PVC sheet contained only pigments and stabilising additives, whereas the wall paper and wall-cloth contained in addition an alkyl ester plasticiser.

Conditions of test did not permit full control of the moisture content of the fuels and the compartment, but the compartment was heated before tests to above ambient temperature for a time sufficient to dry out the cellulosic adhesive, and in most tests to reduce the moisture content of the wood to less than 12 per cent, a value permitting easy ignition⁵.

2.3. Temperature

The temperature of the fire gases was measured 150 mm below the ceiling, at the opening between the compartment and corridor and at 2 m intervals along the corridor to 10 m from the compartment opening, close to the open end of the corridor, Figs 1 and 2, by means of 1.5 mm diameter stainless steel sheathed thermocouples, and plotted by a multi-point potentiometric recorder. Recording was maintained throughout the flame burning period and continued thereafter until the temperature at the compartment opening was less than 300°C.

2.4. Fire gases

The important toxic gases are carbon monoxide and hydrogen chloride in these tests. Samples of fire gases were withdrawn through internally lacquered stainless steel tubes of 6-8 mm bore, which were heated resistively to at least 150°C, and collected

for subsequent analysis. Samples were collected from the opening between compartment and corridor, and 10 m away at the open end of the corridor. Because of the release of a small amount of hydrogen chloride from the coating of lacquer, short lengths of sampling tube fitted with a lining of silica tube were used for the collection of samples from the tests with PVC faced wall-paper and wall-cloth, for which the amount of PVC was small.

The concentration of hydrogen chloride in the fire gases was calculated from the amounts absorbed in aqueous solutions of sodium bicarbonate, through which the fire gases passed at a measured rate for successive measured periods of time during the tests. The concentration of hydrogen chloride in the bicarbonate solution was measured with a selective ion electrode. Separate sampling tubes were used for the collection of fire gases for the measurement of concentrations of oxygen, nitrogen, carbon dioxide and carbon monoxide. After scrubbing to remove most tars and soot, the gases were drawn at a measured rate through a series of gas pipettes, which were isolated from the gas flow and sealed at selected times during tests. The contents of the pipettes were subsequently analysed by gas-solid chromatography.

The measurements of hydrogen chloride were therefore of the average concentration over the periods of sampling, whereas the measurements of the other gases were of the concentrations existing at the time of sampling. The composition of the fire gases is reported for dry gas, and no measurements were made of the water content of the gases.

2.5. Air speed

The speed of entry of air into the corridor was measured by a remote-indicating sensitive anemometer placed 500 mm above the floor at 10 m from the compartment opening, Figs 1 and 2. The output was recorded for about 20 min where the anemometer had to be removed to prevent thermal damage. The values so obtained were used to calculate the flow of air into, and of fire gases out of, the corridor.

2.6. Smoke

The method adopted for the measurement of smoke utilised the attenuation of a beam of light. A quartz-halogen lamp, placed on the roof of the corridor at its open end, was focussed onto a selenium photocell, the output from which was arranged to be proportional to the incident light flux. The photocell was fixed rigidly 5 m above the ground at 10 m beyond the open end of the corridor, Fig.3.

Separate experiments had shown that the angle of incidence of the light beam to the smoke plume did not change the recorded attenuation from that for light passing at right angles to the smoke plume⁵, and that the only significant alteration in the capacity of the smoke was that due to the lateral increase in cross section of the beam.

The attenuation of a beam of light on passing through a particulate suspension (smoke) is given by:

$$I = I_0 e^{-knL} \quad (1)$$

where I_0 = unattenuated light flux at photocell
 I = attenuated light flux at photocell
 L = path length of smoke traversed by the light beam
 n = number of particles of smoke in unit volume
 k = an extinction coefficient, containing contributions from the particle sizes and their distribution (assumed constant)

Optical density is defined as the logarithm to base 10 of the ratio of incident to attenuated light flux (I_0/I), and is thus directly proportional to the path length L through the smoke. Measured values were converted to the value within the corridor 10 m from the compartment opening, by multiplying by the ratio of the width of the plume at the point of measurement to that of the width of the corridor⁵. Thus values of temperature, toxic gases, and smoke are presented for a single site close to the open end of the corridor.

Because the optical density is directly proportional to the number of particles of the same distribution in unit volume, n , of the measured smoke, an estimate could be made of the amount of smoke evolved during each test by

$$P = \int_0^t S D_m A dt$$

over the time t min of smoke evolution, where

where S = exit speed of fire gases and smoke, m/min
 D_m = optical density for 1 m path length through smoke
 A = area of cross section of smoke, m^2
 P = estimate of total particulate matter (smoke)

The optical density of smoke over a fixed distance, D_m , permits comparison of the obscuration of vision at a given time by smoke produced from different fire conditions and fire loads⁸, whereas the quantity P permits a comparison of the total output of smoke between different fire conditions and fire loads⁹. The value of D_m at any selected site can be calculated from the measured value of D and the observed thickness of the smoke layer at that site, assuming that the thermal conditions at that site do not alter the amounts of non-solid material in the smoke, and that aggregation and precipitation have not occurred.

2.7. Observations

Tests were observed during the burning period to note the nature of burning, and the corridor and compartment were examined after each test, to determine the nature and extent of any residues. Particular note was taken of the thickness of the layer of smoke and fire gases at the open end of the corridor, and of the extent of flaming emerging from the compartment into the corridor. These observations were an addition to data obtained by measurement.

3. RESULTS

The results of the tests are summarised in Table 1. Extreme values only are presented for gas concentrations, temperatures and optical densities of smoke, but the complete experimental records of these quantities, in conjunction with the average rate of flow of the fire gases^{1,10}, were used to calculate the total yields of carbon monoxide and hydrogen chloride, and the integrated smoke density, P . The observed thickness of the layer of smoke in the corridor at the point of measurement 10 m from the opening between compartment and corridor was 1 m when the fire had developed fully; hence the recorded values are of D_m , directly applicable to calculations of P and visibility through smoke⁸.

3.1. Statistical analysis

The results in Table 1 are grouped so as to permit comparisons between tests with wood cribs and linings, and tests of wood cribs alone⁵. Statistical analyses are necessary to determine the significance of observed differences and trends. Although cumulative and average values have a Gaussian distribution and can be examined by standard analyses of variance, this is not so for extreme values for which special methods must be used. The extreme values recorded here have been examined in this way, a full report being given elsewhere⁶. Table 2 presents data for significant extreme values in related tests in Table 1, and Table 3 presents data for some of the integrated values in Table 1. The levels for significance that should be adopted are dependent upon the number of tests analysed and the

method of analysis; a level of 25 per cent was adopted (2 tests) for data in Table 2⁶, and 10 per cent (8 tests) for the data in Table 3. The tests used to construct these tables are Nos 1,2,3,6,8,10,11 and 13, these being the only tests in which the factors are fully tested. The absence of significance for all 'other' factors (column 3, Table 2) for any 'test' factor (column 2, Table 2) implies overall non-significance of the test factors. However, some consistent differences were recorded which are discussed below.

3.2. Wood fire load

An increase in the fire load of wood increased the maximum temperatures of fire gases (Table 1 compare test 1 with tests 8 and 9, and test 3 with tests 11 and 12) and also increased the total amount of carbon monoxide produced and the time of burning. Although the maximum optical density of the smoke was little altered by an increase in fire load, the total amount of smoke was greater for the greater fire load (for example, compare tests 3 and 11). The presence of the fire load as wall lining and crib or as crib alone made little difference to the maximum temperature of the fire gases, but gave higher maxima at the open end of the corridor (compare tests 8 with 9 and test 11 with 12). No consistent variations were shown between the compositions of the fire gases, or the maximum optical densities of smoke between the two distributions of the fire load of wood.

3.3. Wood and PVC fire loads

The presence of a heavy PVC lining in the compartment produced a slight but universal increase in maximum temperature at the compartment opening (Table 1), and when a similar load of PVC was present in the corridor only, there was a large increase in the temperature at the open end of the corridor, although only part of the PVC was consumed. (Table 1, compare tests 6 and 13 with tests 7 and 14). The effect of the presence of PVC on maximum concentrations of carbon monoxide is complex. The significant effects noted in Table 2 for concentration at the compartment opening for the two fire loads of wood are in opposing directions, and further tests are needed before the apparent effects can be fully explained. It would appear, however, that the effect of the presence of PVC at the larger degree of ventilation was small when the fire load of wood was small.

The variations in optical density of smoke with differing fire loads, Table 1, were apparently erratic. Although it is often stated that PVC produces dense black smoke, under the conditions investigated, tests with PVC did not differ greatly in maximum densities from those of wood alone, and in many tests were less (compare tests 3, 8 and 11 with 6, 10 and 13, Table 1).

TABLE 1
SUMMARISED RESULTS OF FIRE TESTS

Test No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Wood kg	Crib Wall	120.5 0	120.5 0	120.5 0	120.5 2.0	120.5 2.3	120.5 0	120.5 0	241 0	103.5 137.5	241 0	241 0	103.5 137.5	241 0	241 0
PVC kg	Wall Corridor	0 0	95 0	0 0	0.91 0	2.63 0	95 0	0 115	0 0	0 0	95 0	0 0	0 0	95 0	0 115
Vent width, mm		240	240	700	700	700	700	700	240	240	240	700	700	700	700
Max. fire gas temp. °C	Vent Corridor	870 300	950 300	925 420	930 430	880 410	975 430	970 500	960 380	960 570	1010 340	1100 635	1070 680	1020 550	1090 650
Time of burning, min*		30	40	20	15	15	20	20	40	45	50	30	25	30	30
Oxygen min. per cent	Vent	2.3	4.8	2.8	1.3	7.5	1.4	8.8	8.2	6.8	14.0	5.0	7.2	4.5	2.2
CO ₂ max. per cent	"	18.8	14.6	17.7	18.8	13.9	16.4	12.8	14.2	12.9	6.4	13.7	12.1	14.5	13.8
CO max. per cent	"	0.2	4.6	1.1	2.5	0.2	2.0	0.5	3.5	4.8	>1.8	6.0	2.4	1.9	7.2
HCl max. per cent	"	0	5.6	0	0.003	0.068	3.1	0.34	0	0	3.8	0	0	4.0	1.9
Oxygen min. per cent	Corridor	14.5	13.8	12.2	11.0	17.4	11.8	12.0	11.9	9.2	F	7.0	7.1	12.8	6.1
CO ₂ max. per cent	"	7.0	6.0	9.1	10.6	5.3	7.7	8.4	8.2	11.4	F	14.1	13.1	7.3	13.0
CO max. per cent	"	0.8	2.3	0.3	1.7	ND	0.35	ND	2.7	1.1	F	1.6	1.3	1.8	2.1
HCl max. per cent	"	0	>0.08	0	0.003	0.026	0.6	4.65	0	0	0.25	0	0	1.0	12.9
Optical density	Max.	2 41.3	2.9 196.6	3 77.4	3.4 63.6	3.3 71.5	2 120	5.6 105.6	4.0 106.1	2.5 217.4	>2 >200	3.2 242.8	4.7 273.6	2.6 244.8	4.0 308.8
CO kg	Vent	1.9	21.6	4.4	8.2	0.75	11.8	1.6	12.2	19.6	9.7	50.6	16.2	34.7	67.0
HCl kg	"	0	71	0	0.03	0.87	67	5.1	0	0	32	0	0	40.2	43.8
HCl yield per cent	"	0	151	0	6	58	142	21.7+	0	0	67.3	0	0	84.6	84.6+

Notes: * = Time of burning with luminous flames

F = Fault in sampling system. Loss of sample

ND = Not detectable. Limit of detection for carbon monoxide = 0.01 per cent (100 ppm)

+ = Estimated value, allowing for incomplete combustion of PVC

TABLE 2
SIGNIFICANT COMPARISONS FROM EXTREME VALUES, TABLE 1

Measurement	Test factors compared	Other factors	Z
Max. Temp. vent	$P_0 \text{ v } P_{95}$	$L_{241} + V_{700}$	0.689
Max. CO ₂ vent	$V_{240} \text{ v } V_{700}$ $P_0 \text{ v } P_{95}$	$P_{95} + L_{241}$ $L_{241} + V_{240}$	0.898 0.563
Max. CO vent	$V_{240} \text{ v } V_{700}$	$P_0 + L_{241}$	0.726
"	$P_0 \text{ v } P_{95}$	$L_{120.5} + V_{240}$	1.066
"	"	$L_{241} + V_{700}$	0.936
"	$L_{120.5} \text{ v } L_{241}$	$P_{95} + V_{240}$	0.971
"	"	$P_0 + V_{700}$	0.842
Min. O vent (Test 7 excl)	$P_0 \text{ v } P_{95}$	$L_{120.5} + V_{240}$	0.702
Max. CO ₂ Corr.	$P_0 \text{ v } P_{95}$	$L_{241} + V_{700}$	0.589
Max. CO Corr.	$V_{240} \text{ v } V_{700}$	$L_{120.5} + P_{95}$	0.581
"	$P_0 \text{ v } P_{95}$	$L_{120.5} + V_{240}$	0.578
Min. O Corr.	$P_0 \text{ v } P_{95}$	$L_{241} + V_{700}$	0.731
"	$L_{120.5} \text{ v } L_{241}$	$P_{95} + V_{700}$	0.597

NOTE: The groups examined for statistical analysis in this table are compared against isolated pairs of the other two factors. The analysis therefore differs from an analysis of variance, in which the effect of changes in one factor are analysed for all combinations of the other factor. The necessarily small numbers of tests thus result in the adoption of a higher significance level than is usually accepted.

TABLE 3
SIGNIFICANT COMPARISONS FROM INTEGRATED VALUES, TABLE 1

Measurement	Site	Factors	Sum of squares	Degrees of Freedom	Variance Ratio	Significance %
Total CO	Vent	Wood load	569.5	1	3765	1
		PVC load	9.5	1	62	-
		Vent size	393.4	1	2601	5
		WP	258.8	1	1711	5
		WV	624.8	1	4130	1
		PV	82.6	1	546	5
		Residual	0.15	1		
Total smoke	Corridor	Wood load	16056.3	1	297	5
		PVC load	10789.8	1	199	5
		Vent size	2485.1	1	46	-
		WP	1300.5	1	24	-
		WV	6160.5	1	114	-
		PV	5132.6	1	97	-
		Residual	54.1	1		
Time of burning	-	Wood load	200	1	10	10
		Vent size	450	1	22.5	1
		Residual	100	5		

Abbreviations

CO = carbon monoxide

W = wood load

P = PVC load

V = vent size

WP = interaction between the two factors

Test Nos 1, 2, 3, 6, 8, 10, 11 and 13 used to construct Table

The release of hydrogen chloride from those tests in which PVC was present as a thick wall lining in the compartment (Tests 2, 6, 10 and 13, Table 1) produced similar maximum concentrations at both the degrees of ventilation, as would be predicted from laboratory pyrolyses and small scale fire tests, in which it was shown that although the rate of release of hydrogen chloride from PVC was highly dependent on fire gas temperature the rate was so fast at temperatures in excess of 400°C that differences were insignificant^{2,7}. The calculated total amount of hydrogen chloride released in the above tests varied from 67 to 151 per cent of the amount that would be produced from the total conversion of the chlorine content of the polymer, (about 50 per cent by weight), but the average value for the four tests was not significantly different from 100 per cent.

The presence of a thick wall lining of PVC in the corridor (Tests 7 and 14) resulted in much higher concentrations of hydrogen chloride in the fire gases at the open end of the corridor, than were measured in the tests of compartment wall linings and, although no PVC was present in the compartment, relatively large concentrations of hydrogen chloride were also measured in the fire gases emerging from the compartment (Table 1). The calculated total amounts of hydrogen chloride in the fire gases are substantially different from those obtained in tests of compartment wall linings. The hydrogen chloride released from wall linings of wall-paper and -cloth, Tests 4 and 5, Table 1, were small in concentration, and the amount released for the tests with wall-paper was a very small proportion of the amount theoretically available.

3.4. Temperature of fire gases

Typical curves of the temperature of fire gases leaving the compartment are plotted against time of burning in Figs 4-8; the width of vent is indicated.

When all the fuel was in the compartment, for each vent size integration of temperature against time up to a final temperature of 300°C gave values approximately proportional to the heat of combustion of the combined fuel load⁵. The heat of combustion of PVC, estimated from the difference between the integrated curves for 121.5 kg of wood (heat of combustion 18.5 MJ/kg) and for 121.5 kg of wood plus 95 kg of PVC, is 18.5 MJ/kg compared with a quoted value of 19 MJ/kg¹⁵.

The reduction in temperature as fire gases passed through the corridor is illustrated in Figs 9-12. There was a large reduction in temperature between the thermocouple station at the opening between compartment and corridor and the station 2 m away in the corridor, after which the temperature decreased much less

rapidly between stations. Such a reduction could be brought about by dilution of the fire gases with some of the incoming air, enhanced by the observed turbulence arising from the change in direction of flow as the fire gases left the compartment and entered the corridor. The calculated rate of flow of air into the compartment and the rate of flow into the open end of the corridor, calculated from the speed of entry of air (see below), were used to calculate the temperature of the mixed air and fire gases emerging from the corridor, Table 4. The calculations were made for the maximum temperature at the compartment vent, and the temperature recorded at the same time at the open end of the corridor, with the assumptions that the air entered the corridor at 20°C and that the specific heats of air and the fire gases were the same. Maximum temperatures were recorded at the same time at both sites, except for tests 7, 9, 12 and 14 for which the maxima were 500, 570, 680 and 650 respectively. Calculated values for the smaller vent opening between compartment and corridor were less than, and for the larger opening, more than, the measured values. The calculated values for the larger opening approximated more closely to the measured values.

Although temperatures were not measured at different heights at the open end of the corridor, some measurements of the concentrations of toxic gases at 150 mm and 300 mm below the ceiling showed that higher concentrations were present closer to the ceiling, as would be expected from the mixing of counterflowing incoming air and outflowing fire gases, Fig.13. Mass and energy balances cannot therefore be drawn accurately from the typical measurements made 150 mm below the ceiling. However, a simple analysis of variance on the measured temperatures indicated that the weight of wood and the size of the compartment opening were of high significance, as also was their interaction, for the tests listed in Table 1. Other variables and interactions were not significant.

The temperature of the fire gases began to fall at about the time when it was observed that the combustion accompanied by bright flames was replaced by combustion with flames of low luminosity, at which stage the wood cribs had been reduced largely to carbonaceous residues, and when the PVC in the compartment was reduced mainly to convoluted heaps of a grey friable ash, at the base of the walls, some green tinged flames emerging from the larger heaps in the corners. The residues from the wood cribs continued to burn for at least as long as the brightly flaming combustion. The weight of PVC left at the end of flaming combustion was small, and when conditions became such that the corridor could be entered, it was estimated as less than 1 kg. No residues except ash were present at this stage from the wall linings of PVC paper or cloth.

TABLE 4

ESTIMATES OF EFFECT OF AIR ENTRAINMENT ON TEMPERATURE OF FIRE GASES

Test No.	Rate of flow Sm ³ min ⁻¹		Temperature at vent °C	Temperature from corridor, °C	
	Air	Fire gas		Measured	Calculated
1	91	20	870	300	207
2	91	20	950	300	224
3	104	60	925	420	542
4	105	60	930	430	540
5	103	60	880	410	521
6	104	60	975	430	571
7	109	60	970	350	543
8	100	20	960	380	208
9	111	20	960	370	189
10	96	20	1010	340	226
11	112	60	1100	635	599
12	112	60	1070	550	583
13	111	60	1020	550	561
14	112	60	1090	540	593

The combustion of 3 mm thick PVC linings in the corridor, Tests 7 and 14, was incomplete, and about 59 and 10 per cent respectively were recovered from the floor of the corridor after these tests. No analyses of variance were therefore made for these tests.

3.5. Movement of fire gases

Rates of flow of the fire gases from the compartment into the corridor, and from the open end of the corridor are required for the calculation of the mass balance of combustion products. Because there is an approximate equivalence between the rate of entry of air into a compartment, and the rate of emission of fire gases, shown by a relationship of the form^{1,10}

$$\dot{M} = \phi AH^{\frac{1}{2}} \quad (3)$$

where \dot{M} = mass rate of flow (of air or fire gases)
A = area of ventilation opening
H = height of ventilation opening
and ϕ = a factor dependent upon the discharge coefficient and increasing with the temperature of the fire gases, up to about 450°C, but substantially constant from 300°C.

Although direct measurement of the rate of flow of air into the corridor was made with an anemometer, for all but the most intense period of burning, the environment was too hostile for an anemometer to be sited at the compartment opening.

An anemometric survey of the area below the neutral plane indicated uniform air speed except close to the walls and the neutral plane separating the incoming air from the outgoing fire gases. Readings were taken from an anemometer at a single site on the axis of the corridor and 500 mm above the floor, which when multiplied by the area of cross section of the corridor below the neutral plane gave an estimate of the rate of entry of air. Also, because of the rapidity with which the neutral plane descended to a consistent distance below ceiling as the fire developed, approximately 1 m, this position of neutral plane was assumed to apply throughout the burning period.

The rates of flow calculated from Equation 3 and from anemometer readings are given in Fig.14, curves 3 and 4, for the input of air at the open end of the corridor, for differing temperatures of the fire gases. Differences between the curves are small for the temperatures of fire gases higher than 450°C; the smaller value of rate of flow for anemometric values below that temperature may be due to the neglected smaller heights of fire gases emerging from the corridor during the initial and final stages of burning. The rates of flow of air into, and hence fire gases out of, the corridor are substantially greater than the rates of flow from the compartment into the corridor, indicating that some of the air entering the corridor was entrained with the fire gases from the compartment.

