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**Fire Research Note
No 1017**

51587

THE HAZARD FROM FIRES OF SMALL LOADS
OF FLEXIBLE POLYURETHANE FOAM

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August 1974

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SUMMARY

Tests have been made in which the toxic gases and smoke produced from fires in rooms of polyurethane flexible foam in amounts representative of those likely to be found in domestic premises, have been measured.

The tests have shown that all types of polyurethane foam tested, (unmodified, flame retardant, high resilience cold cure, and a recently introduced improved foam) ignited from small additional amounts of cellulosic material, and, except for the smallest fire load of two cushion squabs, were completely burned. The last three foams went out leaving some residual foam when only two cushions were tested.

Although the smoke and toxic gases produced during the fires of two squabs were small and unlikely to present a risk to occupants, fires of larger amounts, representative of fully furnished rooms, produced sufficient smoke to impede escape, and amounts of the toxic gases, carbon monoxide, hydrogen cyanide and nitrogen oxides, that would present a lethal risk even after dilution of the fire gases with cool air to temperatures that could be borne for short periods. Tolylene diisocyanate (TDI) was not detected in any test. The detection limit was 3 ppm.

The rate of production of smoke and toxic gases was such that, if they escaped from the room on fire to the remainder of a dwelling, the atmosphere in the whole of the dwelling would become hazardous in a few minutes.

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

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1. INTRODUCTION

Reports on fires of industrial loads of flexible polyurethane foam have
drawn attention to the rapid development of fires, the high density of smoke, and
the high concentrations of the toxic gases, carbon monoxide and hydrogen cyanide[1,2],
present in the fire gases. However, laboratory pyrolyses have shown that the
yields of the products of combustion, in particular hydrogen cyanide, are highly
dependant upon the temperature of pyrolysis. Smaller fire loads, which could
decrease the temperatures reached in fires, could result in a lower hazard.
This could well affect the hazards from the smaller loads such as would be found
in domestic rooms compared with the hazards shown for industrial loads.

A series of tests were therefore performed at the Fire Research Station, in
which (a) loads of flexible polyurethane foam equivalent to that provided by a
fireside chair, (b) loads consisting of two simulated flexible polyurethane foam
mattresses on single beds, with a realistic additional load of paper and cotton
sheeting and (c) a load consisting of 100 cushion squabs arranged in a U-form
similar that that used in fire tests of industrial loads, were burnt in the
compartment of the test-rig of compartment and corridor constructed at the Fire
Research Station for the purpose of such tests[3]. Four flexible polyurethane
foams were used: an unmodified polyether foam, A; a similar foam incorporating
an additive halogenated alkyl phosphate flame retardant, B; a high resilience
cold cure foam, C; and a new type of foam said to possess better properties
in fire, D. Measurements were made of temperatures of fire gases, concentrations
of hydrogen cyanide, carbon monoxide, oxygen and nitrogen, and smoke, in the
same manner as was used in the tests of industrial loads.   In addition,
measurements were made of the concentrations of nitrogen oxides (nitrous gases)
and tolylene diisocyanate (TDI) in the fire gases, because laboratory pyrolyses
had shown that nitrous gases were a product to be expected from the combustion
of hydrogen cyanide[4] as well as from the fixation of nitrogen in air during a
fire[5], and that release of TDI could be expected from exposure of flexible

polyurethane foams to temperatures in the region of $300^{\circ}C$[6]. The tests of large fire loads of flexible polyurethane foam had indicated that TDI was present in the compartment during a fire, but no measurements of TDI had been made from the fire gases issuing from the compartment into the corridor, or from the open end of the corridor[1].

The fire loads examined represent values that could well be present in domestic fires, and therefore the measurement of smoke and toxic gases provides more reliable data to assess domestic risks than the forementioned tests of industrial loads.

2. EXPERIMENTAL

2.1 The test rig

The test rig of compartment and corridor is illustrated in Figs 1 and 2 and is fully described elsewhere[3]. For the present tests the opening between compartment and corridor was maintained at 700 mm. Samples of gases were withdrawn from the opening between compartment and corridor and 10 m (33 ft) away at the open end of the corridor through resistively heated stainless steel tubes of about 6 mm ($\frac{1}{4}$ in) internal diameter at measured intervals during each test. The gases, oxygen, nitrogen, carbon dioxide and carbon monoxide were measured by gas-solid chromatography, hydrogen cyanide by selective ion electrode, and tolylene diisocyanate by gas-liquid chromatography. Nitrous gases were determined by a method utilising a commercial colorimetric indicating tube[4].

Temperatures of fire gases were measured for all tests at the opening between compartment and corridor and for some tests at 2 m (6.6 ft) intervals along the corridor, the final site being close to the open end of the corridor and 10 m (33 ft) from the compartment opening. Smoke was measured after issuing from the corridor, Fig 3, from the attenuation of a light beam registered by a selenium photocell. The recorded attenuation of the light flux at the photocell was used to calculate the optical density, a quantity allowing calculation of the visibility through the smoke[3,7].

2.2 The fire load

The arrangement of the three fire loads tested is illustrated in Fig 4. All three fire loads were made up from squabs measuring 450 mm (1 ft 6 in) square by 75 mm (3 in) thick.

Fire load a, Fig 4a: Two squabs were placed on edge, 25 mm (1 in) apart, and 300 mm (1 ft) within the compartment from the opening. The priming fuel was one half-sheet of newspaper, weighing about 15 g ($\frac{1}{2}$ oz), folded and crumpled into a spill of about 25 mm (1 in) diameter. A fire load of wood wool, of about the same weight and bulk density as foam A, was included for comparison.

Fire load b, Fig 4b: Two simulated bed-frames of slotted steel angle of area 900 mm x 1800 mm (3 ft x 6 ft) with a rectangular grid support of 3 mm ($\frac{1}{8}$ in) wire of 150 mm (6 in) square hole structure, supported 375 mm (1 ft 3 in) above the floor, were each covered with a simulated mattress consisting of two layers of 8 squabs wrapped in cotton sheeting. A crumpled newspaper and further cotton cloth was placed under each bed so that the total weight of cotton and paper associated with each bed was 5 kg. The cellulosic load acted as priming fuel.

Fire load c, Fig 4c: The 100 squabs for this test were arranged in a U-shape against two walls of the compartment under the base of which U were placed two cardboard boxes, measuring 300 x 300 x 500 mm (1 ft x 1 ft x 1 ft 8 in), filled with broken pieces of the foam under test. A 1 kW 240 V spiral electric heating element was placed between the two boxes. One limb of the U was not in contact with a wall and the open end of the U was directed to the compartment opening. The cardboard boxes acted as priming fuel.

Ignition for fire loads a and b was brought about by applying a lighted match to the priming fuel, a single application being made with fire load a, and a multiple application being made with fire load b. Fire load c was ignited by passing mains voltage for one minute through the electrical element, during which time the heated element ignited the priming fuel.

2.3 Temperature of fire gases

Temperatures were measured at the sites indicated in 2.1 throughout each test and were recorded continuously by potentiometric recorders. The recorded temperatures allow estimates to be made of the time of burning and the rate of flow of fire gases[3].

2.4 Fire gases

The fire gases carbon monoxide, carbon dioxide, nitrogen, oxygen and nitrous gases were measured from samples collected at given times during each test by gas solid chromatography. Hydrogen cyanide and tolylene diisocyanate were measured from samples collected for consecutive periods of time during each test, the former with a selective ion electrode, and the latter by gas liquid chromatography. Calculated rates of flow of the fire gases were then used to obtain estimates of the amounts of toxic gases evolved from the measured concentrations[3].