3.6. Smoke

The optical density of the smoke produced by the fires was measured across the plume at the open end of the corridor, but the results presented in Table 1 are expressed as the optical density within the corridor 10 m from the opening between compartment and corridor, where both temperature and gas composition were measured. A test in which the optical density of smoke was measured at both these

locations indicated that the calculated values were sufficiently accurate⁵. Changes in optical density with time of burning are plotted in Figs 15-19. The curves have been smoothed to eliminate the rapid fluctuations of light flux at the photocell (for a typical record, see Fig.20), which had a period of a few hundred milliseconds, the mean value being plotted. Tests 6 and 10 were made with a recording system of limited range, covering only two orders of magnitude of attenuation. The remaining tests were made with recording systems covering 3 to 4 orders of magnitude, more appropriate for this work.

Optical densities, as plotted in Figs 15-19 were used to calculate P , the total amount of smoke, Equation 2 (see Table 1). Because of the similarity in density, and the mass equivalence of rates of flow of fire gases and air, Equation 3, the speed of exit of the fire gases S in Equation 2 is given by the product of the speed of entry of air and the ratio of absolute temperatures of the fire gases and air, and the inverse ratio of the areas of cross section occupied by them. Cross sectional areas were assumed to be constant for all tests, because the neutral plane was at a constant height after the first few minutes until burning was virtually complete.

The analyses of variance for the main group of tests, Nos 1, 2, 3, 6, 8, 10, 11 and 13, Table 3, indicated significance at the 5 per cent level for the effect of crib weight and presence of PVC on the parameter P . An analysis for the four tests Nos 6, 7, 13 and 14 did not indicate a significant effect of position of the 3 mm PVC lining (in compartment or corridor) although the effect of weight of wood was significant at the 5 per cent level. However, the incomplete combustion of the PVC in the corridor, and the small number of tests does not allow the conclusion to be drawn that no difference exists.

The effect of the presence of PVC as a wall lining in the compartment on the maximum optical density, Tests 1 and 2, 3 and 6, 8 and 10, and 11 and 13, Table 1, is not systematic but the presence of PVC in the corridor, Tests 7 and 14, resulted in higher optical densities than either wood alone, or wood and PVC in the compartment, although much of the PVC in the corridor was not consumed.

In most tests, the maximum optical density occurred within 5 min of the ignition. The exceptions were Tests 2 and 10, Table 1, in which PVC wall linings were present in the compartment, with a 240 mm wide opening for ventilation. In these tests the optical density increased gradually to a maximum at 15-20 min after ignition, Figs 15 and 18. The tests with PVC lining in the corridor gave the typical behaviour, Fig.19.

3.7. Toxic gases

The extreme values of the concentrations of oxygen, carbon dioxide, carbon monoxide and hydrogen chloride are given in Table 1 for all tests. Carbon monoxide and hydrogen chloride may present a toxic risk to occupants in a building fire. Graphs of the variation in concentration of these gases with time of burning are given in Figs 21-28 for some of the tests. The concentration of the gases in the fire gases has been plotted as multiples of the minimum concentrations presenting a short term (30 min) hazard, taken as 0.3 per cent volume (3000 ppm) for carbon monoxide, and 0.15 per cent volume (1500 ppm) for hydrogen chloride^{1,2}. More recent work as yet unpublished suggests that the appropriate value for carbon monoxide may be somewhat higher.

The data given in Table 1 and in Figs 21-28 suggests that PVC decomposes in a fire to give much hydrogen chloride and little carbon monoxide, with the exception of Test 2, in which the maximum concentration of carbon monoxide at the compartment vent was high compared with that in Test 1 of wood alone. The significances for carbon monoxide noted in Table 2, rows 5 and 6 are for effects of opposite sign, and therefore difficult to interpret. A simple analysis of variance suggested that only the weight of crib was likely to have a significant effect (compare Table 2 rows 7 and 8), but that there were strong interactions between the variables, crib weight, presence of PVC and width of vent. A simple analysis of variance on the calculated total amount of carbon monoxide passing through the compartment opening also indicated that the effect of the weight of crib was significant to the 1 per cent level, and the width of compartment vent was significant to the 5 per cent level, Table 3; again the interactions were of high significance. Statistical analyses of the concentrations or total amounts of hydrogen chloride at the compartment opening, between tests with PVC in the compartment or in the corridor would not probably be meaningful, because only part of the hydrogen chloride released from PVC in the corridor would be transferred to air entering the compartment and then re-emerge in the fire gases. Concentrations of any toxic gas at the open end of the corridor would also be unsuitable for analysis because of the stratification of fire gases at this point. However, it is shown from Table 1, and the rates of flow of the fire gases at compartment opening and at the open end of the corridor, that some of the hydrogen chloride may be lost on passing through the corridor, and that the concentrations from wall linings in the corridor were greater than those produced from wall linings in the compartment.

The concentrations of hydrogen chloride produced from wall linings of wall-paper and cloth, tests 4 and 5, Table 1, were very low. The lining of wall-paper not only gave a low maximum concentration, but also a particularly low recovery of available hydrogen chloride from the PVC.

4. DISCUSSION

The tests reported here were made to examine the hazards presented by fires of wood, and wood together with PVC, on a scale comparable with those of rooms in dwellings. An earlier report had indicated that the concentration of carbon monoxide from small scale fires could be predicted with reasonable accuracy from the parameter $AH^{1/2}/W$ Fig. 29¹. However, for large-scale fires, when the fire load was small or the ventilation large, no such relation was indicated, the concentrations of carbon monoxide deviating in a random manner from the previously determined relation⁵. Another series of small-scale tests had shown that the evolution of hydrogen chloride from a mixed fire load of wood fibre insulating board and rigid PVC sheet was dependent on fire gas temperature but not necessarily on ventilation².

It has been observed that darker and denser smoke is produced during large-scale fire tests on cellulosic materials than during small-scale tests, and that the introduction of halogenated material such as PVC can increase the density of smoke. However, there are few systematic measurements of the effects of fire load on smoke generation in small-scale fire tests¹¹ and a series of small scale fire tests is being conducted at the Fire Research Station to examine the effects of scale.

The present tests, although few in number, allow an estimate to be made of the significance of fire load ventilation of the compartment on fire and of the composition of the fire load on the rate of development and the intensity of burning (temperature), and on the concentration and the amounts of toxic gases and smoke from fires of PVC and wood, where wood is the major combustible.

4.1. Temperature of fire gases

The rate of burning of fuel in a ventilated compartment depends upon its distribution and the access of air for combustion and on its consistency in composition. The access of air depends upon the distribution and packing density of the fuel¹², and the ventilation area provided to the compartment¹. For a consistent fuel, the temperature of the fire gases leaving the compartment will become constant when the rate of burning and heat losses through the walls of the compartment have stabilised. The construction of the compartment and corridor used in the present tests was such that heat losses were small⁵, but the fuels used, wood

and PVC, are not consistent during combustion. Their composition changes as combustion proceeds, wood losing volatile tars and gases¹³, and PVC losing hydrogen chloride and volatiles³, during the first stages of combustion, leaving carbon-rich residues. Thus the records of temperature at the opening from the compartment do not show a simple plateau of maximum temperature, (Figs 4-8), although the three stages, (a) fire development, (b) fully involved flaming combustion, and (c) combustion of carbonaceous residues, are well-defined. The maximum recorded temperatures should therefore permit comparisons of the combustion of the similarly behaving fuels.

The small losses of heat claimed for the test rig are confirmed by comparison with the results from the small-scale less well insulated test rig. At similar rates of ventilation and fire load, the maximum fire gas temperature in the 0.7 m³ compartment ranged from 350-650°C², compared with 870-1100°C in the present tests. Such higher temperatures would be expected to result in the more rapid release of hydrogen chloride (this is discussed below) and to favour the production of carbon monoxide over that of carbon dioxide.

The reported analyses of variance, Table 2, indicate that the effect of the presence of PVC on fire gas temperature was barely significant between tests at the higher wood fire load and the higher degree of ventilation. A simple analysis of variance over all conditions tested did not indicate significance of the presence of PVC. It is difficult to reconcile this finding with the observation that PVC contributed to the thermal output of a mixed fire load of wood and PVC, other than by assuming that PVC interferes with the combustion process, increasing the period of time at the higher temperatures (see Figs 4-7). Possible mechanisms that could apply are put forward to explain the actions of halogens such as chlorine, in flame retardants¹⁴.

A simple analysis of variance of maximum temperature of fire gases at the open end of the corridor also showed significance only for the variables, weight of wood crib and size of compartment ventilation opening, a finding consistent with that for the temperature at the compartment opening. It was also shown that the presence of part of the weight of the wood fuel as a wall lining had no significant effect on the maximum temperature of the fire gases. However, the presence of PVC within the wood crib would be likely to have an effect on such temperatures because of local interference with combustion processes².

The reduction in temperature of the fire gases as they passed through the corridor, Table 4, shows in general a dependence upon the size of the opening between compartment and corridor. At least some of the deviation between the

recorded and calculated values of temperatures can arise from the difference in flow rates of fire gases into the corridor, 20 m³/min and 60 m³/min for the smaller and larger widths of opening. Such differences would be expected to result in differing levels of neutral plane. Small differences of the order of 10 per cent would have been difficult to detect, because of fluctuations in density and level of visible smoke as it left the corridor. Similarly, differences in the distribution of admixed air in the fire gases leading to different gradients in the composition of the fire gases would not have been detected, because of the single site of the thermocouple. Factors such as these are likely to have been of more importance than the small thermal losses through the walls of the corridor.

4.2. Carbon monoxide

The relation between the maximum concentration of carbon monoxide and the factor $AH^{1/2}/W$ obtained from a series of small scale tests is given in Fig.29, together with points plotted for the present tests, the presence of PVC being indicated. The scatter about the curve does not indicate any significant differences between the fuel systems, but suggests that the relationship represented by the curve does not apply at values of $AH^{1/2}/W$ greater than 5×10^{-3} . While the reason for this divergence is not clear, factors such as the random collapse of the wood crib as burning proceeds, and the differing flow patterns that could become established in a compartment, may have some bearing. The values of W adopted for fires of wood and PVC include the weight of carbon and hydrogen in the PVC in addition to the weight of wood, as this part of the molecule could contribute to the evolution of Carbon monoxide.

The significance of the weight of crib, noted previously, on the maximum concentration of carbon monoxide is supported by the times of burning given in Table 1. For a given ventilation, the time of burning does not increase in proportion to the weight of crib; for example compare Test 1 with Test 8. As the heavier crib burned relatively more rapidly than the lighter crib, at about the same rate of flow of air into the compartment, less efficient combustion, with the formation of larger amounts of carbon monoxide would be expected. Other factors that could affect the production of fire gases have been noted elsewhere, such as the restraint imposed on the access of air by the structure of the crib¹². The size of vent as well as the weight of crib would be expected to influence the total amount of carbon monoxide evolved, Table 3, because a smaller vent would reduce the rate of flow of air and hence reduce the efficiency of combustion, although this effect would be offset to some extent by the increase in production of carbon monoxide to be expected at the higher temperatures associated with a more generous

supply of air.

The lack of significance indicated for the variable, PVC, Tables 2 and 3, may possibly be an indication that the polymer does not produce much carbon monoxide in fires. Such a finding if fully confirmed is of importance, particularly if the behaviour is common to vinyl polymers. The results for PVC coated wall-paper and cloth, Tests 4 and 5, Table 1, do not indicate large increases in the total amount of carbon monoxide, suggesting that the cellulosic backing adds little to the amount of carbon monoxide produced.

4.3. Hydrogen chloride

Laboratory pyrolyses have indicated that hydrogen chloride is the only significant halogenated product to be expected from fires involving PVC³, and small-scale fire tests produced yields of hydrogen chloride not at variance with a quantitative yield of hydrogen chloride from the halogen in the plastic². The present tests show a high recovery of hydrogen chloride, Table 1, for all tests with PVC in the compartment, except tests 4 and 5 with PVC coated wall-paper and cloth, for which the yields were a small proportion of the theoretical, the yield being the greater for the thicker wall lining.

The concentration of hydrogen chloride in the fire gases was reduced on passage through the corridor to an extent greater than could be accounted for by dilution with that part of the incoming air which was recirculated in the corridor, for all tests with mixed loads of PVC and wood in the compartment, except Test 4 of coated wall-paper. Such a result could indicate that absorption of hydrogen chloride by the lime-rich surface of the corridor walls and ceiling required a high concentration to be apparent, or to the increasing lack of precision of the method of analysis as the concentration became small.

The tests with 3 mm PVC wall linings in the corridor, Tests 7 and 14, Table 1, indicate that some recirculation of the fire gases into the compartment took place: an effect that would be expected from counter-flowing gas streams. The measured concentrations of hydrogen chloride emerging from the corridor show that a high degree of risk is rapidly developed when a fire breaks out into such a lined corridor.

No dependence of evolution of hydrogen chloride with crib weight or ventilation was indicated by analyses of variance. This is in accord with the findings from laboratory pyrolyses, which have shown that the release of hydrogen chloride from PVC is quantitative and very rapid at temperatures above 350°C⁷. However, the rate of release in the present large-scale tests is much slower than would be predicted from pyrolysis. This effect could arise from the insulation

provided to underlying undecomposed PVC by the highly expanded, low permeability char produced by exposure of PVC to high temperatures². The effect of a proportionate reduction from the fire gas temperature, such as might be produced in this way, on the evolution of hydrogen chloride calculated from the kinetics of decomposition is shown in Figs 30-33 for the tests with 3 mm PVC wall linings in the compartment. The curves in the figures are of the proportion of the maximum recorded release of hydrogen chloride, calculated from the concentration in the fire gases and their rate of flow, and the proportion calculated from kinetic data, assuming that the recorded fire gas temperature was reduced to a constant fraction⁷. The figures broadly support the suggestion that insulation by carbonaceous char can account for a lower rate of release of hydrogen chloride from PVC, by the reduction of the temperature of the dehydrochlorinating PVC to about 0.3 of the fire gas temperature. Exact equivalence with such a simple model would not be expected, because the thickness of char would be expected to increase as time of exposure in the fire increased, and the softening of the PVC sheet would lead to its detachment from the wall and collapse into convoluted heaps, with a different exposure and insulation from a wall lining.

4.4. Toxic effects

The concentrations of both carbon monoxide and hydrogen chloride found in the fire gases from these test fires in compartment or corridor are in general greater than those taken as presenting a hazard to life in about 30 min, namely 0.3 per cent (3000 ppm) and 0.15 per cent (1500 ppm) for carbon monoxide and hydrogen chloride respectively. Exceptions are the concentrations of carbon monoxide in the fire gases at the compartment opening for tests 1 and 5, and hydrogen chloride in the fire gases from both the compartment opening and the open end of the corridor for tests 4 and 5. All of these tests are of the smaller fire load of wood and the latter two are of the thin wall linings of wall-paper or -cloth. However, the temperatures at these sites are likely to prove fatal for all tests¹⁵. A comparison of the concentrations of toxic gases produced by admixture of fire gases with air at 20°C to provide an atmosphere at 120°C, which could be borne for the short time needed for escape¹⁵ affords a more viable comparison of toxicities. Values for the tests are given in Table 5 for carbon monoxide and Table 6 for hydrogen chloride. Values in Table 5 were above 3000 ppm for carbon monoxide at one or other site for Tests 2, 4, 8, 9, 11 and 14. However, more recent unpublished information suggests that the level of 3000 ppm is too low, and that 5000 ppm may be a more realistic limit. At this value the tests presenting a hazard are 2, 8, 11 and 14. The tests presenting a hazard from hydrogen chloride, Table 6, are 2, 6, 7, 10, 13 and 14.

TABLE 5

MAXIMUM CONCENTRATION OF CARBON MONOXIDE
FIRE GASES DILUTED WITH AIR TO BEARABLE TEMPERATURES (120°C)

Test No.	Fire load, kg		Vent width mm	Compartment vent		Corridor	
	Wood	PVC		Air, parts	CO, ppm	Air, parts	CO, ppm
1	120.5	0	240	7.5	235	1.8	2860
2	120.5	95	240	8.3	4950	1.8	8210
3	120.5	0	700	8.1	1210	3.0	750
4	122.5	0.9	700	8.1	2750	2.9	4150
5	122.8	2.6	700	7.6	232	2.9	ND
6	120.5	95	700	8.6	2080	3.1	850
7	120.5	115	700	8.5	526	3.8	ND
8	241	0	240	8.4	2130	2.6	7500
9	241	0	240	8.4	3720	4.5	2000
10	241	95	240	9.0	1800	2.2	F
11	241	0	700	9.8	5560	5.2	2600
12	241	0	700	9.5	2290	5.6	1970
13	241	95	700	9.2	2350	4.3	566
14	241	115	700	9.7	6730	5.3	3330

Notes: ND = Not detectable, limit of detection 0.01 per cent, 100 ppm

F = Fault in sampling system. Loss of sample

TABLE 6

MAXIMUM CONCENTRATION OF HYDROGEN CHLORIDE
FIRE GASES DILUTED WITH AIR TO BEARABLE TEMPERATURES (120°C)

Test No.	Fire load, kg		Vent width mm	Compartment vent		Corridor	
	Wood	PVC		Air, parts	HCl, ppm	Air, parts	HCl, ppm
2	120.5	95	240	8.3	6020	1.8	290
4	122.5	0.91	700	8.1	3	3.1	8
5	122.8	2.3	700	7.6	79	2.9	67
6	120.5	95	700	8.6	3230	3.1	1460
7	120.5	115	700	8.5	360	3.8	9690
10	241	95	240	9.0	3800	2.2	780
13	241	95	700	9.2	3920	4.3	1890
14	241	115	700	9.7	1800	5.3	20500

However, hydrogen chloride is an extremely irritant gas, and it is difficult to breathe air containing more than about 50 ppm.

The results of these tests therefore suggest that, while a risk from a cooled fire atmosphere may always be presented from carbon monoxide from a fire involving normal loads, principally of wood, the risks are not high for well-ventilated fires. The presence of large quantities of PVC in the room on fire, however, will produce highly dangerous atmospheres, but wall-papers and cloths will add little to the risk from a fire.

Risks presented by thick PVC wall linings in corridors were much greater than those from similar amounts in rooms. The conclusion must therefore be drawn that thick linings of PVC in corridors are most undesirable. The rapid rise in concentration of hydrogen chloride (Fig.28), at the time when escape becomes important, that is, when the fire breaking into the corridor first reaches full intensity, suggests that the thickness of wall lining need not be great to put life at risk.

The above argument assumes the free access of clean air for dilution. This condition may not apply in a dwelling unit with windows in place. The rates of flow of fire gases for the two compartment ventilation widths in the above tests, 240 and 700 mm are about those to be expected from a partially or fully opened door.

Assuming that a dwelling at risk had the average volume of 250 m^3 , the rates for flow of air into a room on fire would be $20 \text{ m}^3/\text{min}$ and $60 \text{ m}^3/\text{min}$ respectively, depleting the air in the dwelling completely under plug-flow conditions in about 12 and 4 min respectively. However, as the fire gases would be emerging at about 1000°C their equivalent flow rates would be about $90 \text{ m}^3/\text{min}$ and $260 \text{ m}^3/\text{min}$; assuming that the fire gases could not escape through windows, or vents, they would displace the air in the dwelling by plug flow in 3 min and 1 min respectively. The movement of fire gases, driven by buoyancy forces, is likely to be the more important, and hence the whole space of the dwelling would present a risk from high temperature, oxygen depletion and toxic gases in a very short time. The shutting of doors other than of the room on fire would accelerate the onset of hazard in remaining communicating areas, although protecting the closed rooms.

It should be noted that this assessment of risk is not dependent upon the presence of PVC, which can add to the toxicity only, the risks from high temperature, oxygen depletion and carbon monoxide remaining the same. Assuming that a room emitting fire gases present this kind of risk when the fire gas temperature attains 300°C (Figs 4-8) at which gas flow approaches its maximum rate, escape may be feasible without serious harm only during the first 5 min after the onset of flaming combustion.

4.5. Smoke

The conditions of combustion used in these tests were adopted to provide conditions under which the PVC would be consumed in the fire. Such conditions of relatively high ventilation produce less smoke from wood products than conditions of restricted ventilation¹⁶, although under conditions of restricted ventilation the rate of emergence of smoke from a vent would be substantially less than with high ventilation. For wood products to burn, usually by smouldering, under restricted ventilation, they need to be in thin section or porous form such as veneers, cloth, flock or fibrous boards^{11,16}, but tests have shown that thin sections of unplasticised, rigid PVC do not smoulder or burn readily⁴.

Under the conditions examined in the tests reported here, none of the three variables, weight of wood crib, width of ventilation opening, or the presence of PVC was significant in effect on optical density, suggesting that the principal controlling factor lies elsewhere. Other than the rate of supply of air being above a boundary value, this is likely to be the area of burning surface¹⁸, controlled in most tests by exposed area in the crib. The most significant area

is probably the top surface of the crib, exposed to high intensity radiation from the flames, and not the sides, over which the flame thickness and hence emissivity are small. A special case is presented by the presence of part of the wood as a wall lining, when a greater area is exposed to radiation and other means of heat transfer from both the flames from the crib and from the burning wall lining, (Fig.17). It would appear that a similar exposure of PVC wall lining in the compartment does not provide smoke producing species of pyrolysis or combustion products, but exposure in the corridor enhances smoke production (Table 1).

Indeed the reduction in optical density occasioned by the presence of PVC in some of the reported fires in compartments emphasizes the inappreciability of behaviour of fires of industrial loads of PVC to those to be expected from fires under other conditions, such as would arise in dwellings.

The total smoke production, P , is significantly increased by an increase in wood crib weight or by the presence of PVC. As optical density is not significantly modified by these factors, the increase in P probably arises from the longer time of burning for the heavier wood crib and from the maintenance of higher levels of optical density for longer periods when a PVC wall lining was present. The curves of optical density for Tests 3 and 6, Figs 17 and 18 indicate that PVC produces smoke to a later stage than wood.

The values of smoke density measured in the present tests do not include the contribution that would be made by the precipitation of a mist of hydrochloric acid solution, which would be formed at or below the dew point of the fire gases. However, at the temperature of mixed air and fire gases at which escape could take place, 120°C , such precipitation is unlikely. Values have therefore been calculated of the optical density of such cooled fire gases, Table 7. The visibility in such diluted atmospheres, less than 2.7 m for all tests, would make escape difficult, adopting the criterion that a visibility of 5 m or more is needed to ensure escape^{8,18}. These data suggest that the restriction of visibility occasioned by smoke increases the risk of exposure to toxic gases and high temperatures.

TABLE 7
OPTICAL DENSITY OF, AND VISIBILITY IN, SMOKE
FIRE GASES DILUTED WITH AIR TO BEARABLE TEMPERATURES

Test No.	Fire load, kg		Vent width mm	Dilution air, parts	Optical density max.	Visibility m
	Wood	PVC				
1	120.5	0	240	1.8	0.71	2.0
2	120.5	95	240	1.8	1.04	1.4
3	120.5	0	700	3.0	0.75	1.9
4	122.5	0.9	700	3.1	0.83	1.6
5	122.8	2.3	700	2.8	0.85	1.6
6	120.5	95	700	3.1	0.49	2.4
7	120.5	115	700	3.8	1.17	1.2
8	241	0	240	2.6	1.11	1.3
9	241	0	240	4.5	0.45	2.6
10	241	95	240	2.2	0.63	2.0
11	241	0	700	5.2	0.52	2.3
12	241	0	700	5.6	0.71	2.0
13	241	95	700	4.3	0.49	2.4
14	241	115	700	5.3	0.63	2.0

5. CONCLUSIONS

The following conclusions are drawn for fires of the kind represented by the reported tests.

5.1. The tests reported here indicate that under the experimental conditions the development of a fully flaming fire can take a few minutes only and fire gas temperatures of 300°C can be reached within a minute of the inception of flaming. Such a temperature would be intolerably high, and close to that at which the flow of fire gases would take place at the highest rate.

5.2. Smoke was produced in the tests shortly after ignition, whether or not PVC was present with the basic wood fire load. Optical densities greater than unity were recorded in the corridor 10 m from the opening from the compartment from

2 to 8 min after ignition, and the visibility through the smoke was less than is considered adequate for escape, even after dilution of the fire gases with air to a temperature that could be borne for the few minutes needed for escape.

5.3. The tests have shown that concentrations of 50,000 ppm or more of carbon monoxide can be found in the fire gases from a fairly well ventilated fire, and that, even after dilution with air to temperatures that could be borne for a few minutes, the concentration was often high enough to present a hazard to life.

5.4. The presence of about 100 kg of rigid PVC sheet in the fire test compartment produced enough hydrogen chloride during a fire to present a hazard to life, and 3 mm PVC sheet lining in a corridor presented an even greater hazard, even after dilution with air to a bearable temperature. However, when the basic fire load of wood was small, 14 kg/m^2 no hazard was shown by hydrogen chloride in the diluted gases². The tests showed that wall-paper and cloth in the compartment did not add significantly to the risk presented by the basic wood fire load, but the behaviour of PVC sheet in the corridor suggests that PVC coated paper or cloth wall linings might produce a highly irritant atmosphere in the event of fire.

5.5. Further information is required to establish relationships for the prediction of carbon monoxide concentrations produced in fires.

5.6. The tests reported here indicate that prediction of hydrogen chloride concentrations produced during fires involving thick sections of rigid PVC are feasible, provided the temperature of the fire gases can be estimated.

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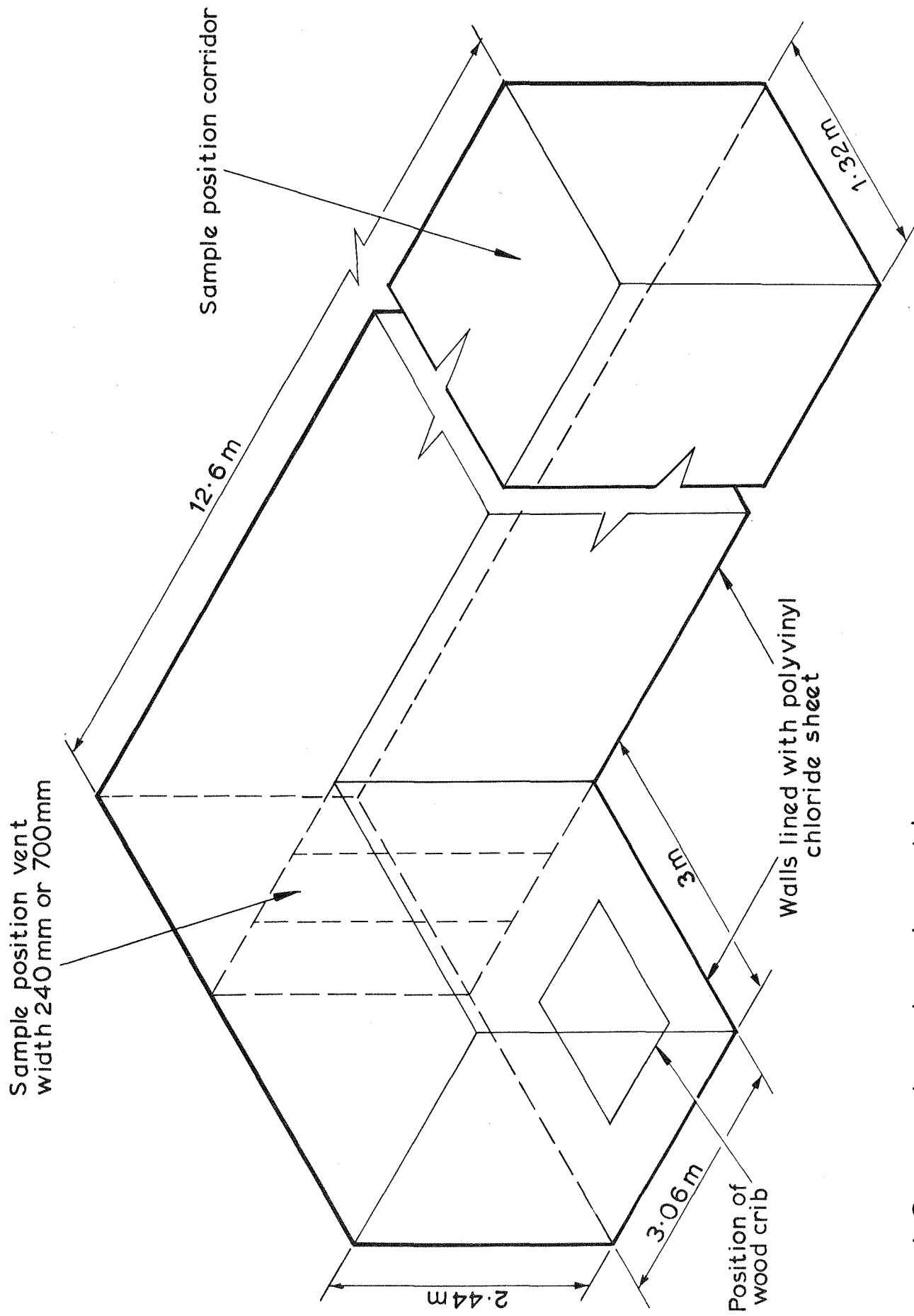


Figure 1 Compartment and corridor

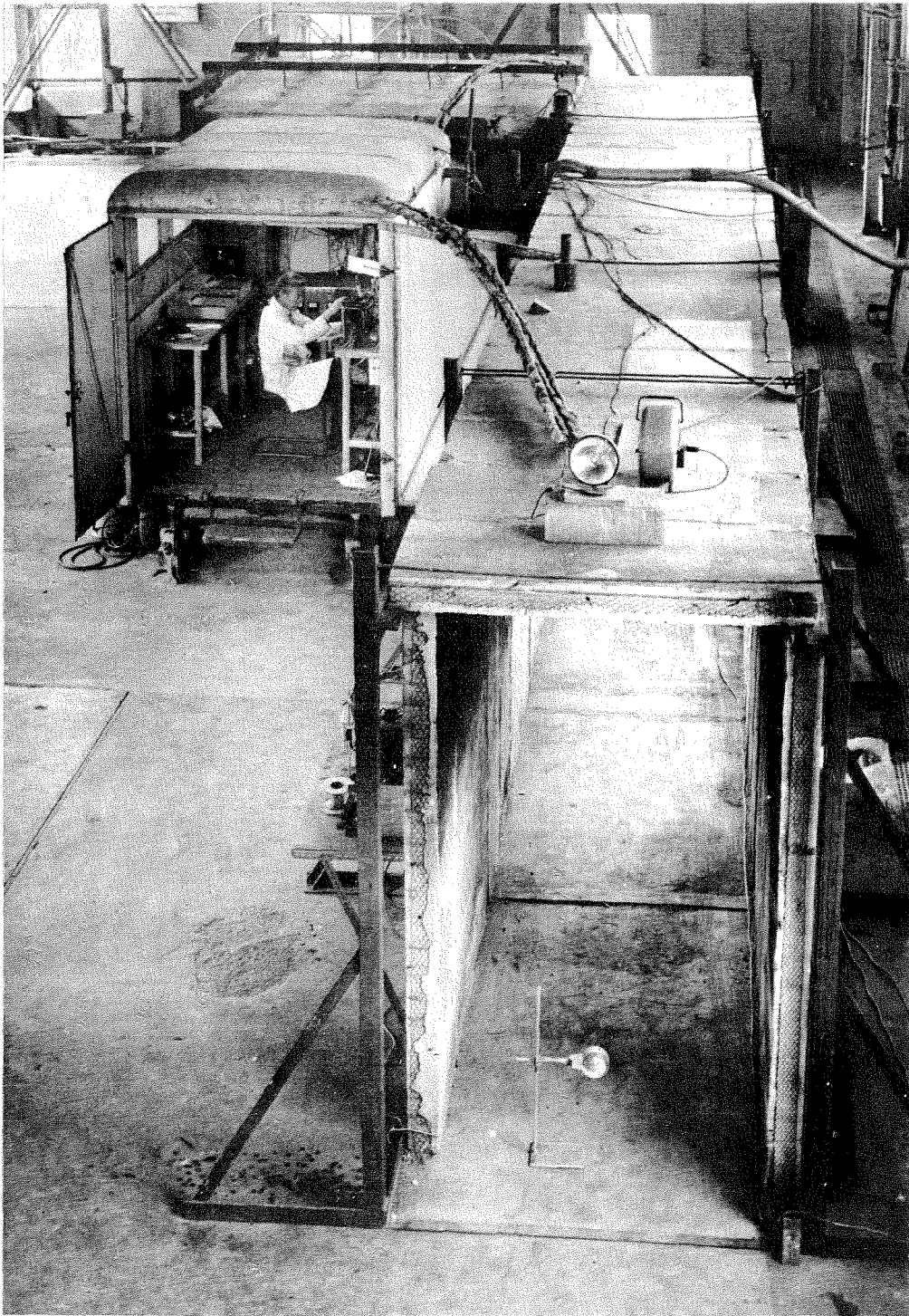


FIG. 2. COMPARTMENT AND CORRIDOR

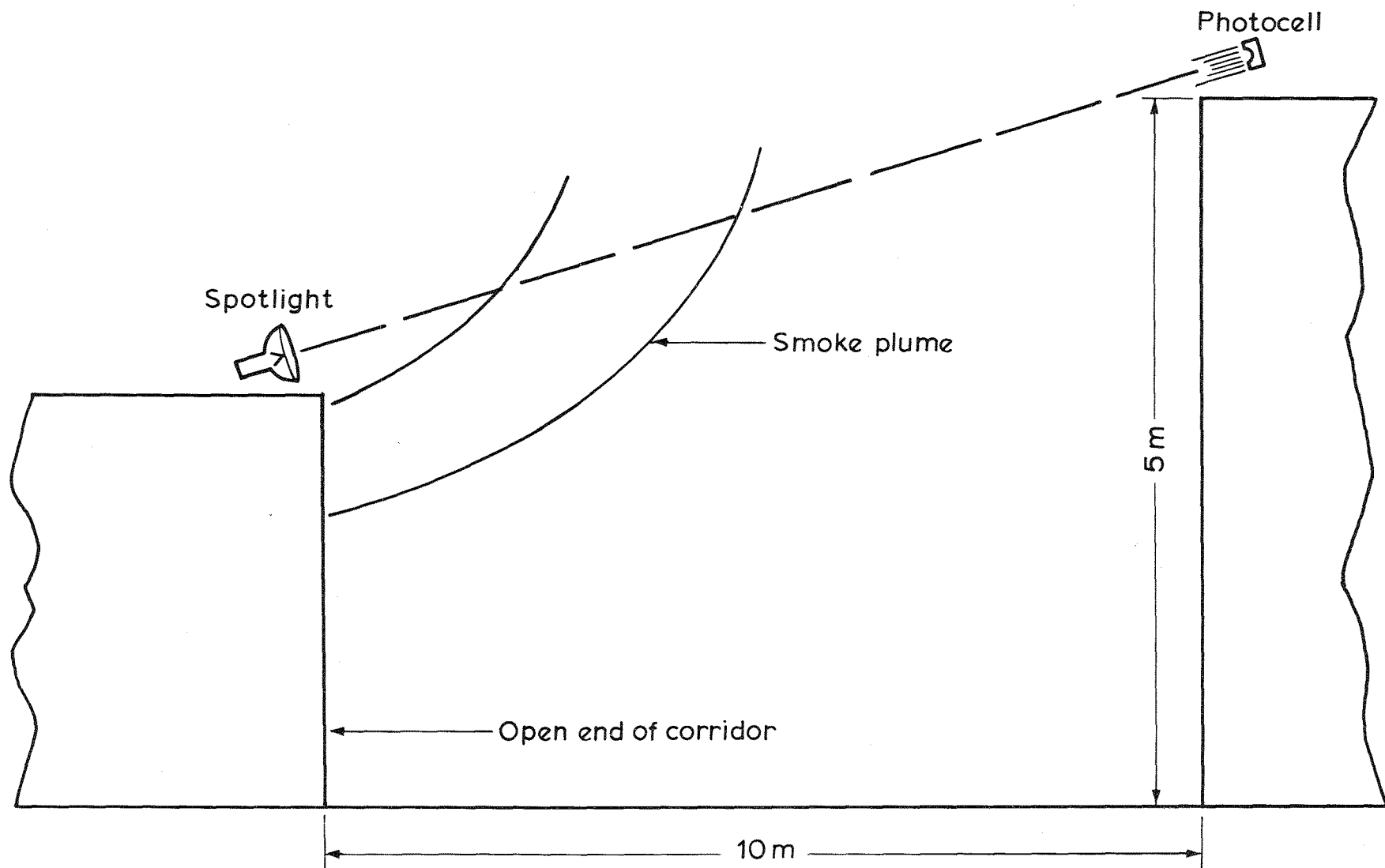


Figure 3 Smoke measurement-arrangement of spotlight and photocell

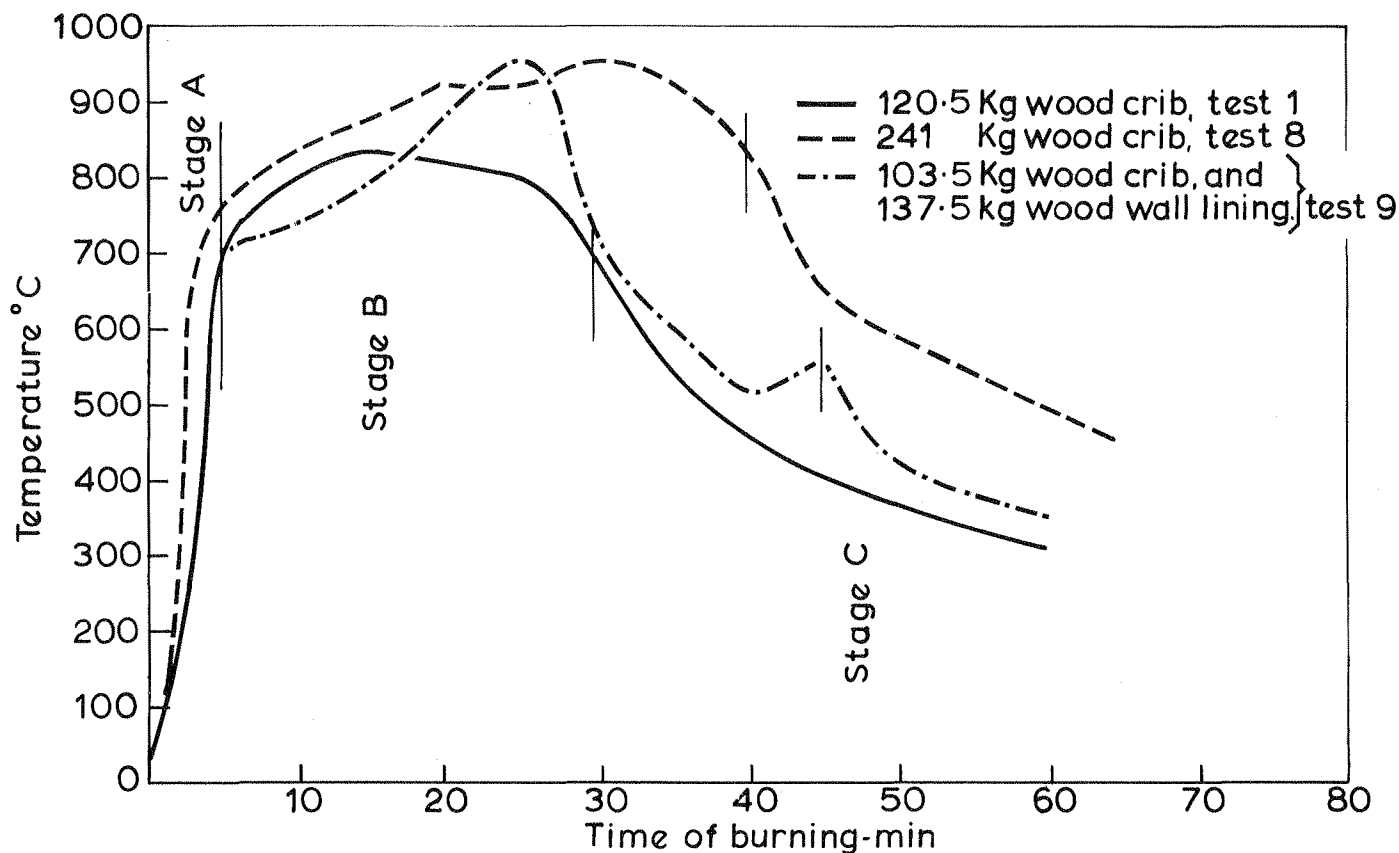


Figure 4 Wood fuel only, 240mm vent. Temperature of fire gases from compartment

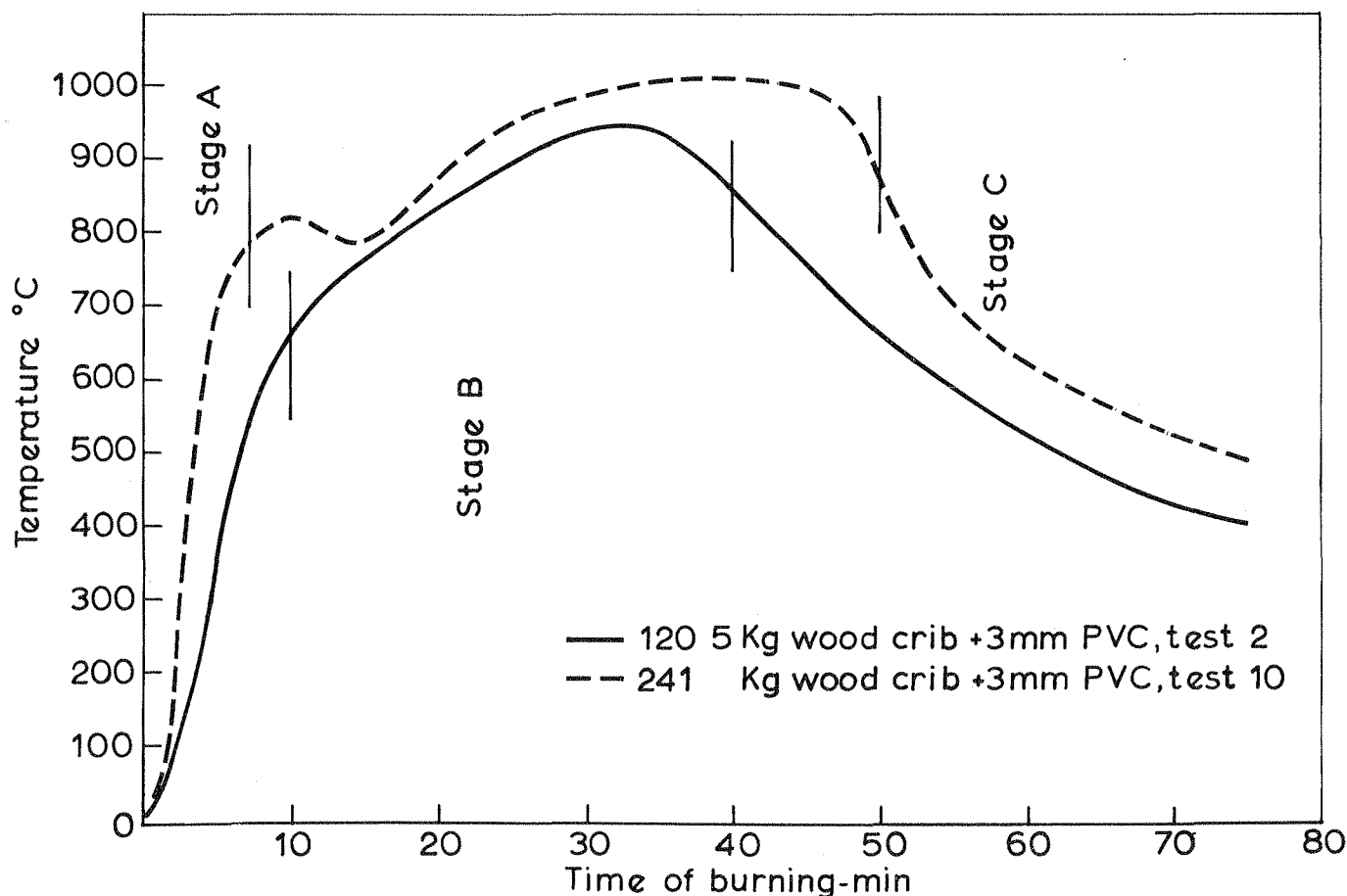


Figure 5 Wood fuel and PVC, 240mm vent. Temperature of fire gases from compartment