2.5 Smoke

The measured attenuation of light falling on the photocell after passage through the plume of smoke were used to calculate the optical density of the smoke over a metre path length*. The total amount of smoke evolved in each test was calculated from the rate of flow of the fire gases and the optical density[3].

3. RESULTS

Table 1 presents the extreme values of temperature, toxic constituents of the fire gases and smoke, and integrated totals for the toxic gases carbon monoxide, and hydrogen cyanide, and for smoke. Further information for each test array is given below. The data for industrial loads, tests 11-13, is included for comparison[8].

3.1 Two squab array

3.1.1 Temperature, time of burning

There was a very small rise above ambient of the temperature of the fire gases, the maximum, for foams A and B, being about $70^{\circ}C$. Times of burning estimated from the graphs of fire gas temperature against time of burning, Fig 5, were less than 5 min for each foam tested. The fire of wood wool, included for comparison, showed a similar pattern of burning to foams, A, C and D. Flame spread over foam C took a long time, about 3 min against 1 min for the other fuels, but the time of burning was similar. The maximum temperature of the fire gases from wood wool was however much higher, about $140^{\circ}C$ above ambient. The rise

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*Optical density = logarithm to base 10 of the ratio of unattenuated to attenuated light flux at the photocell.

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TABLE 1

Smoke and Toxic gases from burning flexible polyurethane foams

Test No	Code	Weight kg	State	Residue after test kg	Maximum Temp. °C	Carbon monoxide Max ppm	Carbon monoxide Total, kg	Hydrogen cyanide Max ppm	Hydrogen cyanide Total, kg	Nitrous gases Max ppm	Optical Density/m Max	Total
1	A	0.8	2 squab	0	95	NR	–	NR	–	200	NR	–
2	B	1.15	"	0.65	95	1000	–	NR	–	450	NR	–
3	C	2.1	"	1.9	30	NR	–	NR	–·	20	NR	–
4	D	0.8	"	0.2	45	NR	–	NR	–	40	NR	–
5	Wood Wool	0.8	150 mm layer	0	160	NR	· –	NR	–	20	NR	–
6	A	12.7	2 Bed	0	900	23000	2.6	450	0.14	200	3.15	11
7	B	17.2	"	0	ND	62000	5.7	1000	0.21	900	3.75	22
8	C	32.2	"	0	970	67000	18.0	2500	0.77	900	4.35	37
9	D	12.7	"	0	890	33000	2.4	1150	0.25	40	3.15	12
10	A	40.0	100 squab	0	1005	36000	7.9	4500	0.76	ND	5.4	64
11	A	127	300 squab	0	1090	140000	247	2760	4.0	ND	4.65	234
12	B	159	"	0	1110	66000	29	3650	4.4	ND	5.85	182
13	C	285	"	0	1220	88000	175	2490	6.7	ND	5.1	440

Notes: Width of ventilation opening 700 mm for tests 1–10, and 1150 mm for tests 11–13.

NR = Not registered (amount less than limit of detection)

ND = Not determined (No measurements made)

in temperature due to the fire gases in the corridor was very small, and was not detected by the recording system at the open end of the corridor. All combustible was consumed in the tests with foam A and wood wool; most of the combustible was consumed in the test with foam D, but considerable amounts were left of foams B and C. (Table 1).

3.1.2 Toxic gases

The concentration of hydrogen cyanide in the fire gases was too low to be measured (detection limit about 15 ppm), as also was the concentration of TDI (detection limit about 3 ppm). Carbon monoxide was only detected in the fire gases from the test with foam B, which also gave the highest measured concentration of nitrous gases. The maximum concentration of nitrous gases from wood was little different from the values for foams C and D.

3.1.3 Smoke

The amounts of smoke formed in tests 1-5 of the foams and wood wool, was very small, the darkest smoke being formed from foam B. The smoke density at no time during the tests either interfered significantly with visibility in the compartment (limiting optical density 0.4 per metre) or through the corridor (limiting optical density 0.08 per metre)[7].

3.2 Two bed arrays

3.2.1 Temperature, time of burning

Temperatures attained by the fire gases leaving the compartment were high, and the time of burning appeared to be related to the amount of foam burnt, Table 1. The variation of temperature with time of burning, Fig 6, indicates an initial period of rising temperature during which flames spread over the surface of the mattresses, followed by a steady burning, after which the temperature fell rapidly. Temperatures were not recorded for the fire of foam B, because of a thermocouple fault. However, the values recorded in the two squab tests, and those recorded previously[1], suggest the temperatures for foam B should be similar to those recorded for foam A. Unlike the behaviour in the two squab tests, foams B, C and D also burnt completely. The maximum temperatures attained by the fire gases are related to the amounts of foam burnt, as had been noted for industrial fire loads of flexible polyurethane foams[8]. Times of burning were similar to those recorded in the fire tests of two squabs. The temperatures attained by the fire gases and the gas flows were sufficient for rates of flow to be calculated.

3.2.2 Toxic gases

Curves of the variation of gas concentration with time of burning for oxygen, carbon dioxide, carbon monoxide and nitrous gases are given in Figs 7-10, and block diagrams for concentrations of hydrogen cyanide are given in Fig 11 for the site at the opening from the compartment. The maximum concentrations of carbon monoxide for the tests, Table 1, are of the same order as those obtained previously with industrial loads of foam (for example, tests 11-13 Table 1) except for foam A. In these two-bed tests, the lowest maximum concentrations were obtained with foams A and D.

The values for the total amounts of carbon monoxide evolved during burning, Table 1, suggest that the concentration and amount of carbon monoxide evolved is directly dependent upon the weight of polyurethane foam. The results for hydrogen cyanide vary in much the same way, suggesting that the evolution of this toxic gas is also directly dependent upon the amount of polyurethane foam. The concentrations of nitrous gases formed are also largest for the greatest fire load (foam C), but the concentration from the intermediate load of foam B is equally high, suggesting that the presence of a flame retardant may have some influence on the products of combustion.

None of the tests gave a measurable concentration of TDI, the concentration of which was below the detection level, 3 ppm.

3.2.3 Smoke

Curves of the optical density per metre against time of burning are given in Fig 12. Although the optical density of smoke was greatest for the greatest weight of foam (foam C, Table 1), differences in optical density between foams were small. The dependence of total smoke on weight of foam was direct and nearly linear. This is supported by the results for fires of larger weights of polyurethane foam, (tests 11-13 in the Table).

3.3 100 squab test

3.3.1 Temperature, time of burning

The temperatures recorded for this test, Fig 13, follow the general form of a rapid rise followed by a short period at high temperature, and then by a rapid fall in temperature[3]. Observation had

indicated that the last stage occurred when the foam had been consumed.
The maximum temperature of fire gases leaving the compartment, was only
slightly less than that recorded for a test in which 300 squabs were
burned, test No 11, Table 1.   The time of burning, Fig 13, is estimated
as about 5 min.   The fall in temperature of the fire gases on passing
through the corridor is similar to that recorded for tests of larger
amounts of polyurethane foam[8].