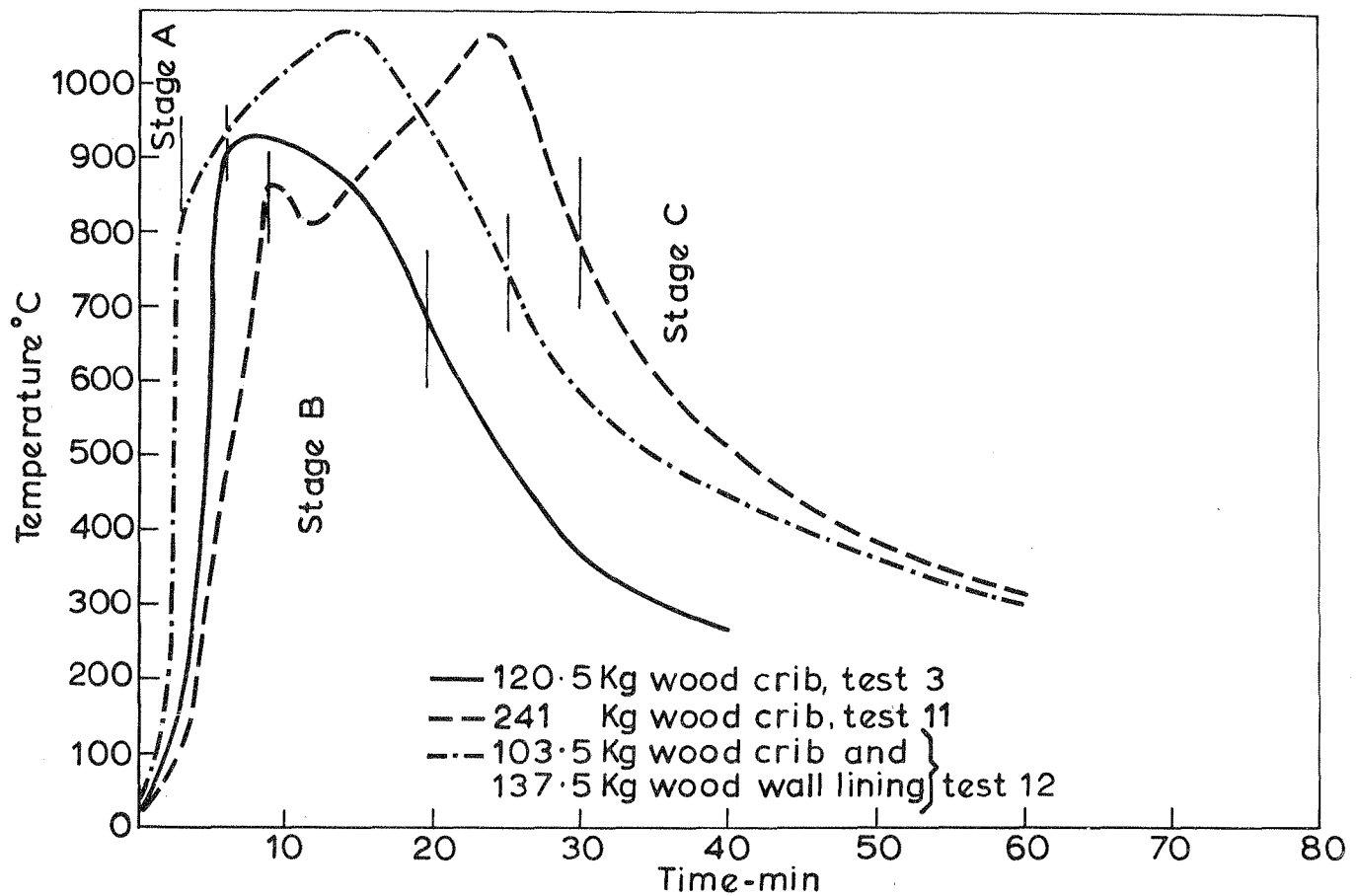


Figure 6 Wood fuel only 700mm vent Temperature of fire gases from compartment

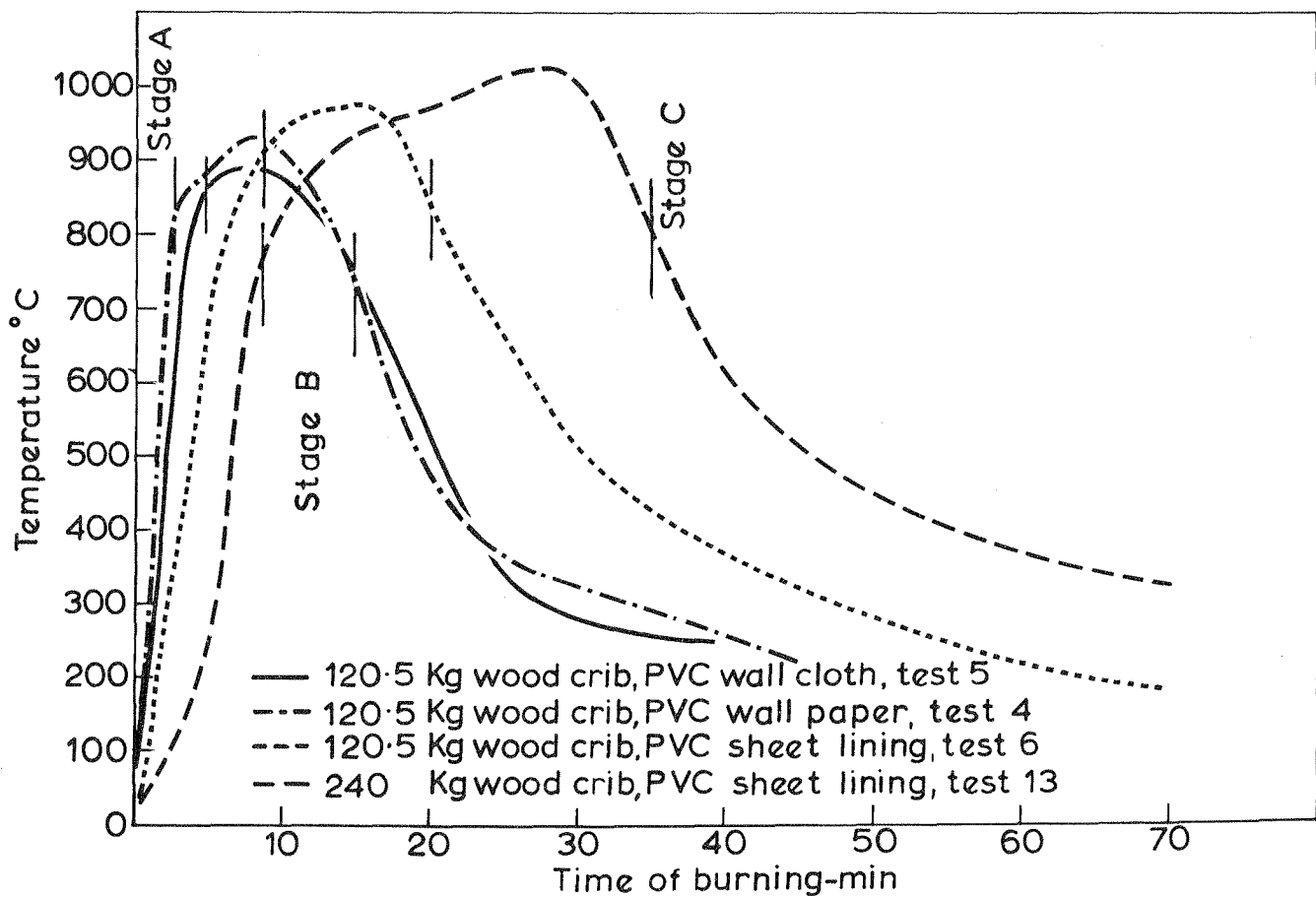


Figure 7 Wood fuel and PVC, 700mm vent. Temperature of fire gases from compartment

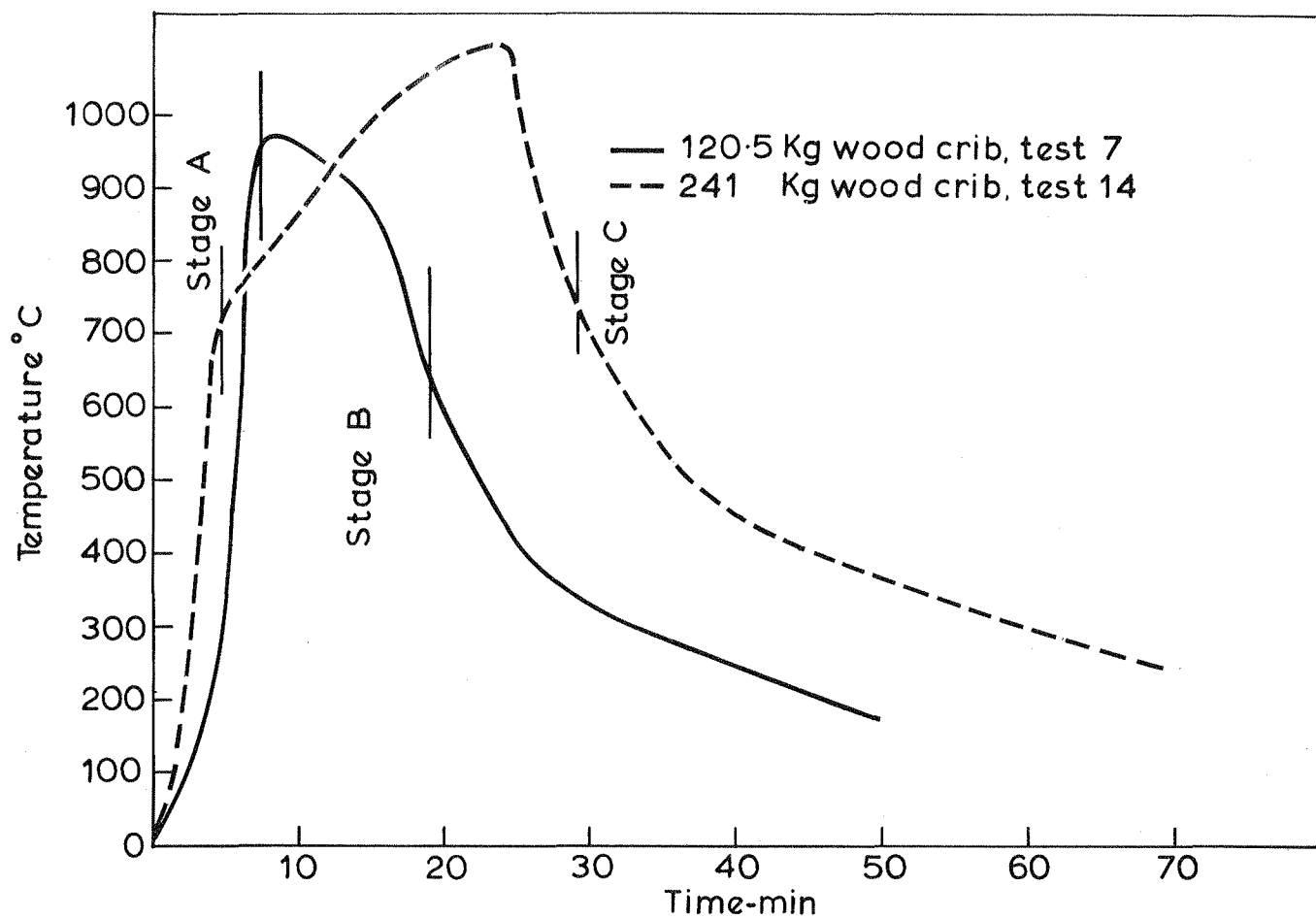
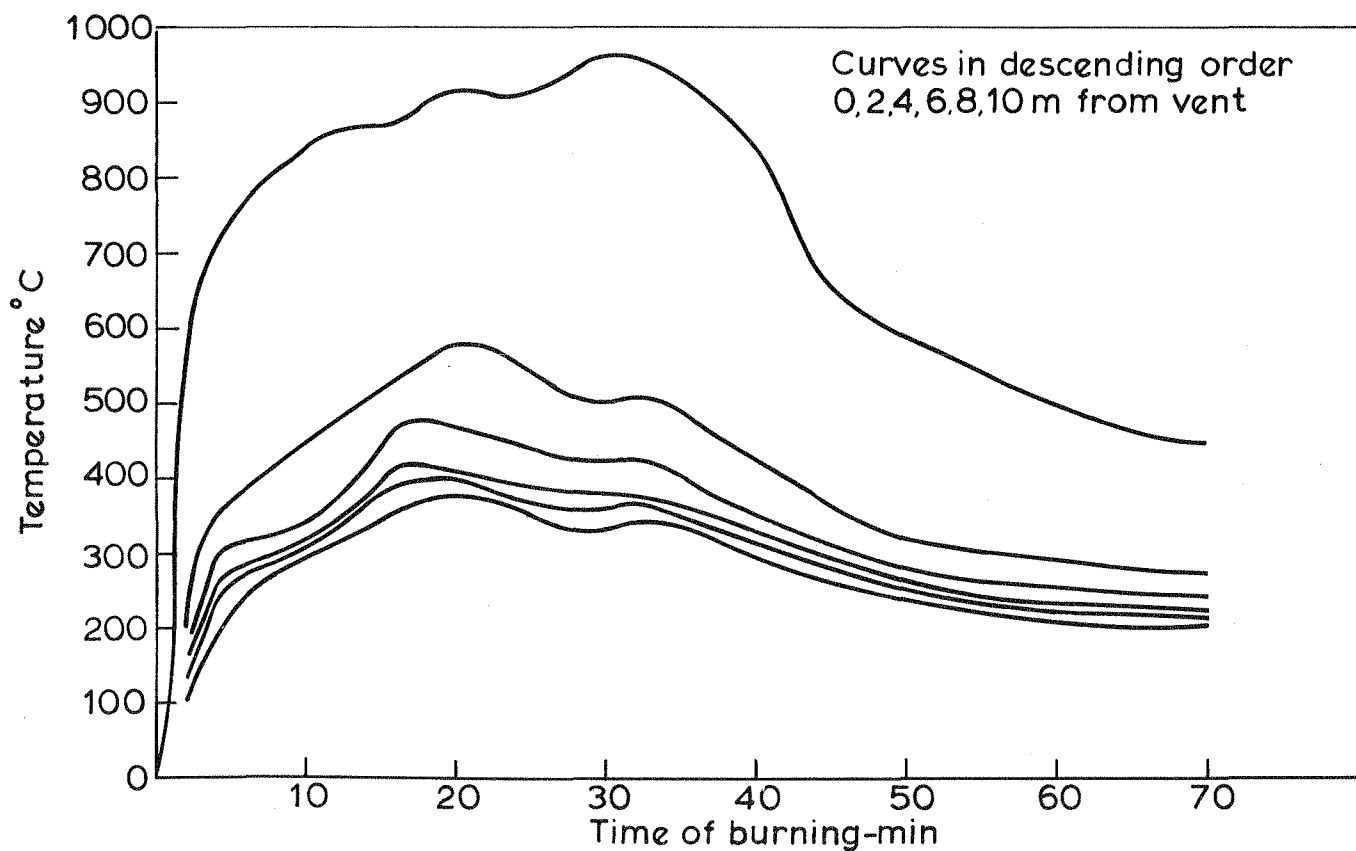
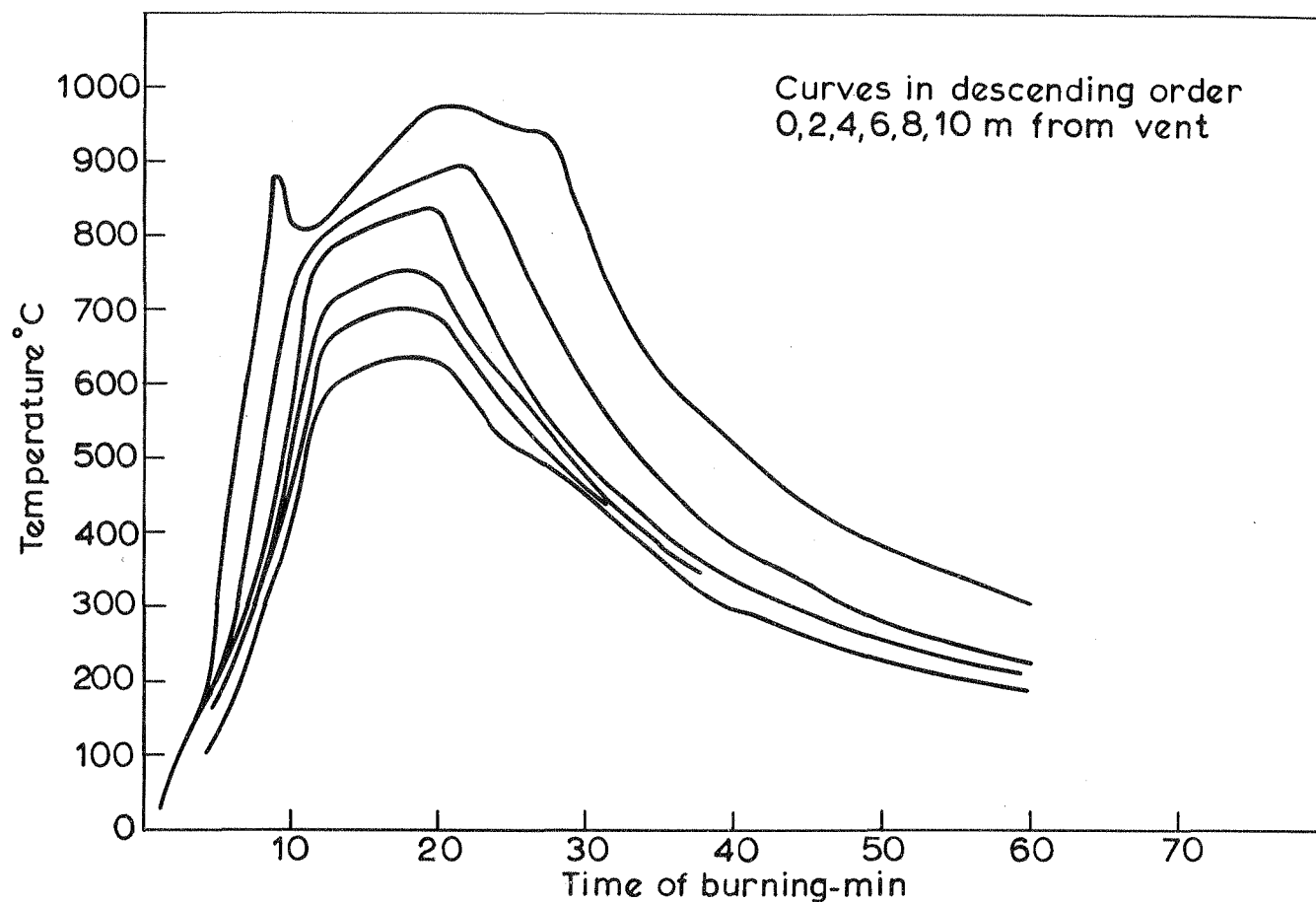


Figure 8 PVC in corridor 700mm vent. Temperature of gases from compartment



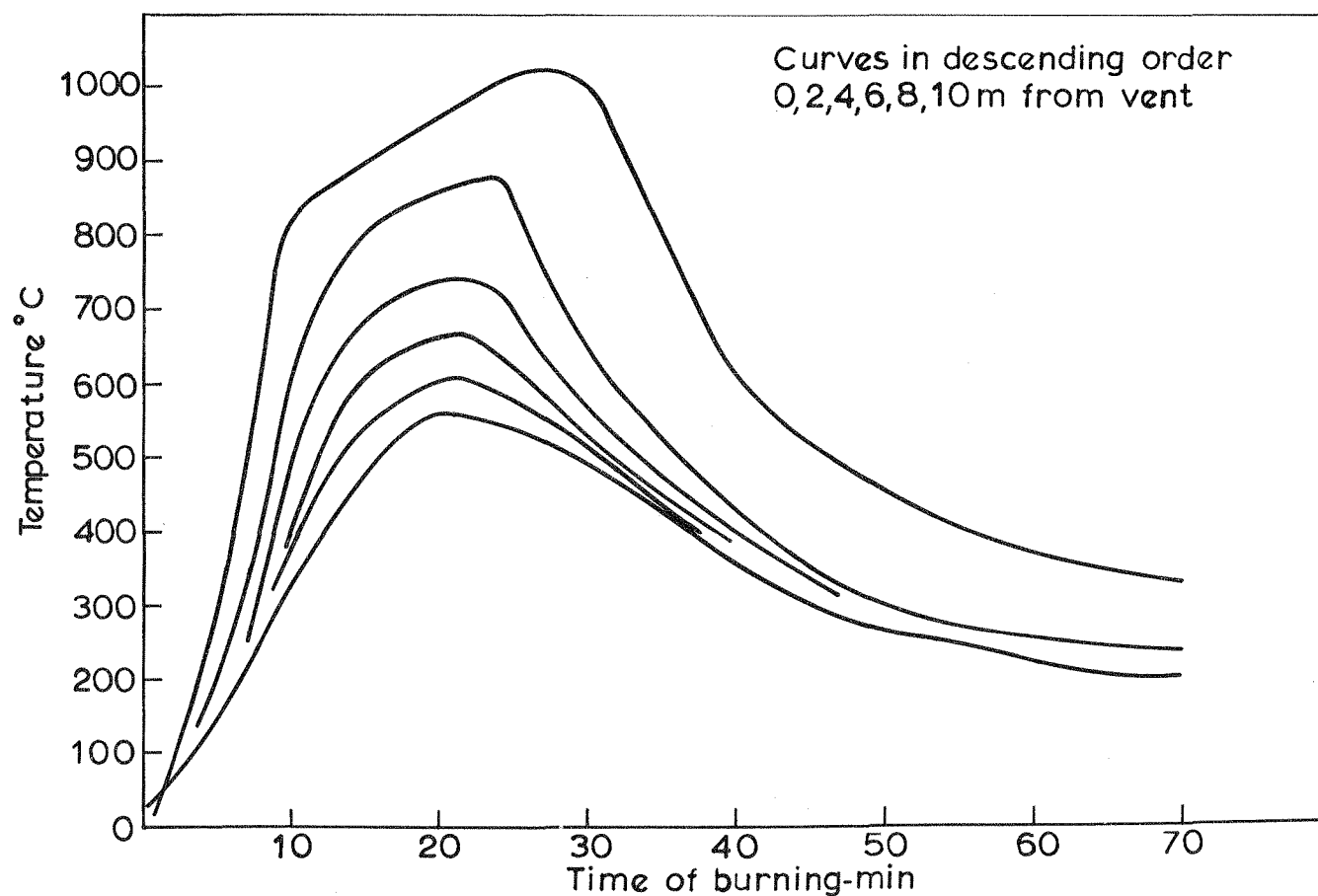
Test 8 241 Kg wood crib only, 240 mm wide vent

Figure 9 Temperature of fire gases in corridor



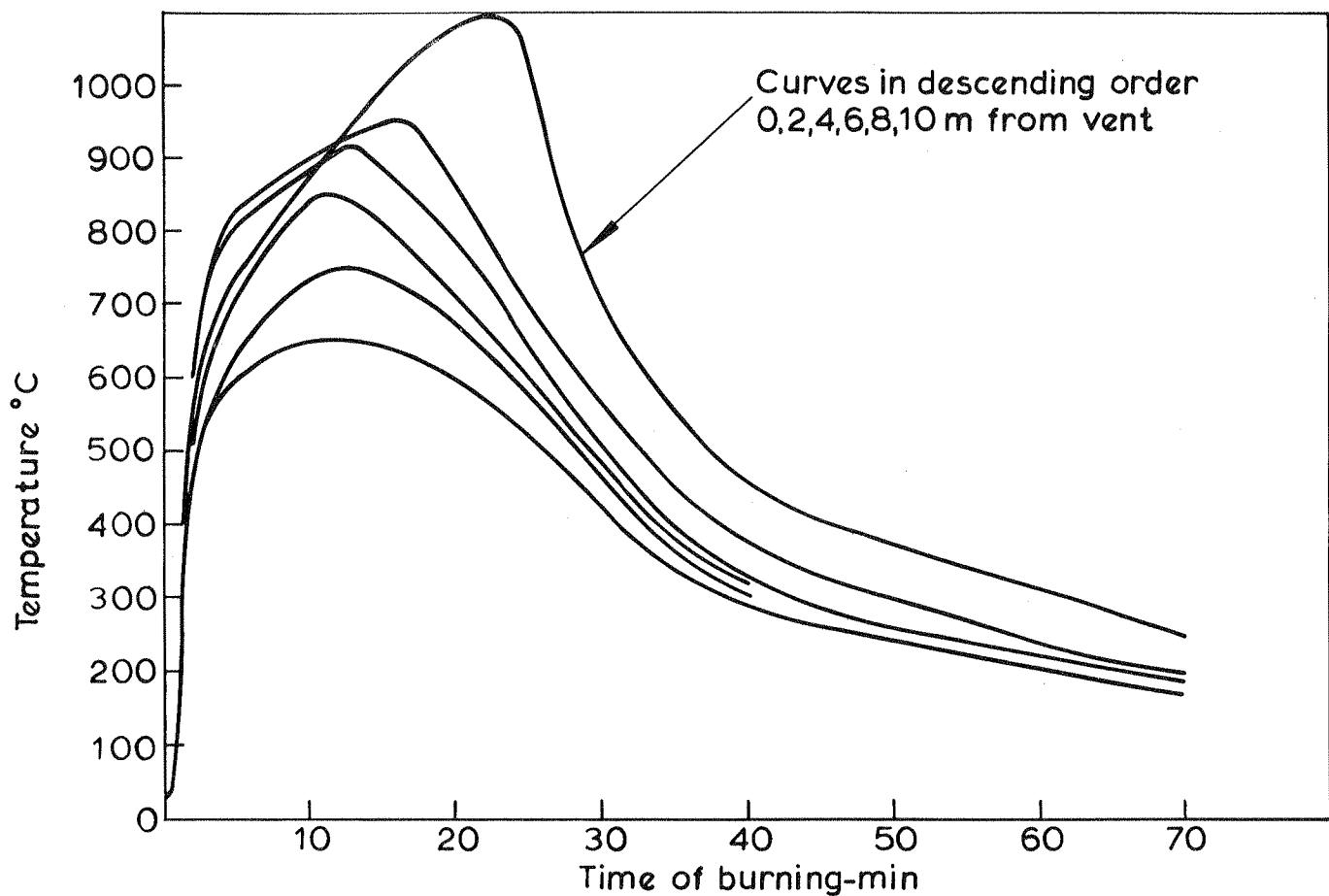
Test 11 241 Kg wood crib only, 700 mm vent

Figure 10 Temperature of fire gases in the corridor

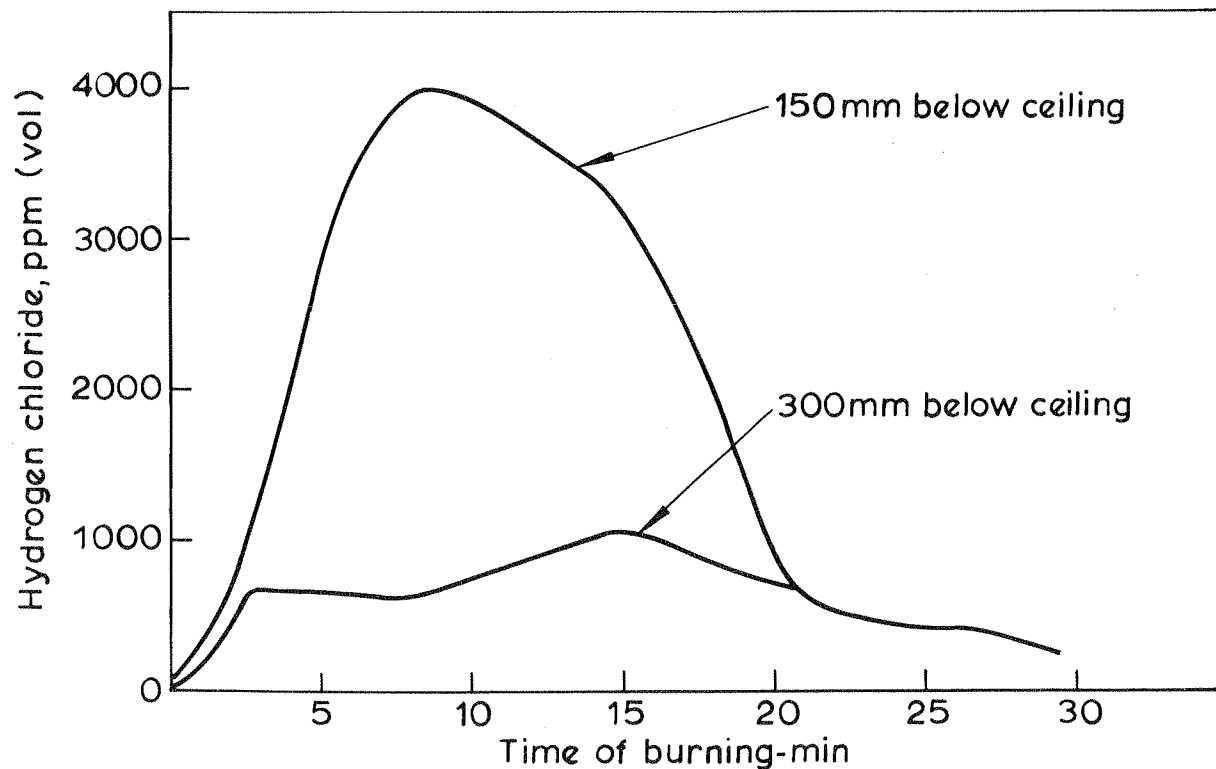


Test 13 241 Kg wood crib + 45 Kg PVC wall lining, 700 mm vent

Figure 11 Temperature of fire gases in the corridor



Test 14 241 Kg wood crib + 115 Kg PVC wall lining in corridor, 700mm vent
Figure 12 Temperature of fire gases in corridor



Test 4 Effect of distance below ceiling
Figure 13 Hydrogen chloride in fire gases in corridor