3.3.2 Toxic gases

Because the fire load used in this test is probably representative
of the highest loads likely to be found in domestic rooms, measurements
of oxygen depletion and of toxic gas concentrations are presented in
detail, Figs 14-17.   Oxygen depletion in gases leaving the compartment
was a maximum after 4 min burning when fire gas temperature was also a
maximum.   The concentration of carbon monoxide in the fire gases was a
maximum, 4 min after ignition, but carbon dioxide exhibited a maximum
earlier, about 2 min after ignition.   High concentrations of hydrogen
cyanide also occurred early in the test, the maximum concentration being
recorded 2-3 min after ignition.

This test also gave no indication of TDI in excess of the
detection limit, about 3 ppm.   No determination was made of nitrous gases,
because of a fault in the sampling system.

The values for depletion of oxygen and maximum concentrations of
toxic gases at the open end of the corridor, 10 m (33 ft) from the
opening between compartment and corridor, are much less than for the
compartment opening.   The depletion of oxygen, Fig 14, gave a minimum
value of 18.7 per cent, the maximum value for carbon dioxide, Fig 15
was 0.4 per cent, and carbon monoxide, Fig 16 was always less than the
detection limit, 100 ppm or 0.01 per cent.   No measurements of other
gases were made at this site,   because of lack of facilities, and the
expectation of freedom from hazard at this site, other than that
presented by smoke.   The reduction in concentrations of toxic gases
at the open end of the corridor is discussed later.

3.3.3 Smoke

The measured optical density is plotted against time of burning
in Fig 18.   The maximum value is similar to those obtained during tests
of loads of 127 kg (280 lb) or more[8], but the total is considerably less;
compare tests 10 and 11, Table 1.

4. DISCUSSION

4.1 Two squab tests

Recent work on toxicity has indicated that 5000 ppm of carbon monoxide, and 100-200 ppm of hydrogen cyanide, present a hazard to life on exposure for a short time, and published data on nitrogen dioxide, to which the nitrous gases become quickly converted, gives the concentrations presenting a risk to life on exposure for a short time as 200-700 ppm[9]. The concentrations of nitrous gases measured from fires of foams A and B, tests 1 and 2, Table 1, are thus not free from risk on short exposure. However, recognising that the measurements of toxic gases were made above normal head height, - 1.6 m, (5.25 ft), at 2.25 m (7 ft 6 in) above the floor, in a fairly thin layer close to the ceiling, rapid first-aid fire fighting might not present a serious hazard.

A fire involving a single fire-side chair upholstered with polyurethane foam would present a similar fire load to the fire loads tested. The low temperatures of the fire gases suggest that a close approach could be made. Although further tests are needed to determine the best methods of fire fighting, a bucket of water poured over such a fire might be sufficient to extinguish it or prevent spread to other furniture. The combustion of part only of the foams B, C and D suggests that some advantage might be obtained from the use of flame retardant foams in small fires of this kind. Although the covering of a chair would influence ignition, the major mass of fuel would be presented by the foam filling, which would burn freely after the integrity of the covering was destroyed.

The density of smoke in the tests reported here was too low to obscure vision either at the compartment or along the corridor, and thus would not hinder fire fighting or rapid escape. This finding appears to be at variance with reported smoke concentrations in actual fire incidents and further tests may be needed to resolve this matter. Such tests should examine the effects of ambient temperature and the amount of ventilation, which was relatively high in the present tests, and approximated to an open door. Conditions in a closed room would be expected to result in higher temperatures and concentrations of toxic gases, but a slower rate of combustion.

4.2 Two bed tests, 100 squab test

The amount of fuel used in these tests approximates to the fire loads of flexible polyurethane foam that might be found in well furnished bedrooms or sitting rooms in domestic dwellings, where flexible polyurethane foam was used in upholstery and mattresses. The conditions of ignition are representative of the stage in the initiation of fire immediately preceding flame spread over the upholstered surfaces. This could arise when a smouldering source burst into flame, or through malicious ignition.

4.2.1 Temperature and fire load

The maximum temperatures of the fire gases leaving the compartment (tests 6-10, Table 1) are somewhat less than those recorded for tests of industrial loads (tests 11-13). The combustion of polyurethane foams has been observed to occur mainly on the upper surface, with some flaming from the sides of stacks of foam. The surface areas of the foam present in the two-bed tests and in the tests of stacked cushions were similar, but there was a greater contribution from the sides of the stacked cushions (height 0.8-1 m (2 ft 7 in - 3 ft 4 in)) than from the beds (height 150 mm (6 in)). The times of burning for the industrial loads of foam were 4-7 times longer than those for the two bed tests, a ratio about the same as that of the heights of foam; the time of burning of the 100 squabs, test 10, was only about twice that of the two bed fire loads, but this reflected the smaller stack height for the smaller fire load of stacked cushions.

The tests on industrial loads of flexible polyurethane foam had indicated that, for a given stack arrangement, the maximum temperature attained in the compartment was related to the weight of foam involved in fire[8], and the curve of this relation is given in Fig 19. The maximum temperatures measured in the present tests have been added to this graph. The revised curve drawn in the figure gives a better representation of the relation between fire load and maximum temperature of fire gases.

4.2.2 Toxic gases

The concentrations of carbon monoxide and hydrogen cyanide in the fire gases leaving the compartment opening, according to published data on toxicity[9], would be lethal in a very short time. Although there is a possibility that an occupant of a building might be exposed momentarily

to fire atmospheres from a burning room, for example, on opening and
rapidly closing a communicating door, longer exposure would result in
death or serious injury from the high temperature[10]. It is more likely
that he would be exposed to fire gases some distance from the fire when
they had mixed with cool air. Reduction of temperature of the mixed
gases to $150^\circ C$ would provide an atmosphere which could be borne for the
short time needed for escape[10]; a lower value would provide a safety
margin. Table 2 lists the concentrations of carbon monoxide, hydrogen
cyanide and nitrous gases that would be present in a mixture of the
fire gases, with air at $20^\circ C$, to give a final temperature of $120^\circ C$,
estimated for fire gases at their maximum temperature and for the
maximum concentration of toxic gases. Data are given for the fire gases
from the compartment, and, where information was available, for fire
gases from the open end of the corridor. Because combustion was not
complete in the compartment, and continued in the corridor, there was
generally a reduction in the concentrations of toxic gases issuing from
the open end of the corridor.

TABLE 2

Hazards presented by fire gases diluted with air
to a temperature of 120ºC

Test No	Fire gases from compartment				Fire gases from end of corridor					
	$Temp$ $^\circ C$	Maximum concentration,ppm			$Temp$ $^\circ C$	Maximum concentration,ppm			Smoke	
		CO	HCN	NO_x		CO	HCN	NO_x	ODm	Visibility,m
6	900	2614	51	23	630	–	–	–	0.36	3
7	900	7045	114	102	630	–	–	–	0.43	2.7
8	970	7053	263	95	680	–	–	–	0.46	2.5
9	890	3793	132	1 5	620	–	–	–	0.36	3
10	1005	3655	457	–	870	–	–	–	0.49	2.4
11	1090	10384	258	–	890	3563	59	–	0.43	2.7
12	1110	6055	335	–	700	4853	165	–	0.54	2.2
13	1220	7333	208	–	720	1429	199	–	0.43	2.7

The maximum concentrations of carbon monoxide in fire gases leaving the compartment are of the same order for all four foams. A preliminary test had given results indicating low concentrations, particularly of carbon monoxide. The reasons for this are not understood, although some variation has been found in tests of wood crib fires at the same ventilation[3]. In the interests of safety, the higher concentrations only are considered.