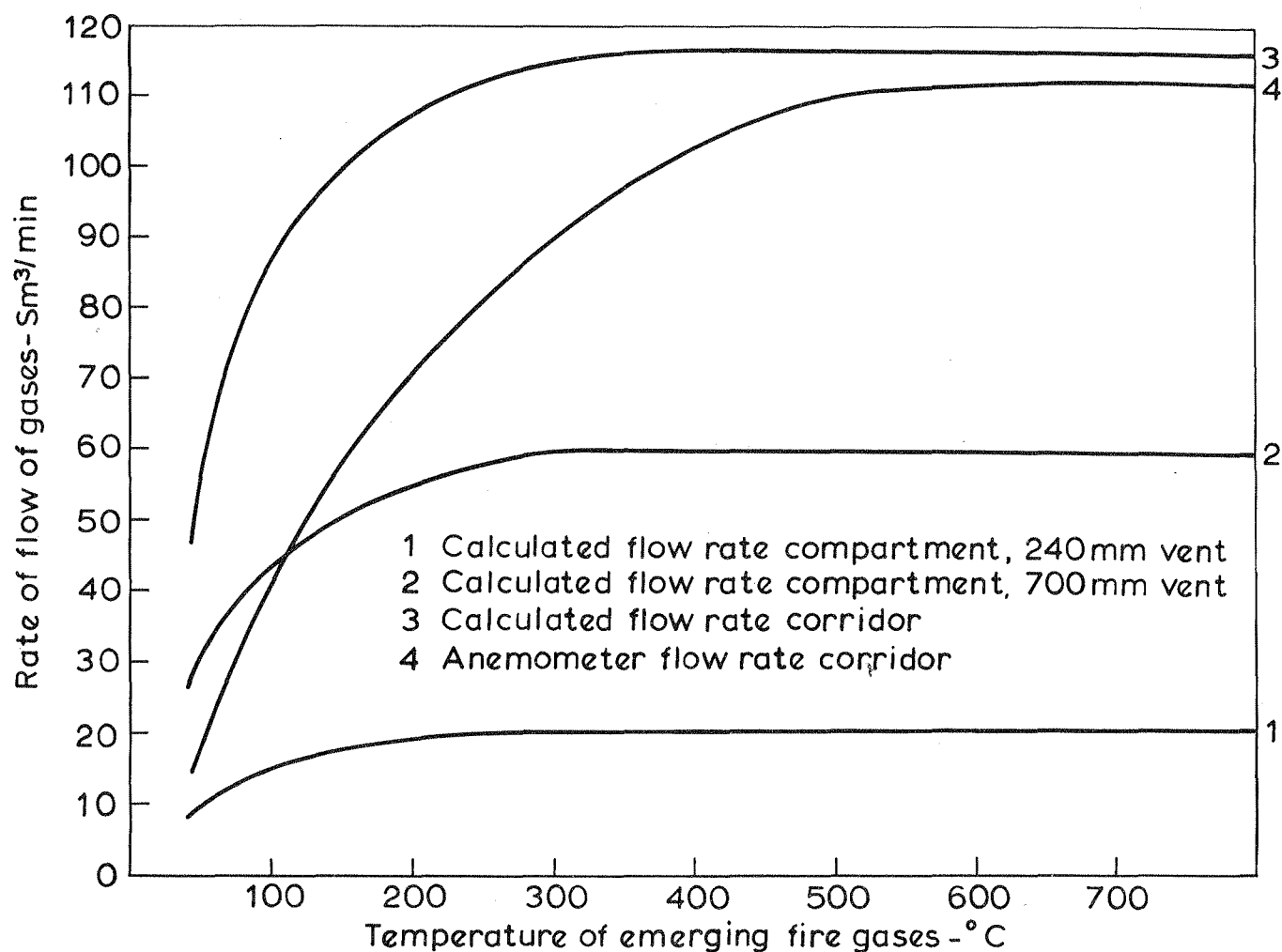


Figure 14 Rate of flow of fire gases

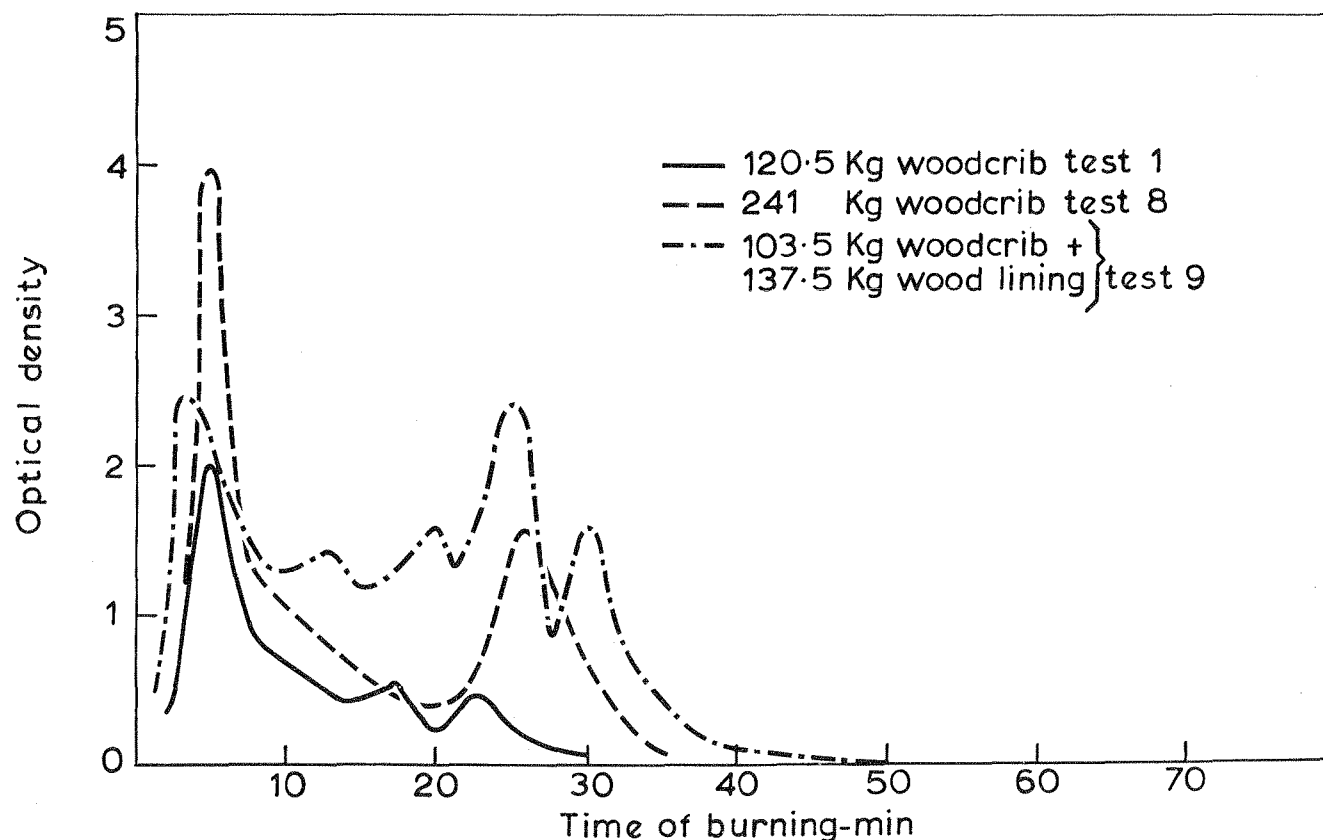


Figure 15 Optical density of smoke wood fuel only: 240mm vent

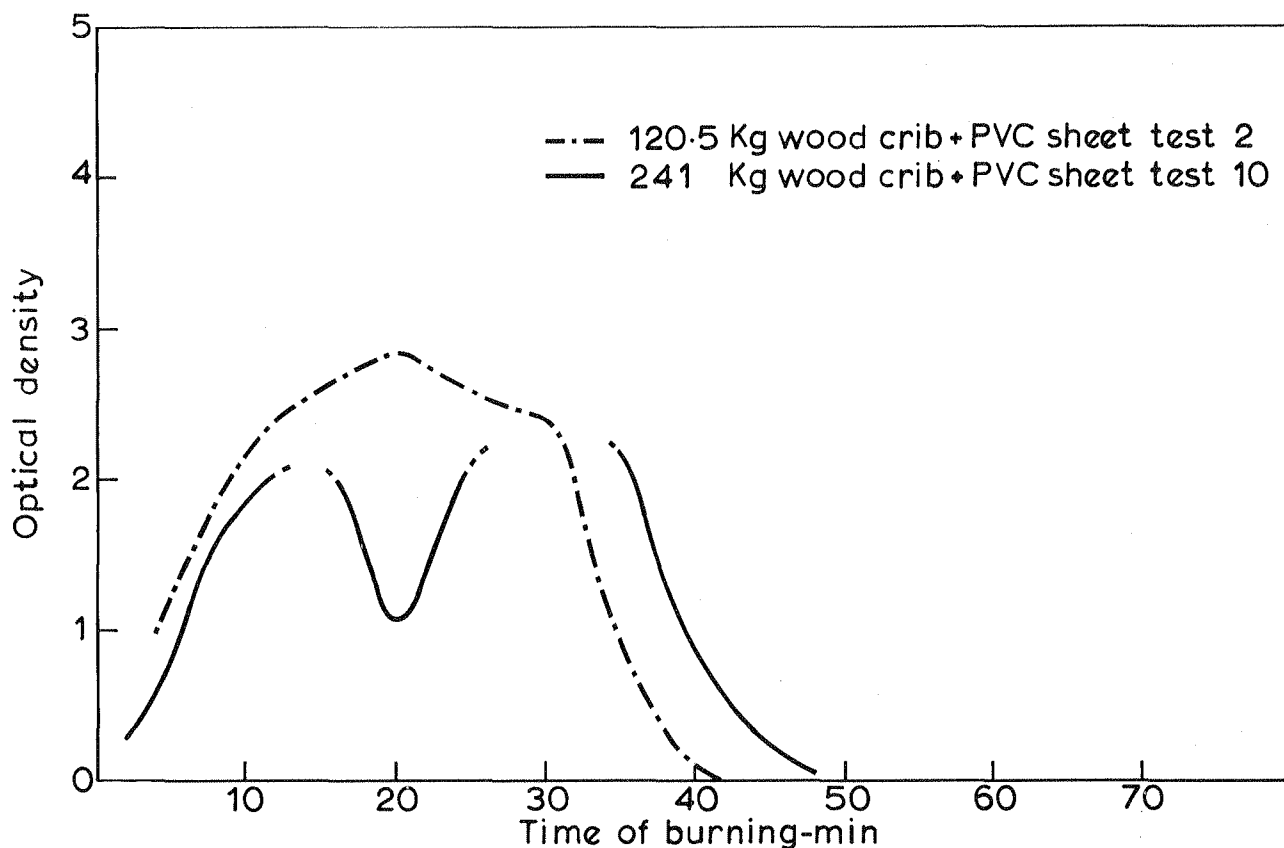


Figure 16 Optical density of smoke wood fuel and PVC 240 mm vent

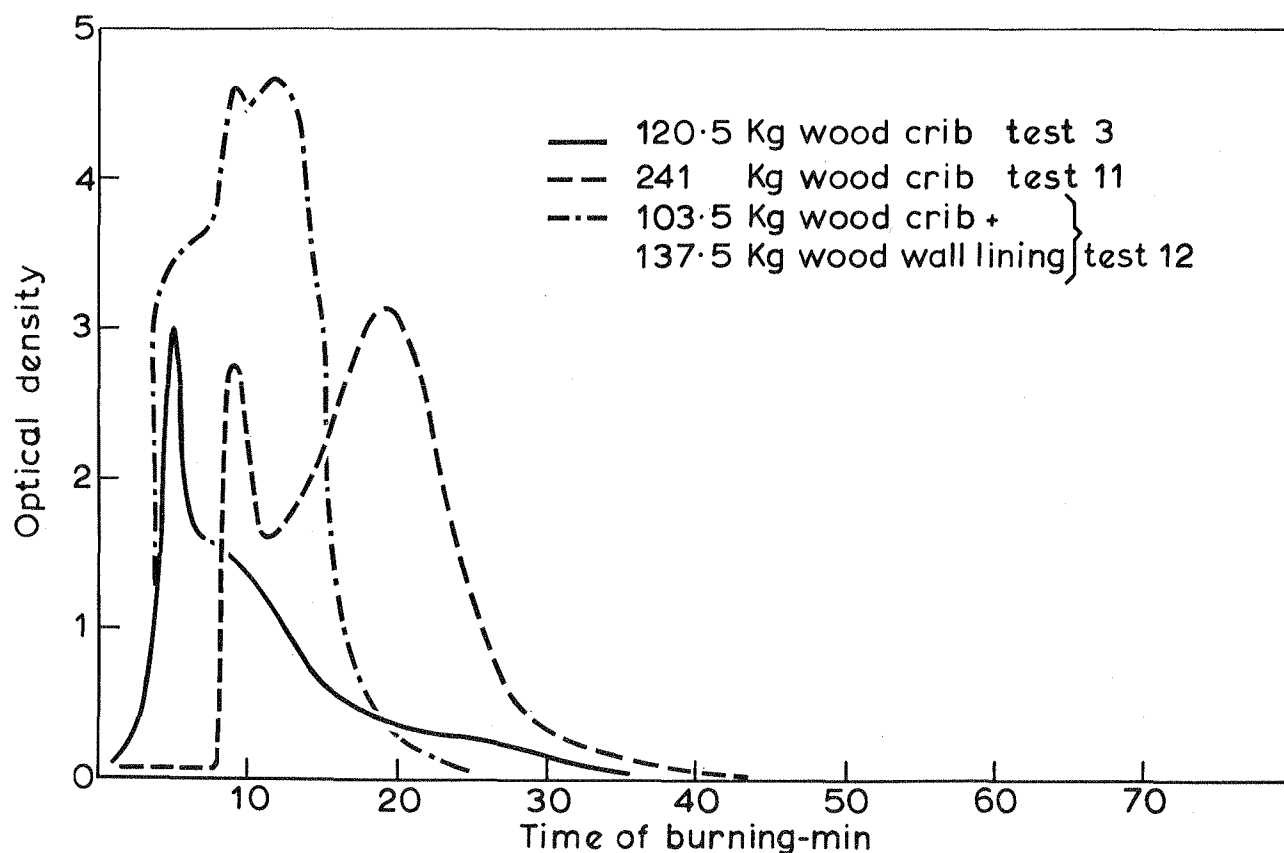


Figure 17 Optical density of smoke wood fuel only 700mm vent

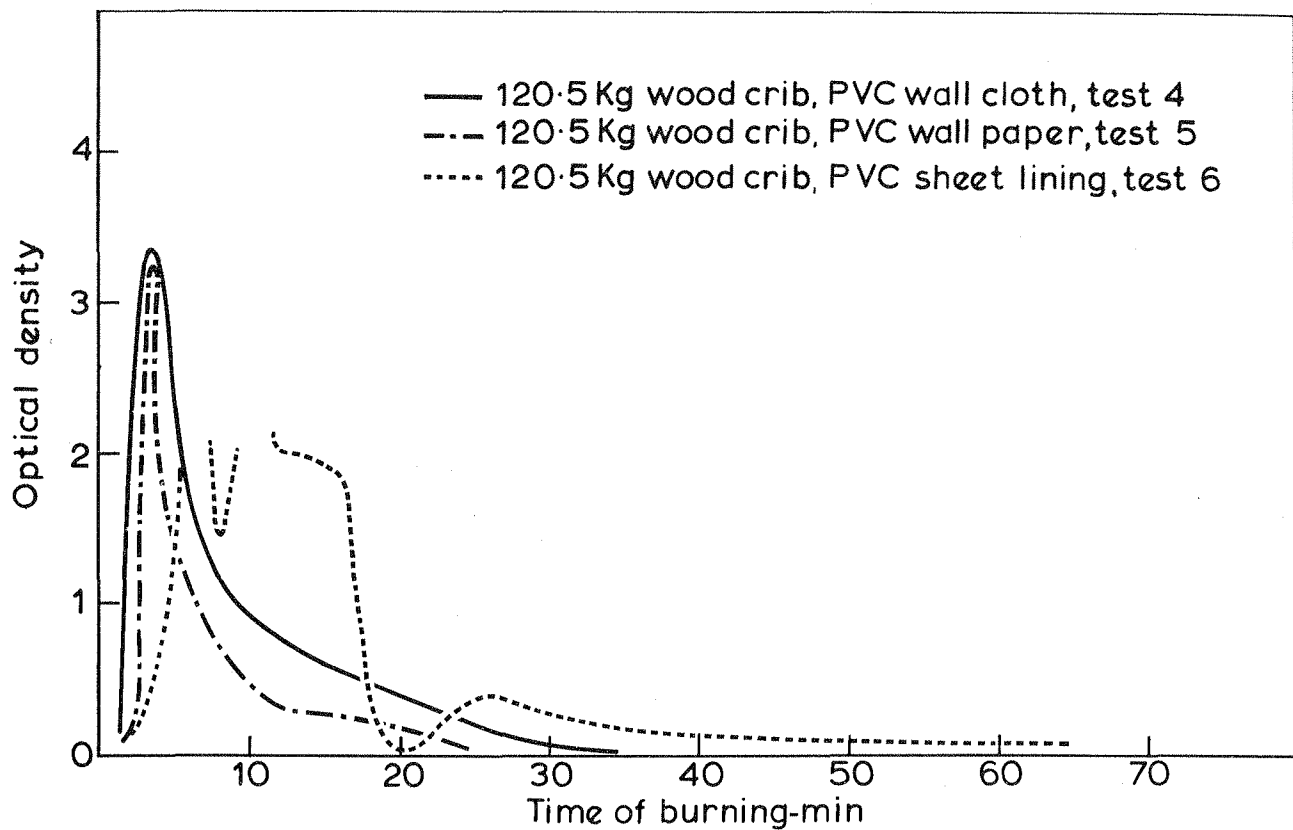


Figure 18 Optical density of smoke wood fuel and PVC, 700 mm vent

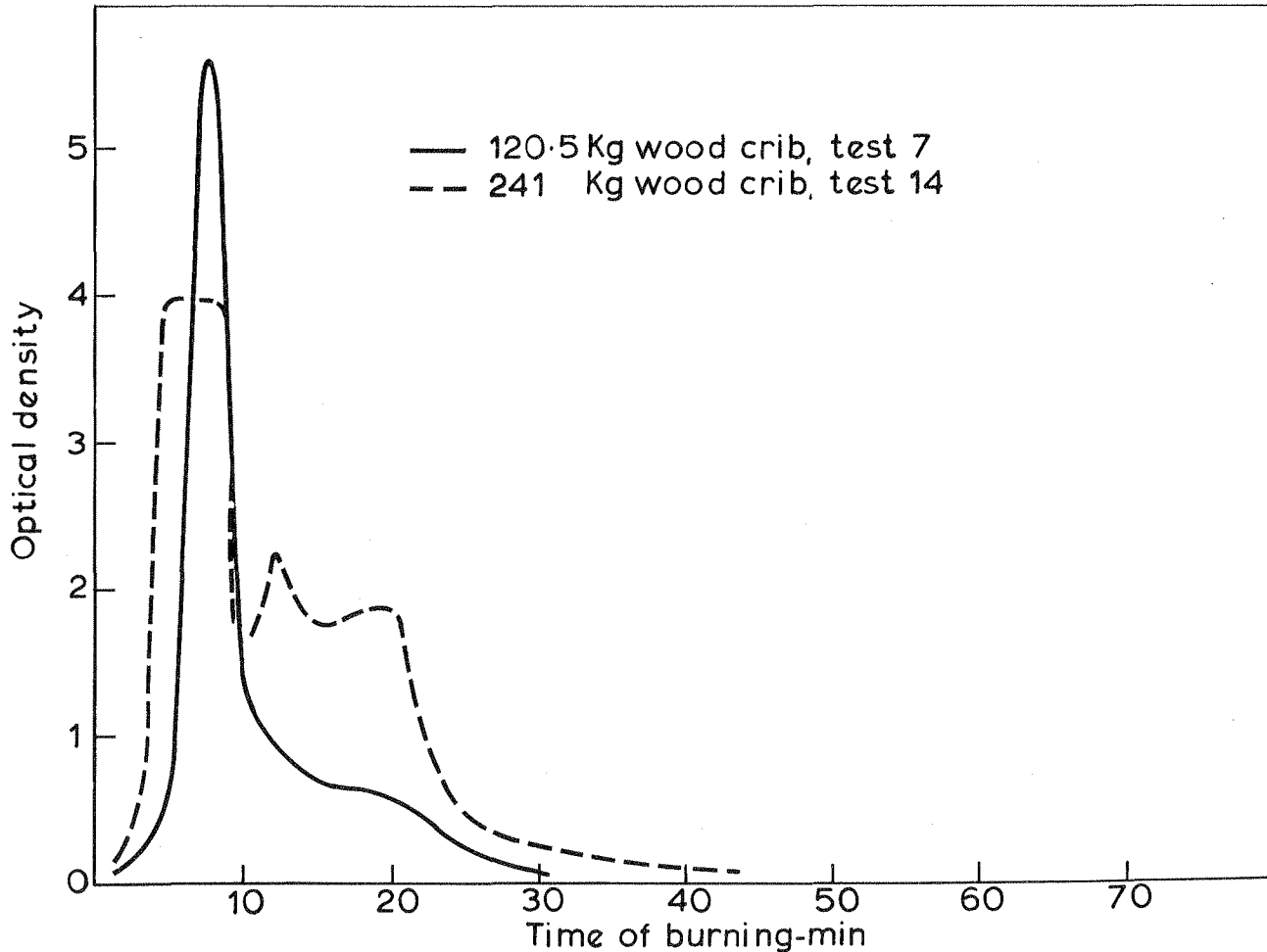
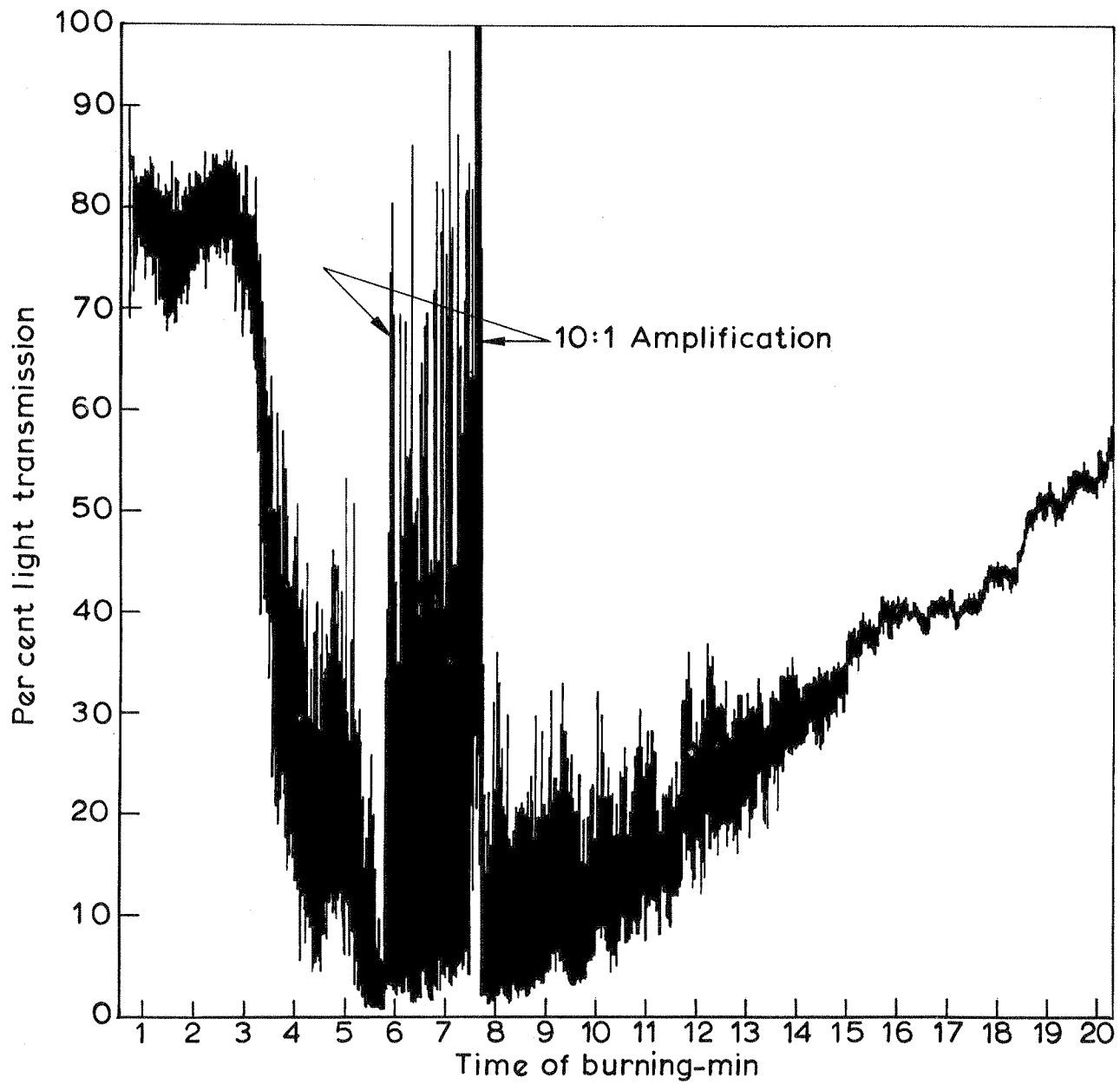
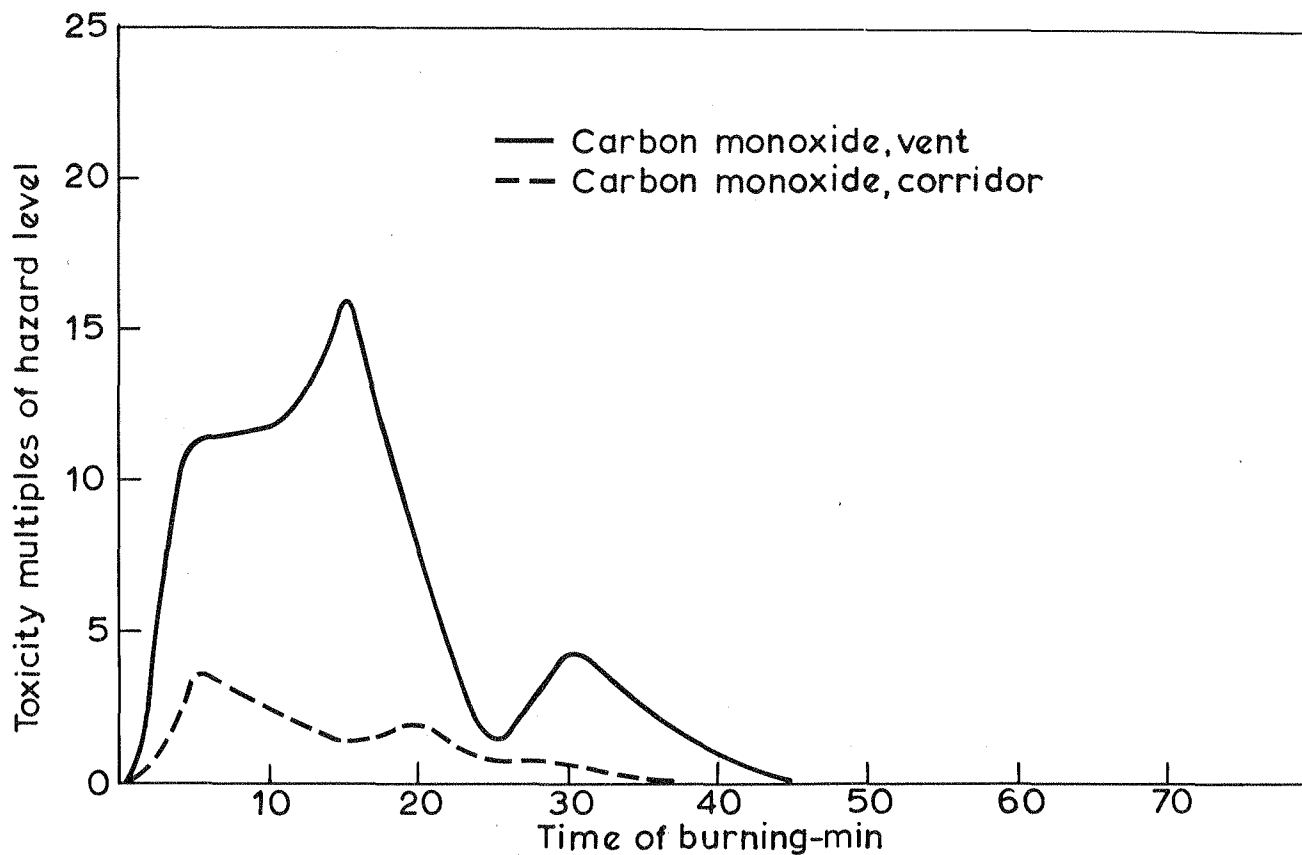


Figure 19 Optical density of smoke wood fuel in compartment, PVC is considered 700 mm vent