The concentration of carbon monoxide in diluted fire gases from the bed tests Nos 6-9, show a lethal risk for tests with foams B and C (Nos 7 and 8) but the concentration in the remaining tests (Nos 6, 9 and 10) are somewhat less than the limiting value, 5000 ppm. A short term lethal risk was also shown for the hydrogen cyanide in the diluted gases for all tests except that of foam A (No 6). If the assumption is made that the toxic effect of the carbon monoxide and hydrogen cyanide are additive, and the short term lethal limit for hydrogen cyanide is 100 ppm, then all tests presented lethal atmospheres.

For the practical situation, in which a furnished room on fire was part of a dwelling, the rate of flow of fire gases, 60 m^3/min from the compartment, and 140 m^3/min from the open end of the corridor[3], the rates being expressed for gas at $20^{\circ}C$, would result in the fire gases flowing rapidly into all communicating spaces. The volume flows at the average temperatures of the fire gases, $933^{\circ}C$ from the compartment and $686^{\circ}C$ from the corridor, would be 247 and 458 m^3/min respectively. The volume of a typical 3-bedroomed dwelling is about 250 m^3, and hence this volume could be filled with the fire gases in a minute or less by direct replacement of air. Although some mixing with air and consequent cooling could be expected to take place, it would be unlikely to provide dilution to the extent mentioned above that would result in a tolerable atmosphere, and hence the atmosphere throughout the dwelling would present a lethal hazard from heat and gases in a very short time. Because maxima of toxic gas concentration were reached in 2-4 min after ignition, such a hazard could be presented in about 5 min after initiation of flaming combustion. It should not however be assumed that fires of traditional furniture and bedding would be free from a similar hazard. A reduction of the rate of spread through the dwelling would result if the door to the room was closed.

The measurements of nitrous gases suggest that these may not of themselves present an important hazard, but they could be expected to add to the risk already presented by the more important toxic gases, carbon monoxide and hydrogen cyanide.

The above results arise from tests in a room freely ventilated through an opening extending to the ceiling, equivalent to an open door and fan-light. A fire could occur in a closed room, in which window glazing did not fail. Under these conditions, the available air in a room of about 25 m^3 volume would be exhausted by the combustion of 10-20 per cent of the fire loads of polyurethane used in these bed tests. The rate and continuity of burning, after the initial stages would thus be controlled by the leakage of air into the room, with a consequent reduction in the rate of burning, and possibly in the temperatures attained in the room. Although there would be expected an accumulation of fire gases, their composition could differ substantially from those occurring in the freely ventilated condition.

The reduction in concentration of carbon monoxide and hydrogen cyanide at the open end of the corridor from the values recorded for the opening between compartment and corridor arises from two or three factors. Firstly, combustion continues in the hot gas stream passing through the corridor, as flames emerged from the compartment and continued down the corridor for several metres. Such combustion would destroy some of the flammable toxic gases. Secondly, the rates of flow of fire gases from the compartment into the corridor, about 60 m^3/min are substantially less than the rate of flow from the open end of the corridor, about 140 m^3/min, indicating dilution with incoming air (the rates of flow are expressed for a temperature of about $20^{\circ}C$). The dilution resulted also in a reduction of fire gas temperature (table 2). Other tests had indicated some stratification or layering of the fire gases at the open end of the corridor, which may be considered as a third factor influencing the change in composition recorded at the open end of the corridor[13].

4.2.3 Smoke

The maximum optical density of the smoke from these fires, measured at the open end of the corridor, Table 1, would restrict visibility to about 0.5 m (1.6 ft)[7]. However, the temperature of the smoke, average $686^{\circ}C$, would be lethal in a short time[10]. Dilution of the smoke-bearing

fire gases with cool air to $120^{\circ}C$ would result in an atmosphere in which the visibility would range from 2.4 to 3 m (8-10 ft), Table 2. This distance is less than 5 m (16 ft), the distance accepted as presenting a reasonable chance of identification of escape routes[7]. A recent survey of the behaviour of people in fires has supported this limiting distance, because people were found to avoid entering smokey atmospheres unless visibilities were greater than 5 m (16 ft)[11]. However, familiarity with occupied premises, such as homes, might assist escape in denser smoke, with a lower visibility than this value. The total amount of smoke produced per unit weight of polyurethane foam, Table 1, was, within a factor of two, the same for each foam under each condition of test. The higher values are largely given by the higher fire loads. Standard optical densities (the optical density per metre produced by the smoke from 1 g of substance dispersed in 1 m^3) fall between 0.1 and 0.2, values in accord with earlier results[14]. The time during which smoke was produced was between 1 and 3 min, during which time, 1000-3000 m^3 (35000-105000 ft^3) of smokey atmosphere at $120^{\circ}C$ would be produced by dilution with air. Thus dilution of the smokey fire gases by mixture with air within a typical dwelling would, in much less than a minute, reduce visibility in the atmosphere to distances considered unacceptable. The rate of development of smokey atmosphere in a dwelling would of course be delayed by closure of the door of the room on fire.

4.3 Effect of fire load

The difference in generation of toxic gases and smoke between the tests involving two squabs (equivalent to the upholstery of a fire-side chair) and the larger fire loads of two bed mattresses or 40 kg of squabs (equivalent to the upholstery of a well furnished bedroom or a sitting room with a deeply upholstered suite) is most marked. Rapid fire fighting action taken on the early discovery of a fire might do much to reduce the spread of fire or the extent of damage, but any fire fighting action would be given a much greater chance of success if covering fabrics for the bedding and furniture were those known to retard the development of fire[12].

5. CONCLUSIONS

5.1 The rate of burning of flexible polyurethane foam is directly dependent on the exposed surface area.

5.2 Fires of small amounts of flexible polyurethane foam, such as could be presented by a small fireside chair, present very little risk from either toxic gases or smoke. Rapid action could be taken to extinguish such a fire. Other workers have shown that the frame of a chair often remains little damaged after burning of the upholstery[12].

5.3 A fire allowed to develop in bedrooms or sitting rooms generously furnished with flexible polyurethane foam upholstered furniture would rapidly make the room untenable, presenting lethal conditions from heat, smoke and toxic gases. Escape from the room would be feasible only within the first minute after the onset of flaming combustion.

5.4 The toxic gases evolved during such fires are carbon monoxide, hydrogen cyanide and nitrous gases. Atmospheres at $120^\circ C$ produced by mixing the fire gases with cool air, which could be borne for the short time required for escape, would also present a lethal risk, except possibly for very short exposure.

5.5 The smoke evolved in such fires was proportional to the weight, and its optical density, to the surface area of flexible polyurethane foam. The optical density of the smoke in the fire gases was high and could severely impede escape.

5.6 Dilution of the smoke-bearing fire gases with cool air to a temperature of $120^\circ C$ would produce atmospheres in which the smoke was sufficiently dense to impede escape, except possibly in familiar premises.

5.7 The rate of production of smoke and toxic gases from the fire loads examined was such as to render the atmosphere hazardous in any communicating spaces in a typical dwelling in less than 5 min of the start of a flaming fire. This time would be increased by closing the door of the room on fire.

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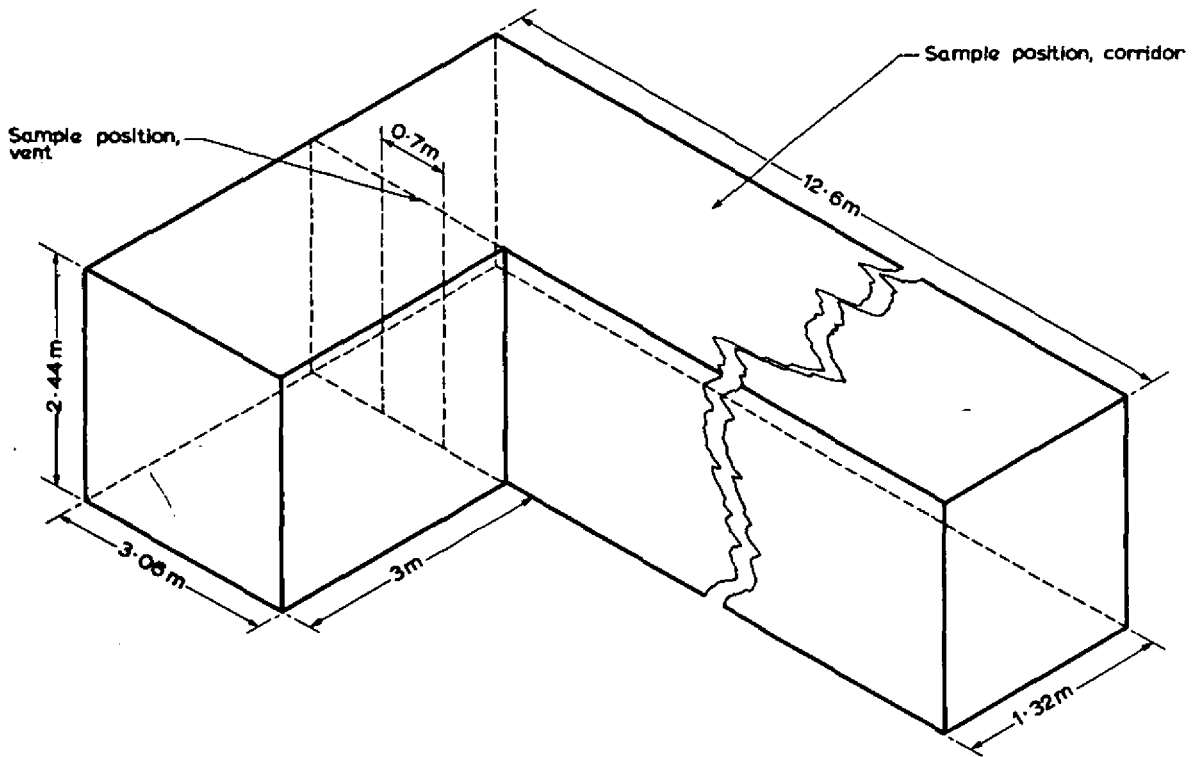
Figure 1 Compartment and corridor
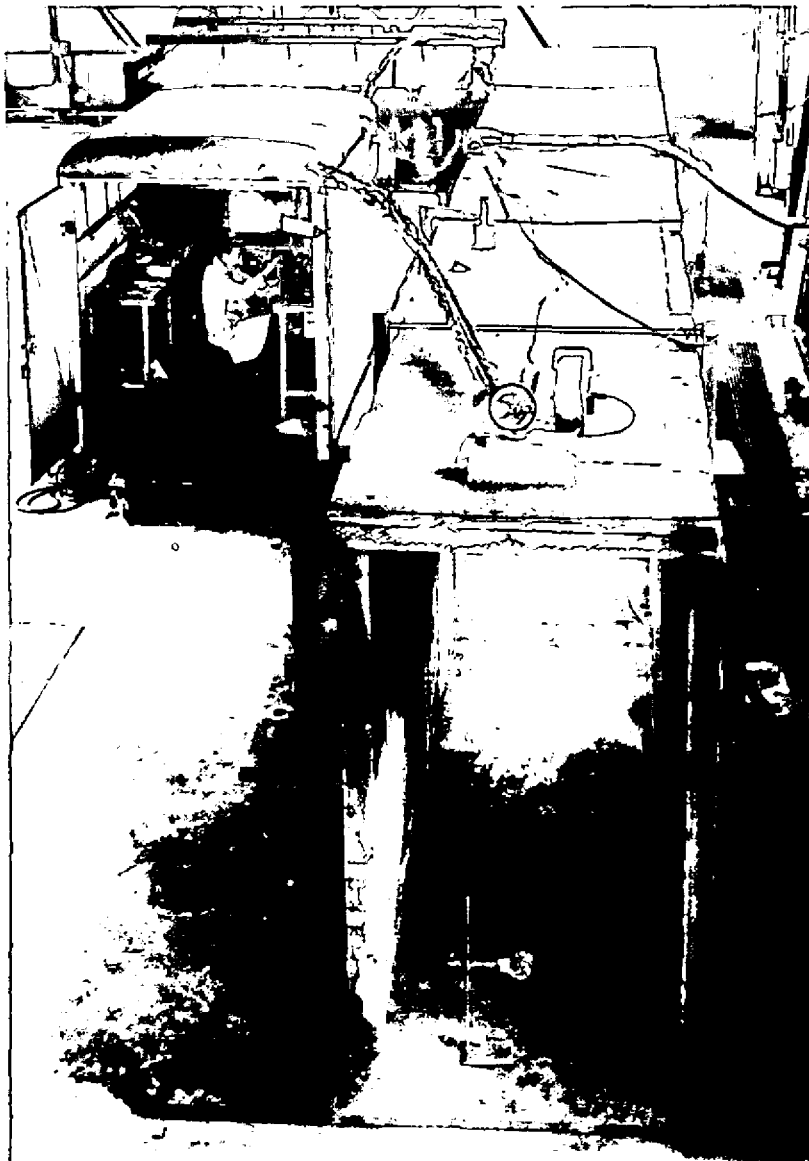
FIG.2. COMPARTMENT, CORRIDOR AND INSTRUMENT CHAMBER
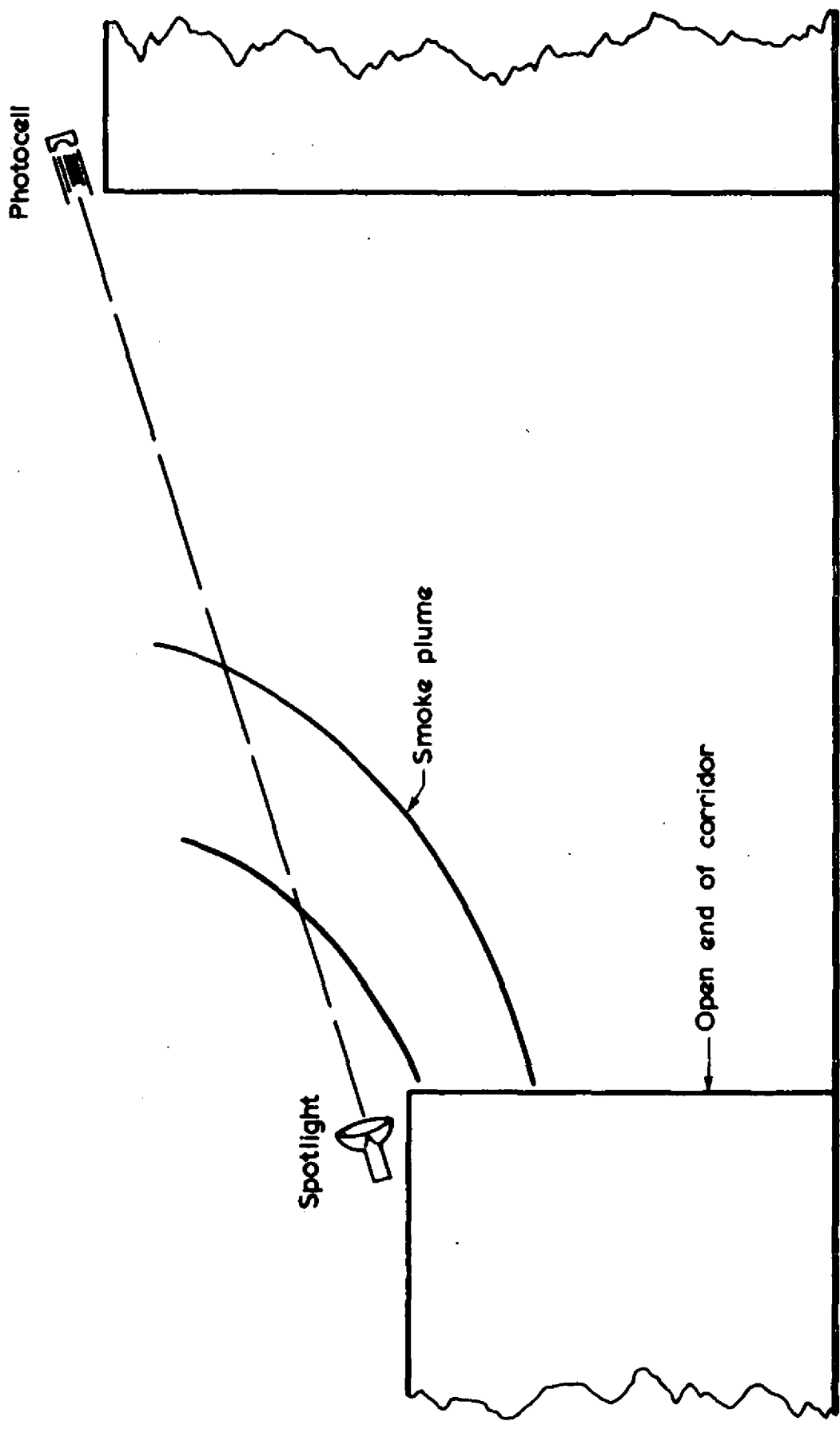
Figure 3 Smoke measurement: arrangement of spotlight and photocell