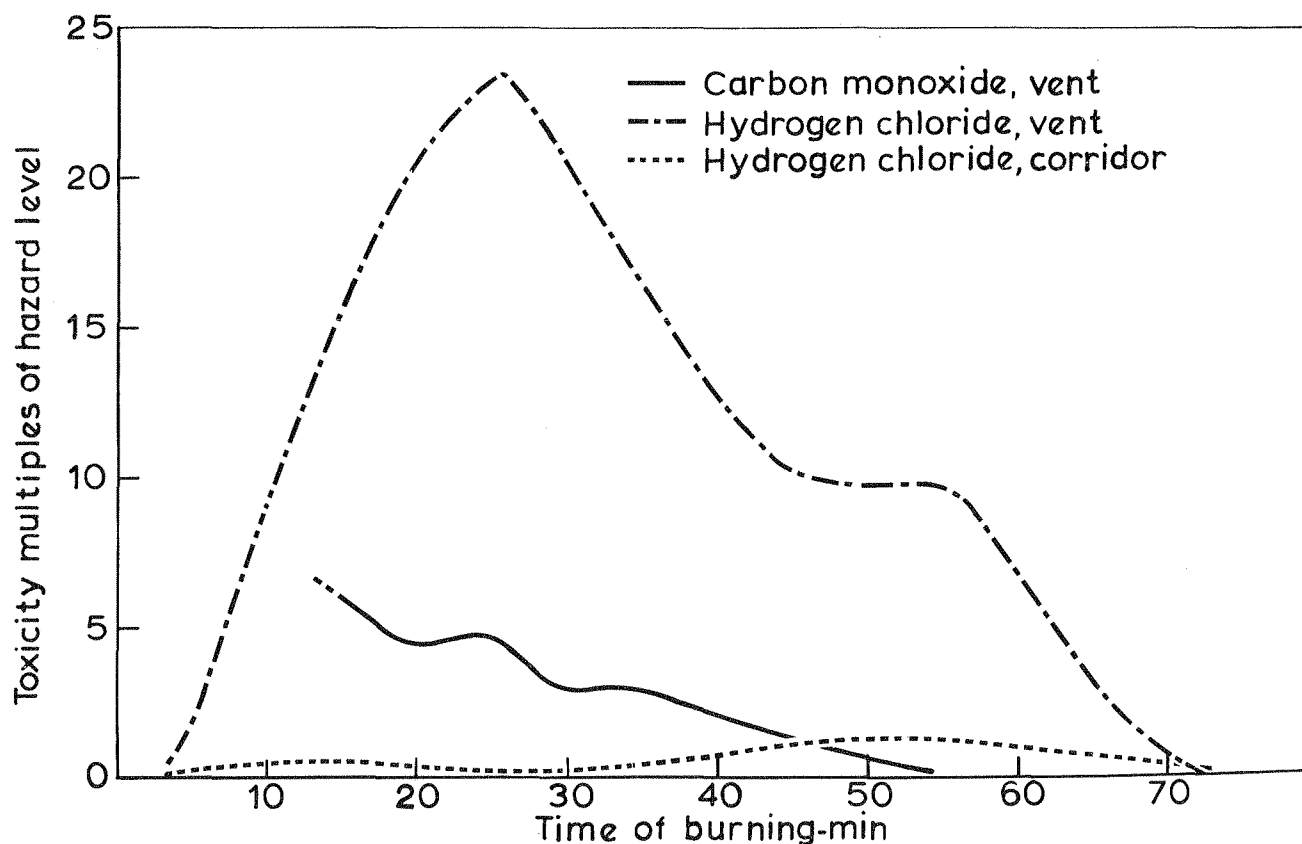


Test 3 Table 1

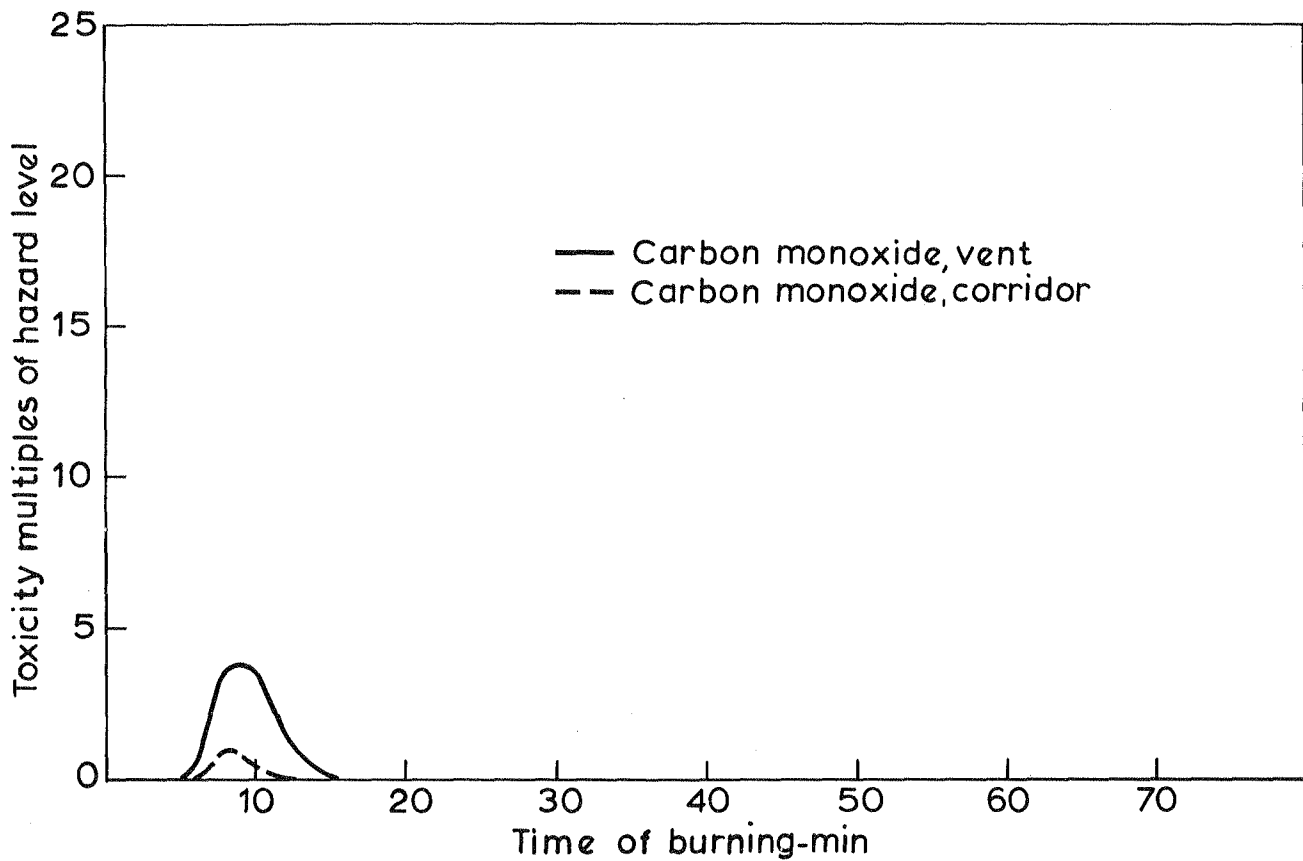
Figure 20 Light transmission record



Test 9 103.5 Kg wood crib, 137.5 Kg wood wall lining, 240 mm vent.
Figure 21 Toxicity levels of fire gases

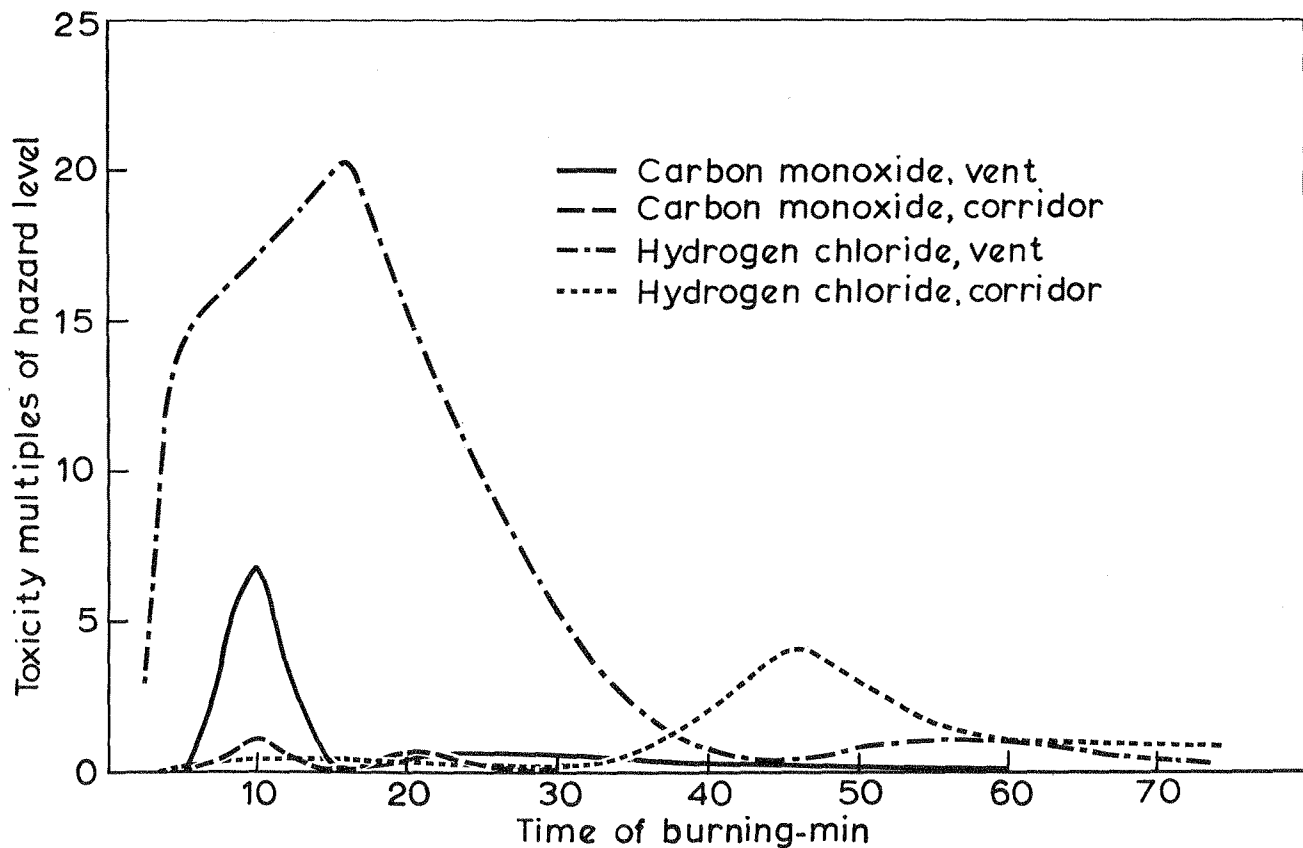


Test 10 241 Kg wood crib, PVC sheet wall lining, 240 mm vent
Figure 22 Toxicity levels of fire gases



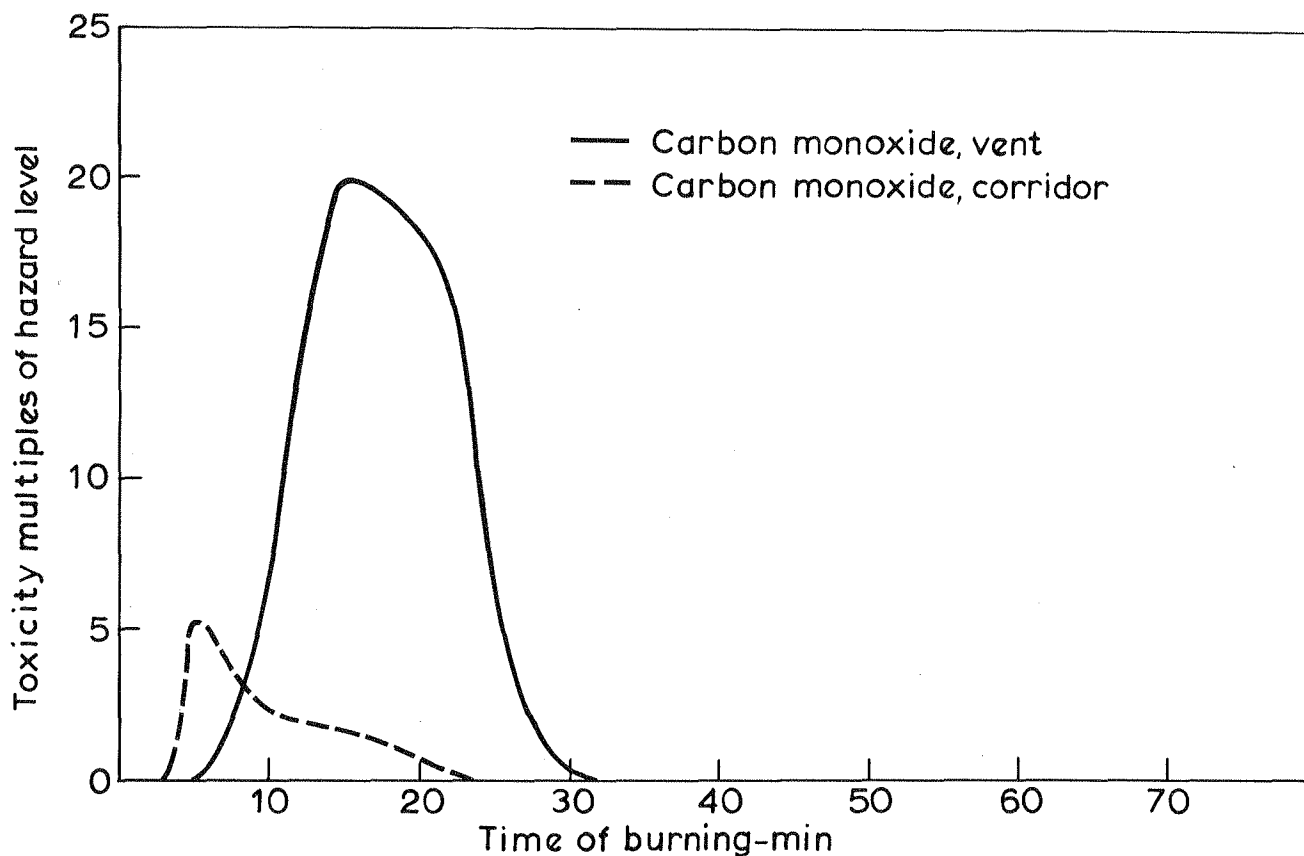
Test 3 120.5Kg wood crib only, 700mm vent

Figure 23 Toxicity levels of fire gases

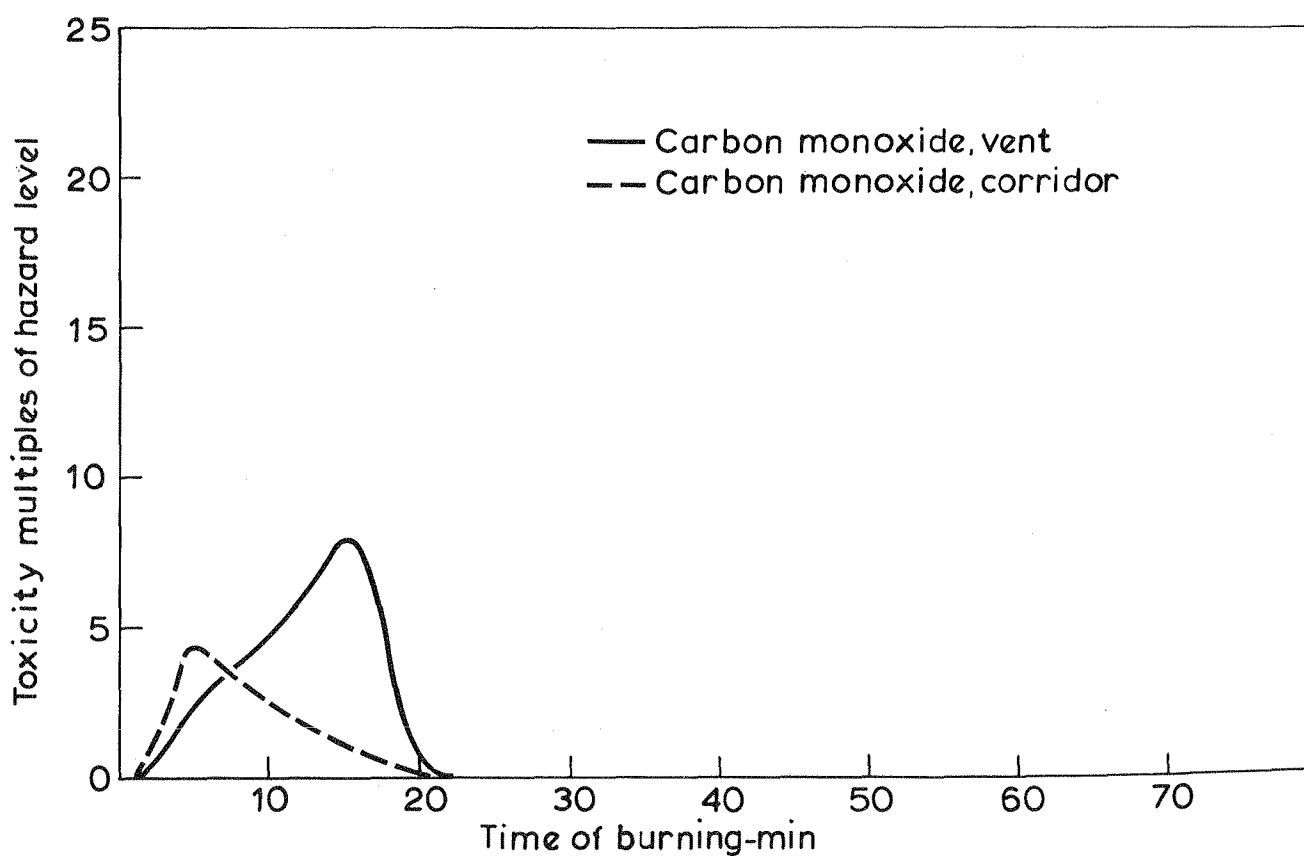


Test 6 120.5 Kg wood crib, PVC sheet wall lining, 700mm vent

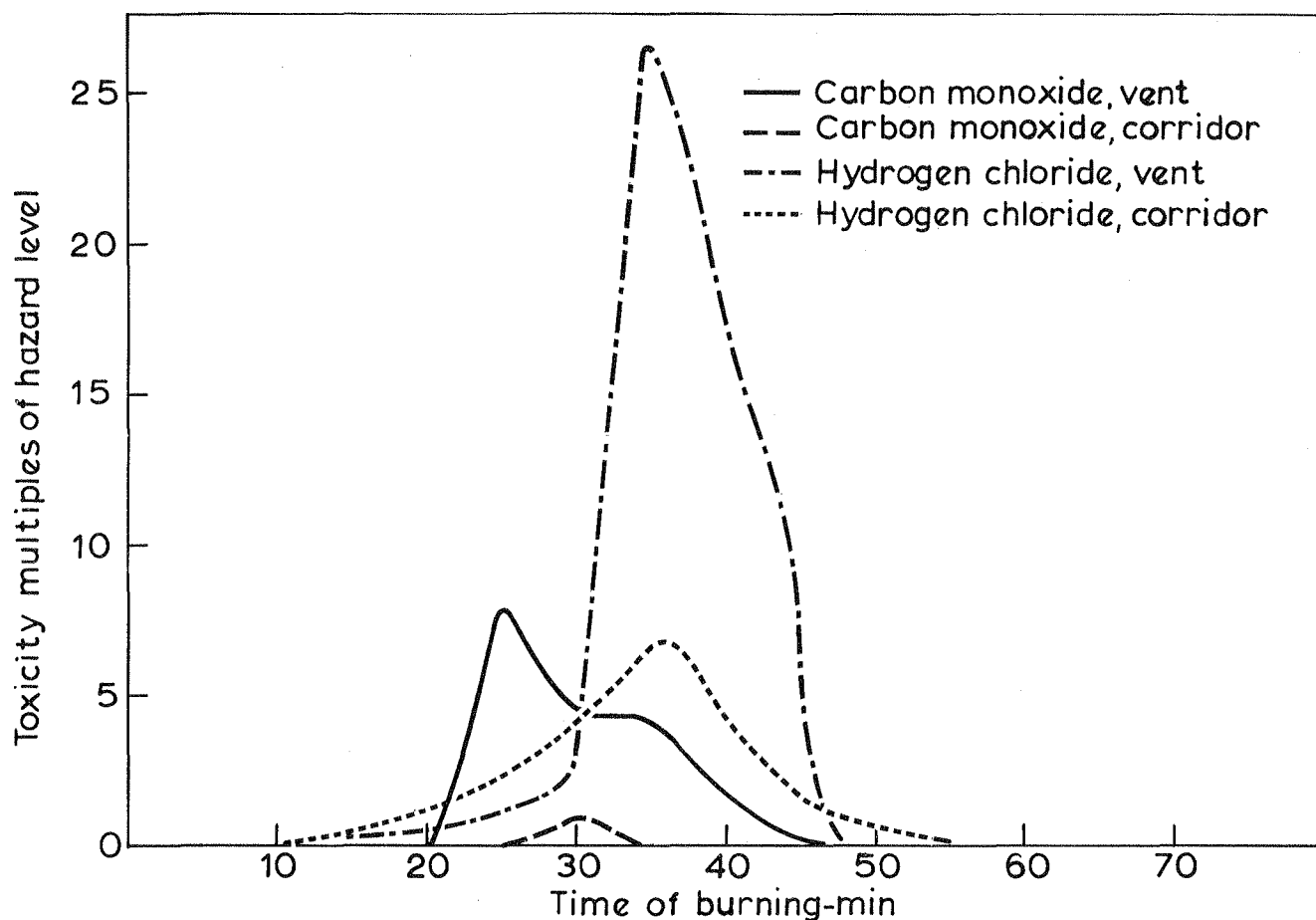
Figure 24 Toxicity levels of fire gases



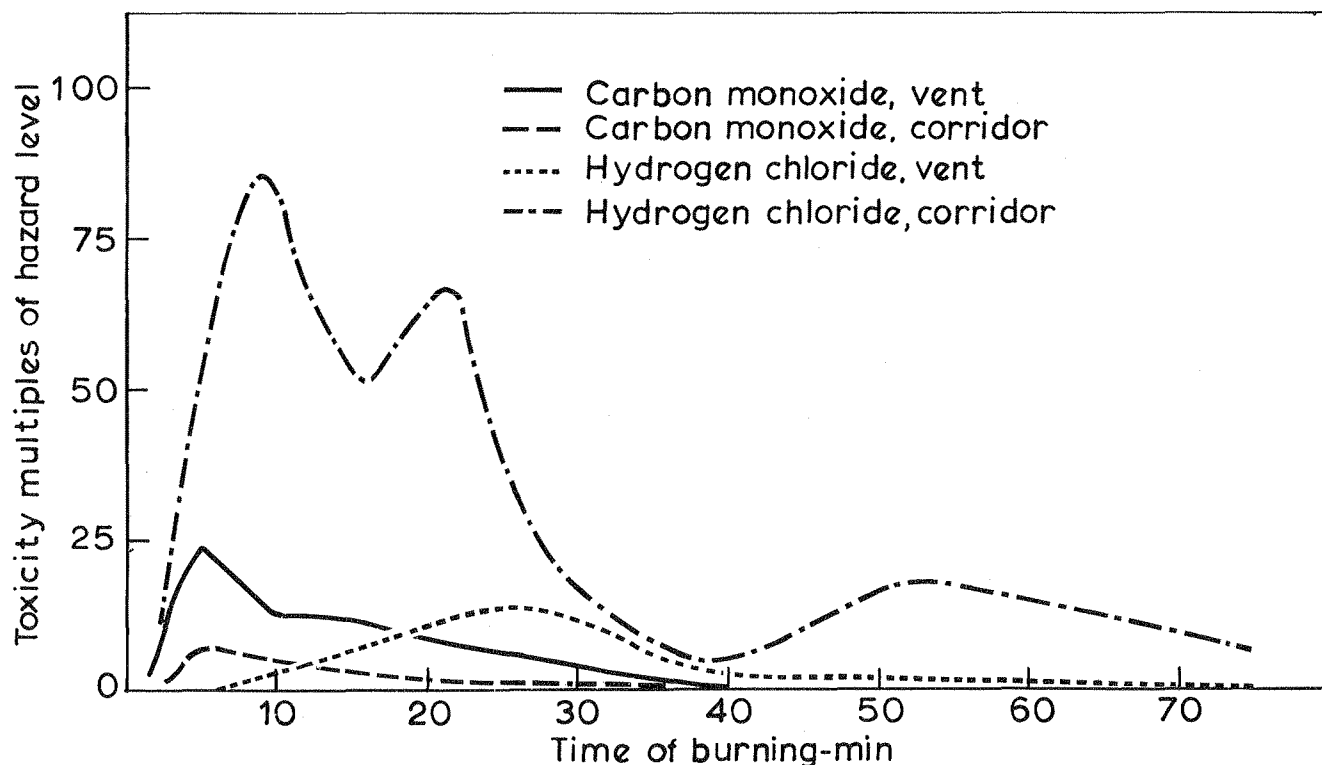
Test 11 241 Kg wood crib only, 700mm vent
Figure 25 Toxicity levels of fire gases