(A) 2 squab tests

Front elevation   Plan section

(B) 2 bed tests

Front elevation   Plan section

Crumpled cellulosic material

(C) 100 squab test

Front elevation   Plan section
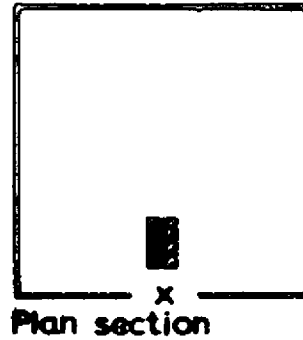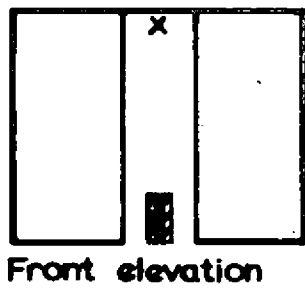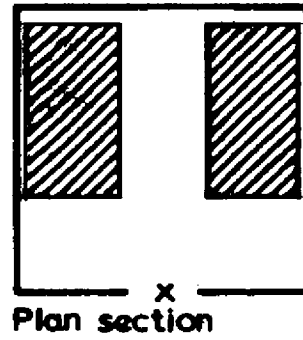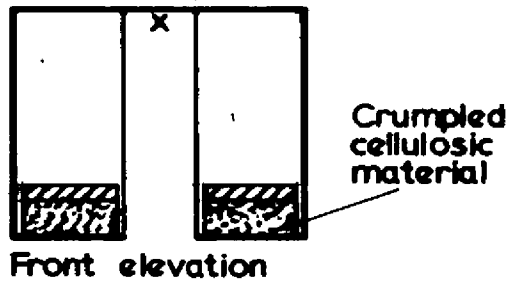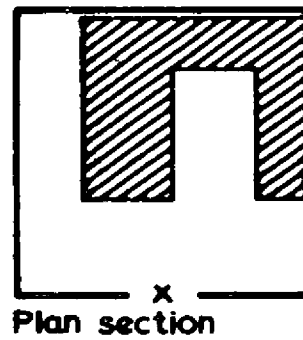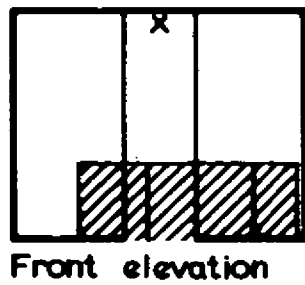
x —— sampling position

Figure 4   Arrangements of fire loads of flexible polyurethane foam in the fire compartment
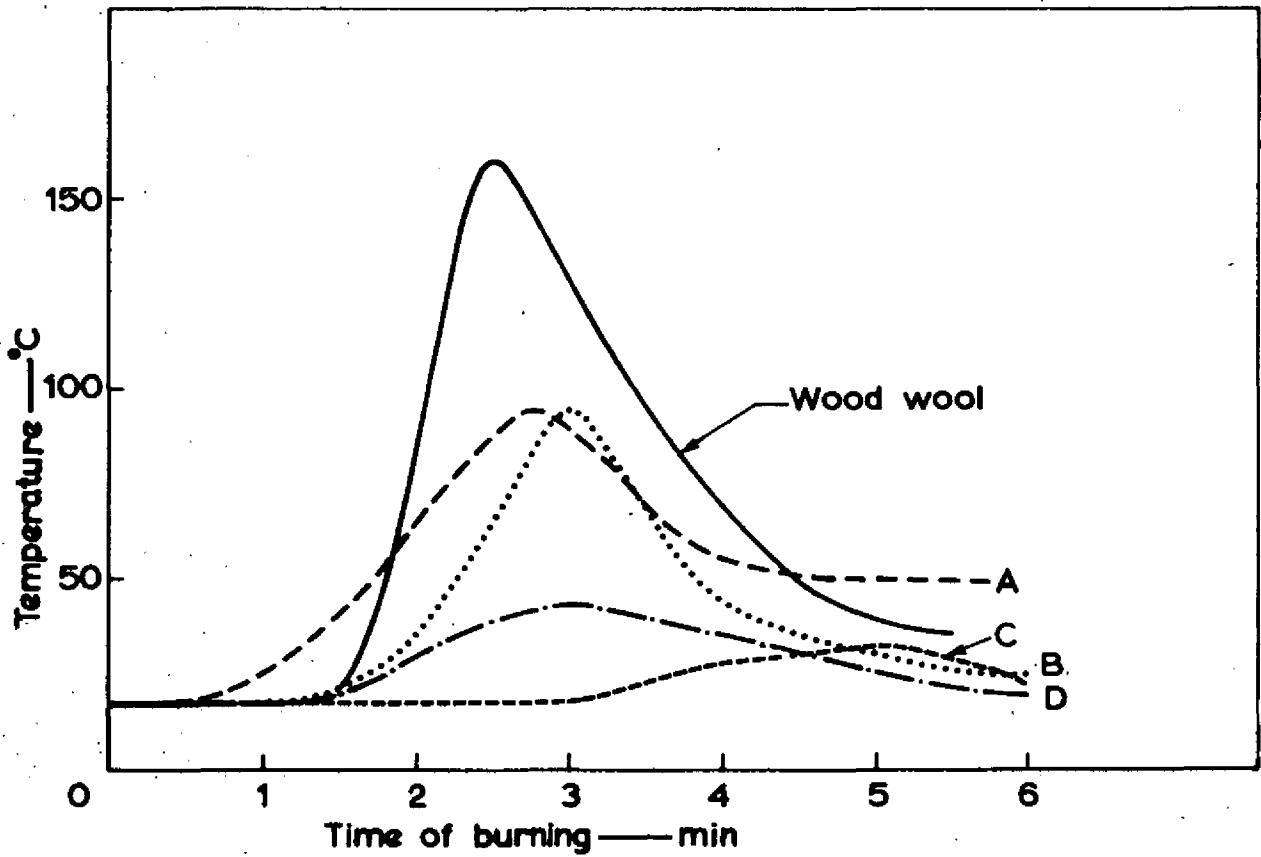
Figure 5 Fire gas temperature at compartment
opening; 2 squab tests
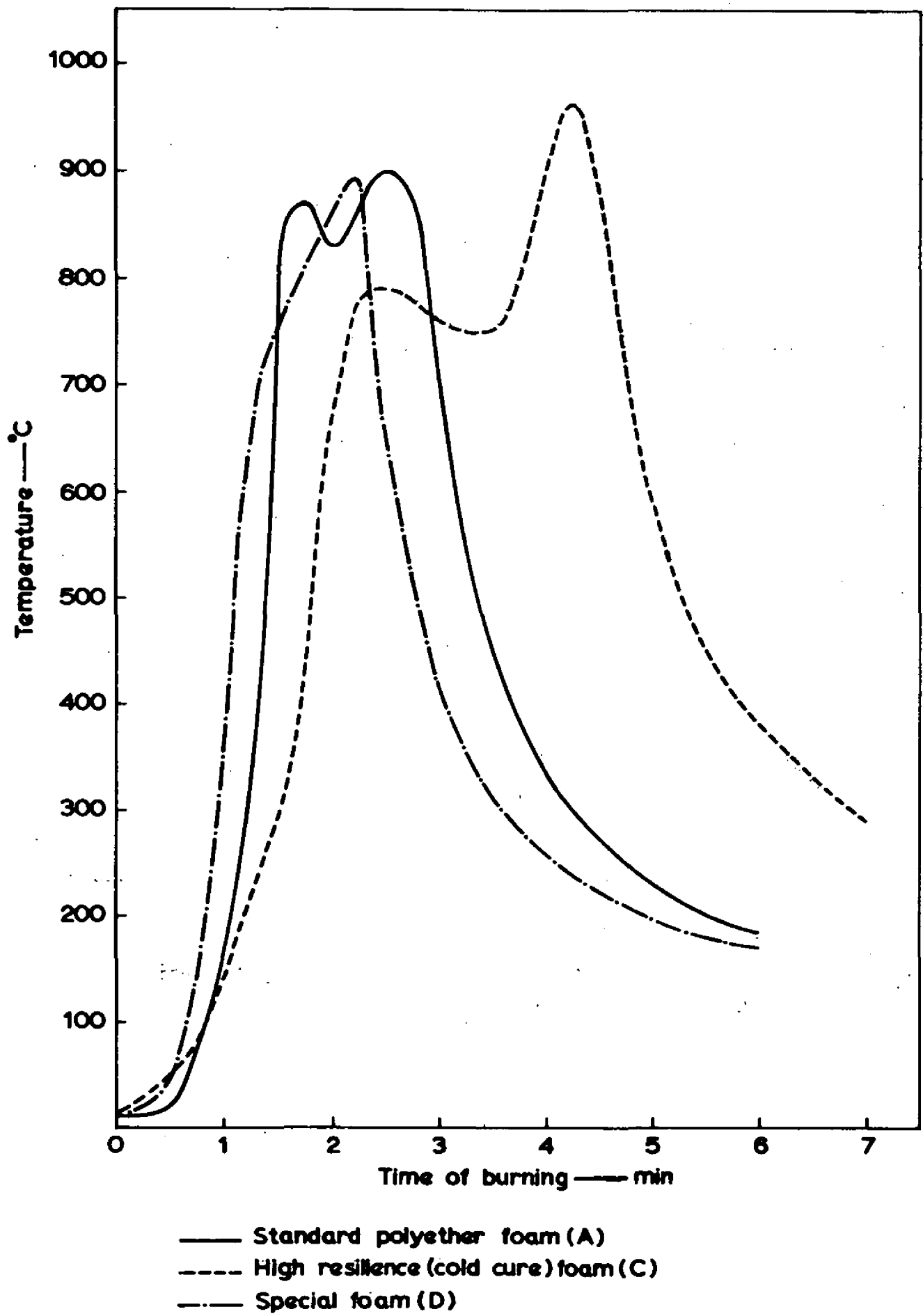
Figure 6   Fire gas temperature at compartment
            opening;   2 bed tests
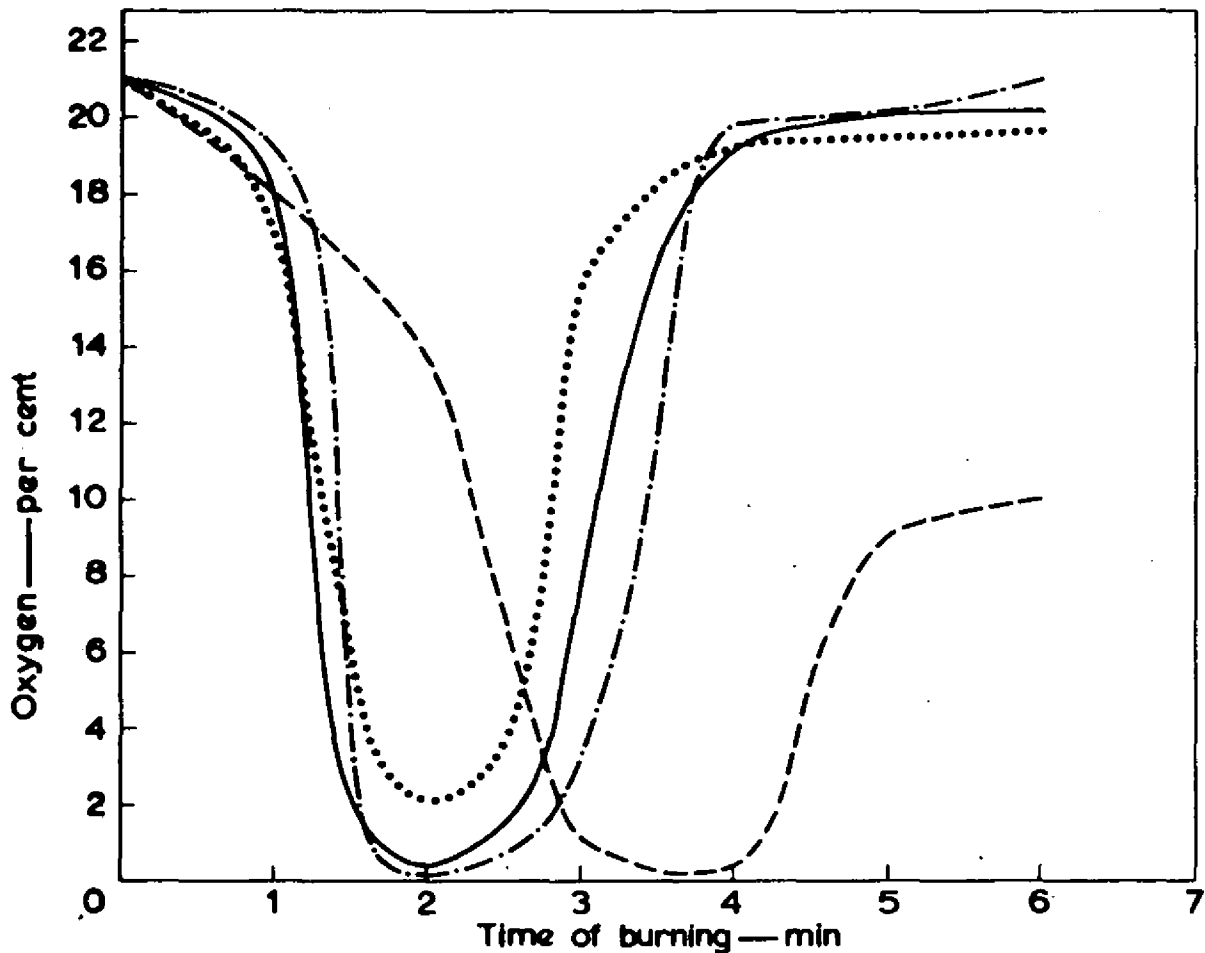
Figure 7   Oxygen in fire gases
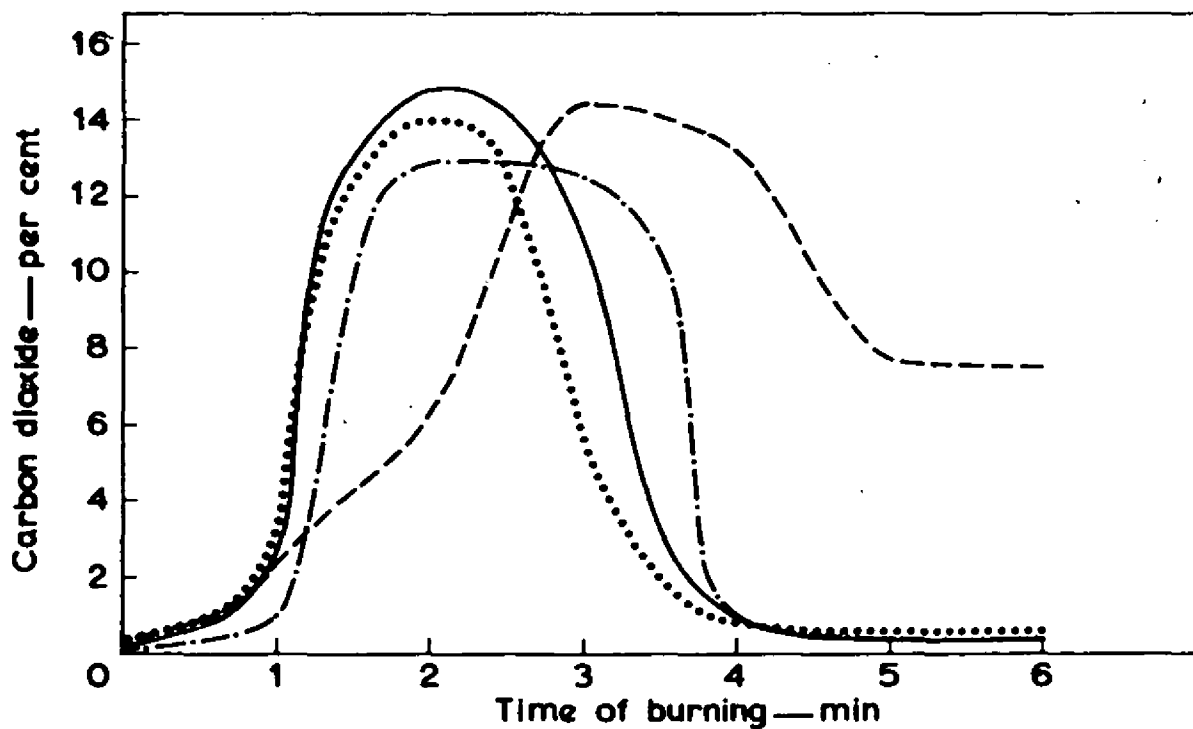
Figure 8   Carbon dioxide in fire gases