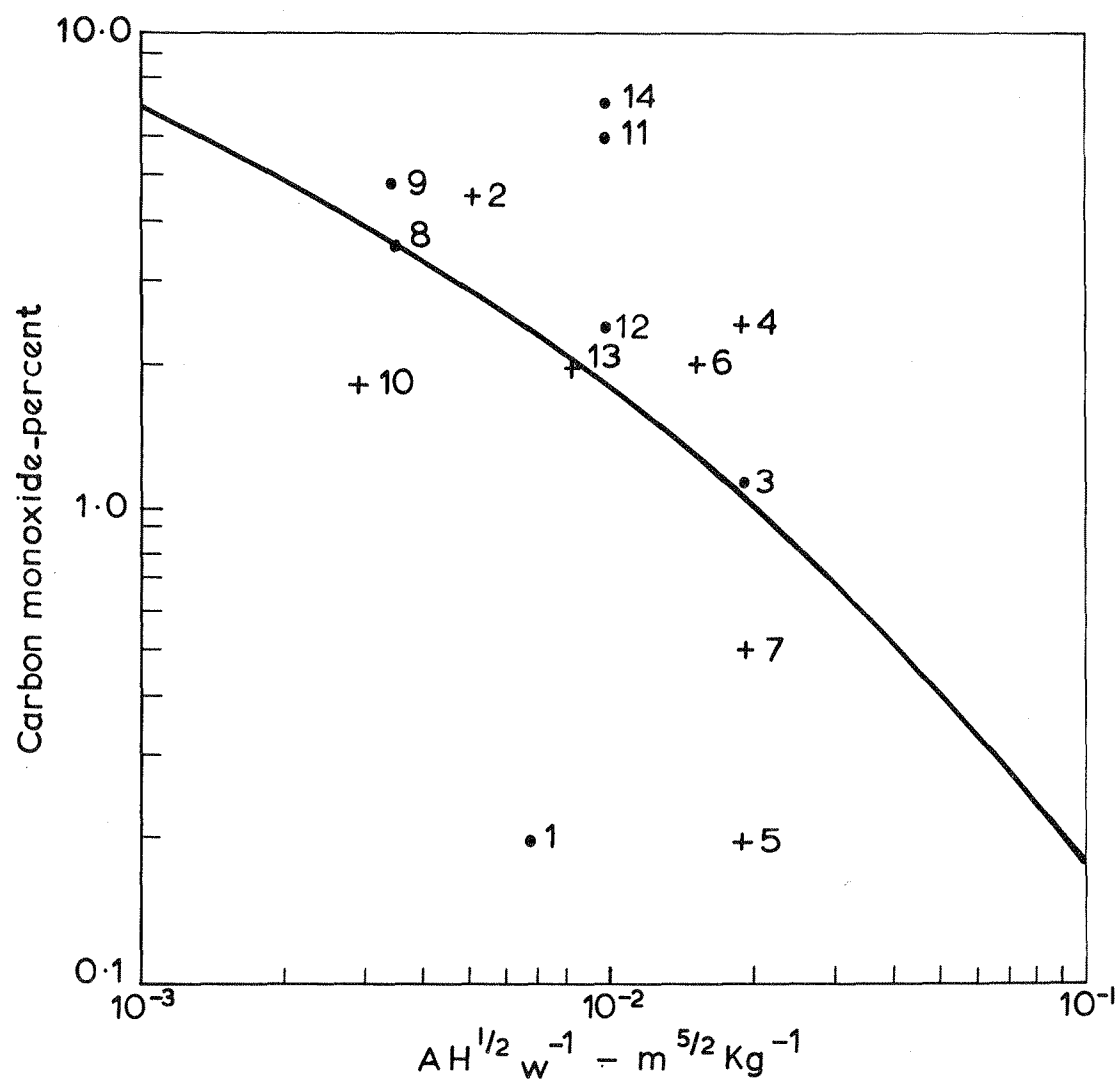
Test 12 103.5 Kg wood crib, 137.5 Kg wood wall lining, 700 mm vent
Figure 26 Toxicity levels of fire gases



Test 13 241 Kg wood crib, PVC sheet wall lining, 700 mm vent
Figure 27 Toxicity levels of fire gases

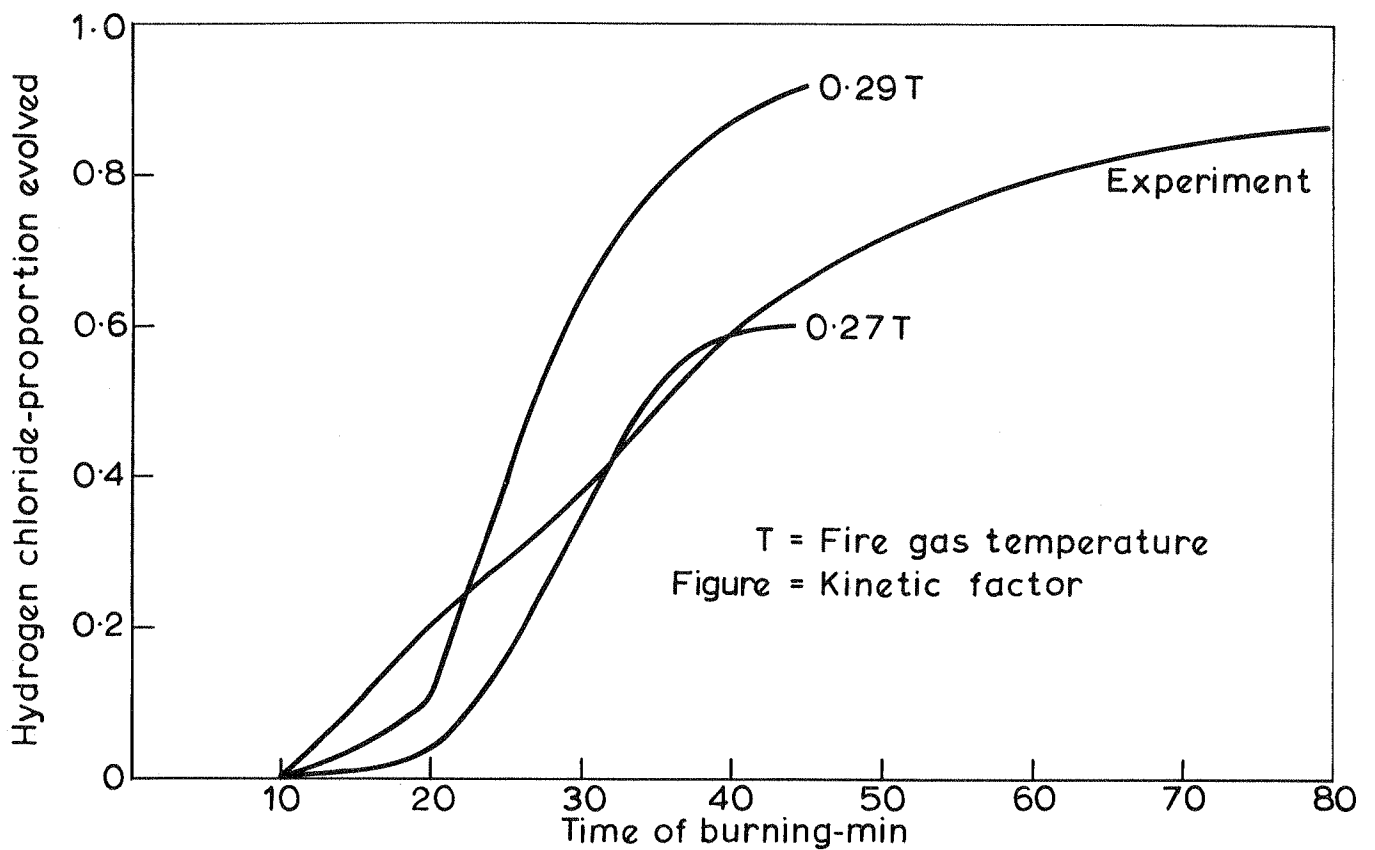


Test 14 241 Kg wood crib, PVC sheet corridor wall lining, 700 mm vent
Figure 28 Toxicity levels of fire gases



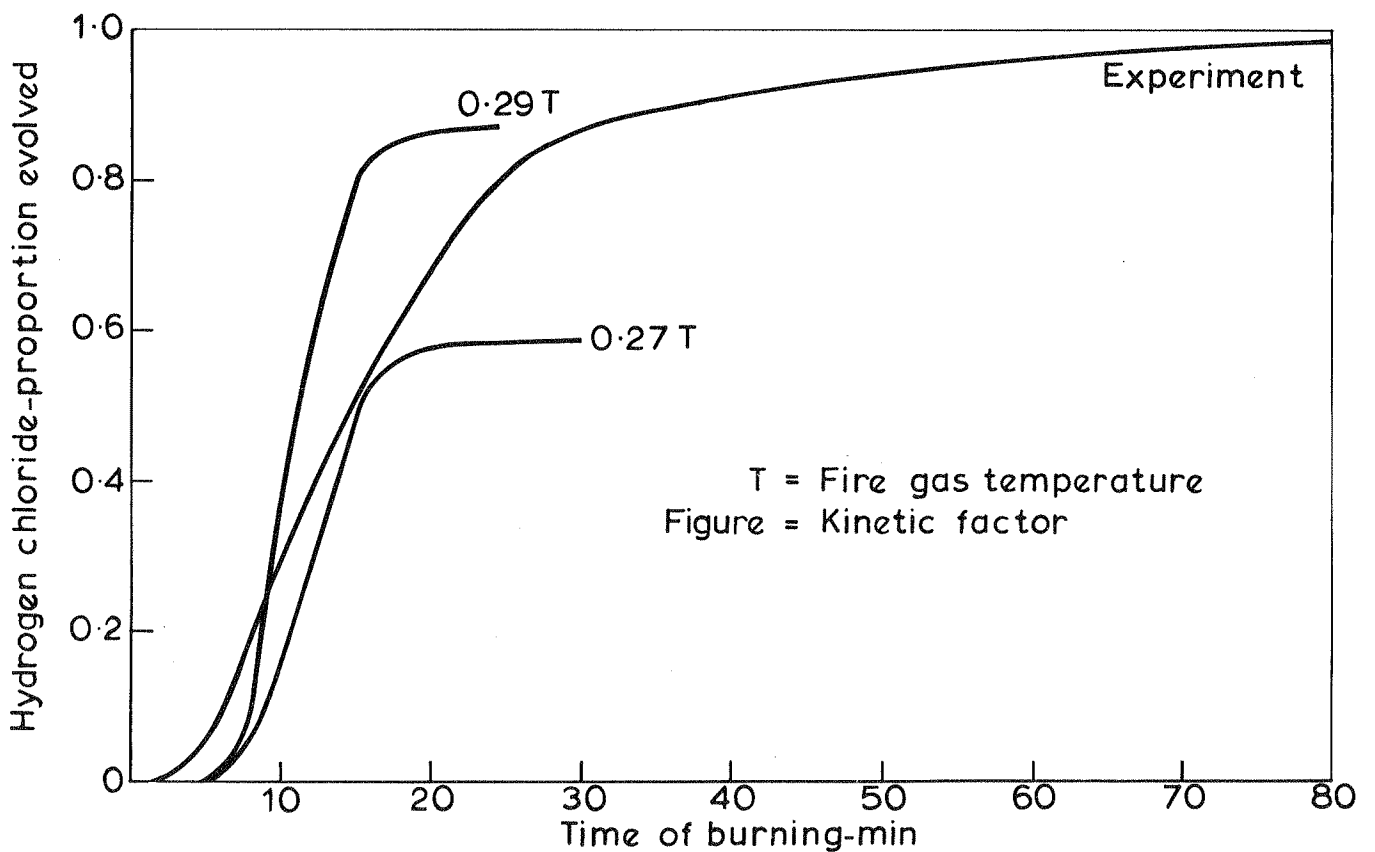
• = Wood only
 + = Wood + PVC
 Nos = Test No, table 1

Figure 29 Effect of fireload and ventilation on maximum concentration of carbon monoxide



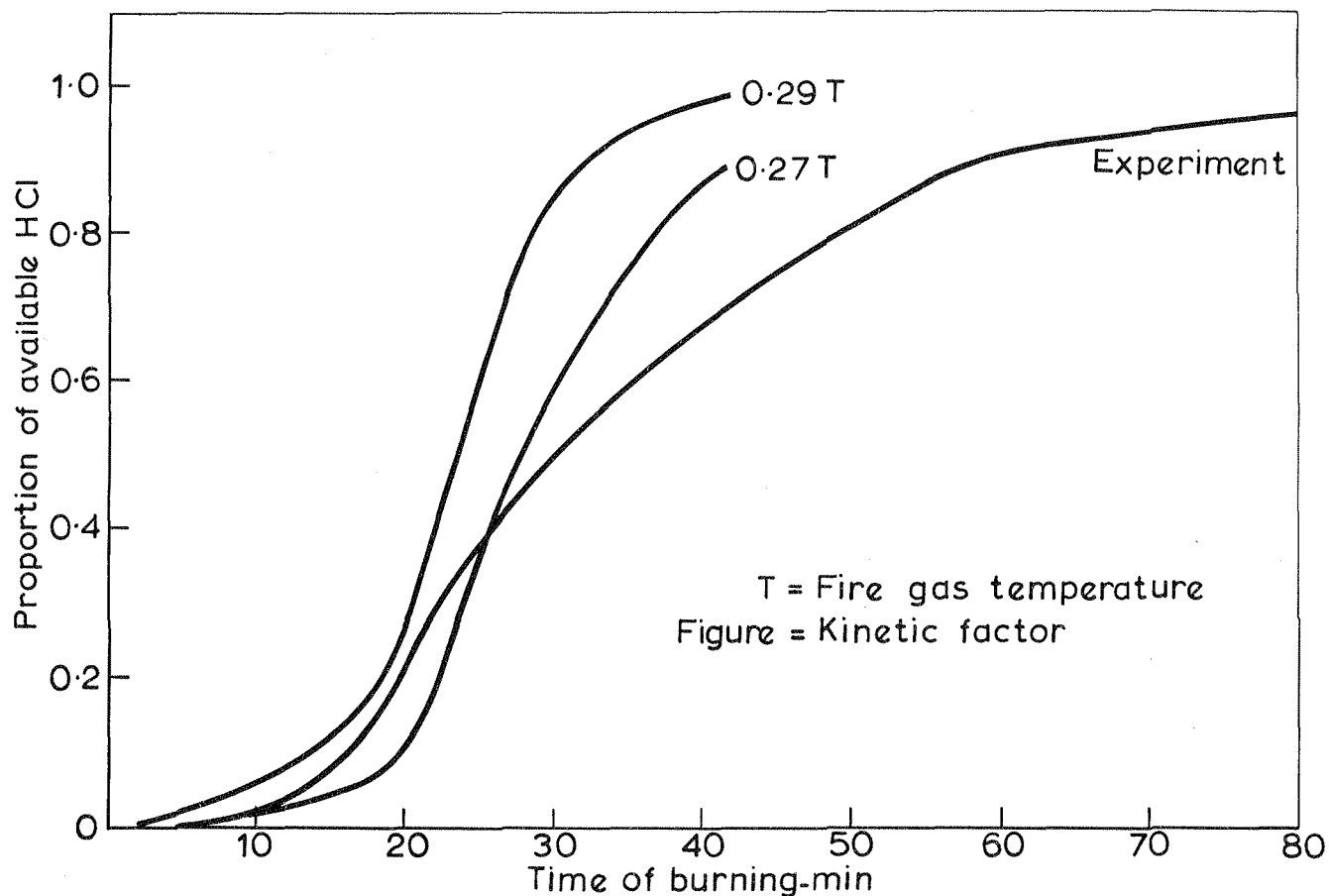
Test 2 Experimental and calculated values

Figure 30 Cumulated release of hydrogen chloride from PVC



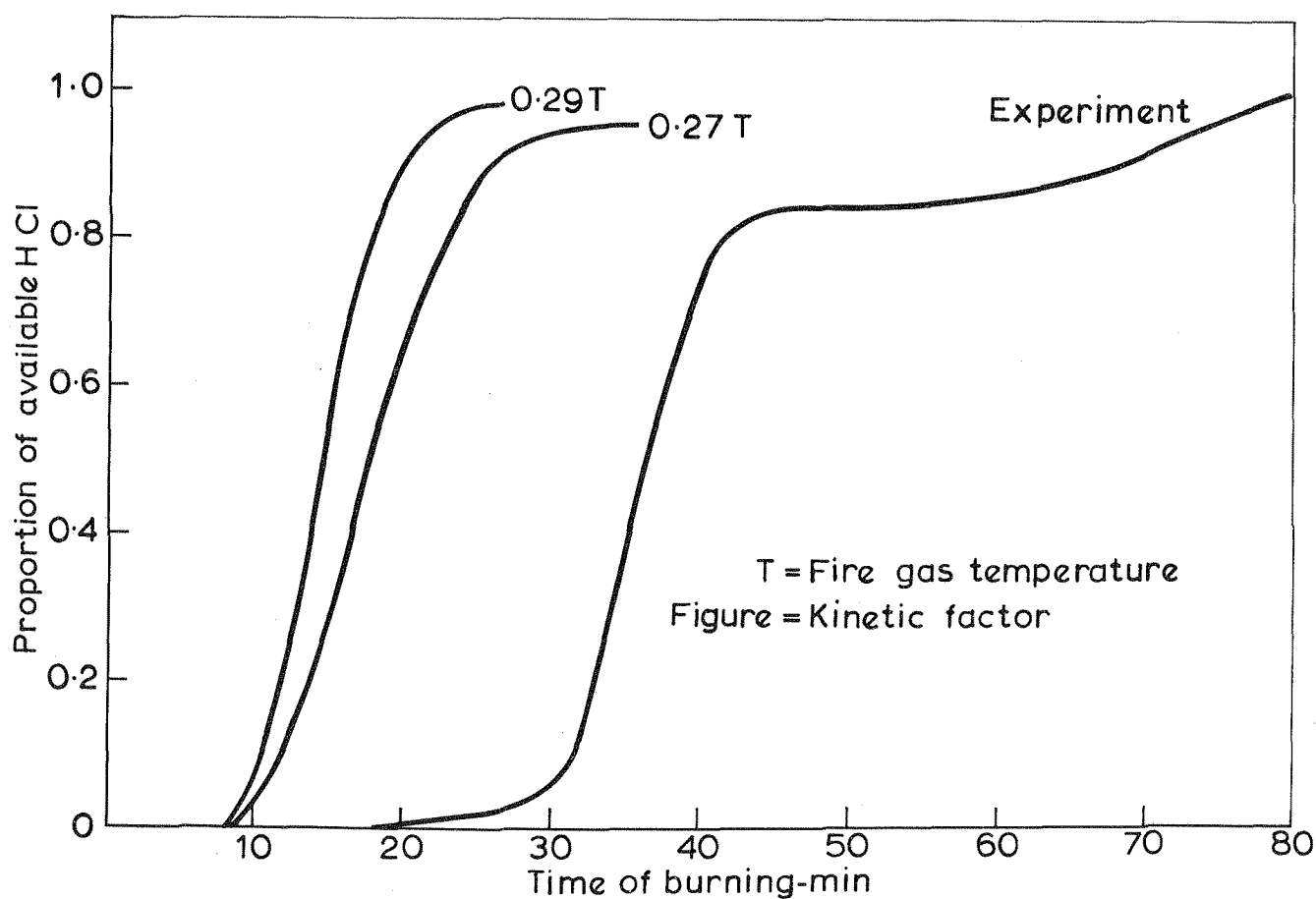
Test 6 Experimental and calculated values

Figure 31 Cumulated release of hydrogen chloride from PVC



Test 10 Experimental and calculated values

Figure 32 Cumulated release of hydrogen chloride from PVC



Test 13 Experimental and calculated values

Figure 33 Cumulated release of hydrogen chloride from PVC