———————— Standard polyether foam (A)
—·——·— Standard foam with added flame retardant (B)
————— High resilience (cold cure) foam (C)
············· Special foam (D)
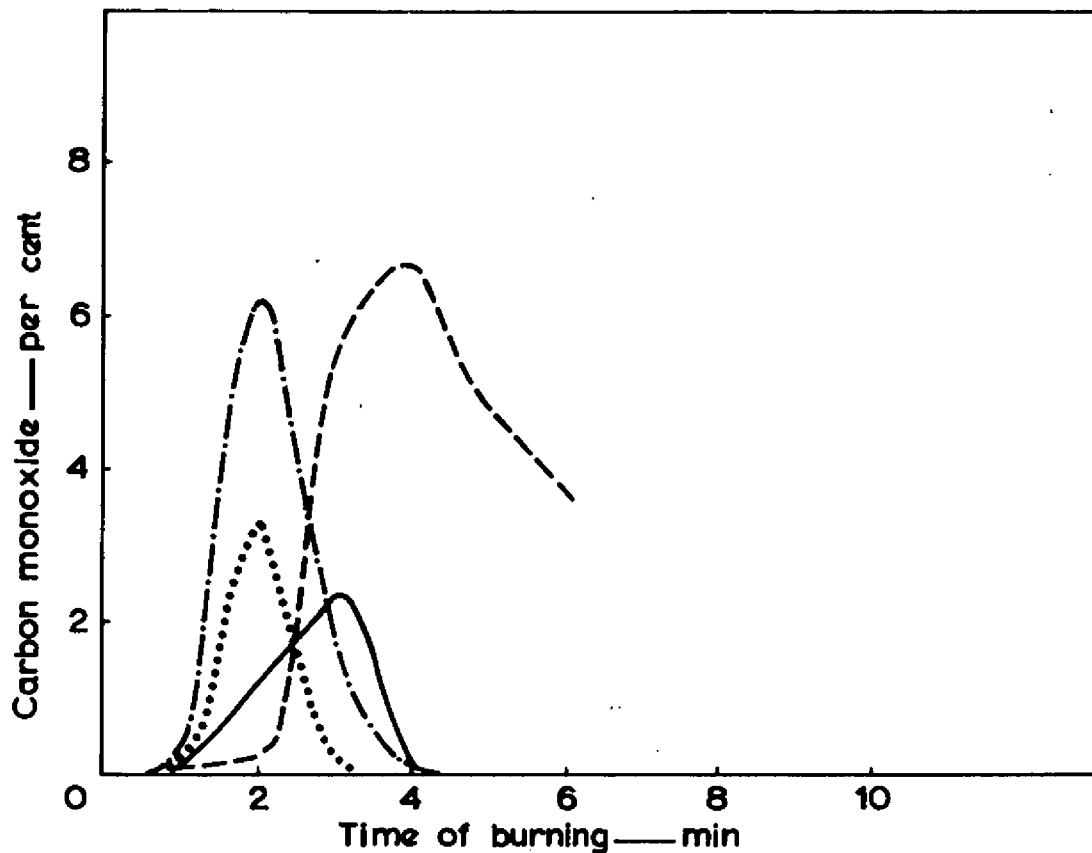
Figure 9   Carbon monoxide in fire gases
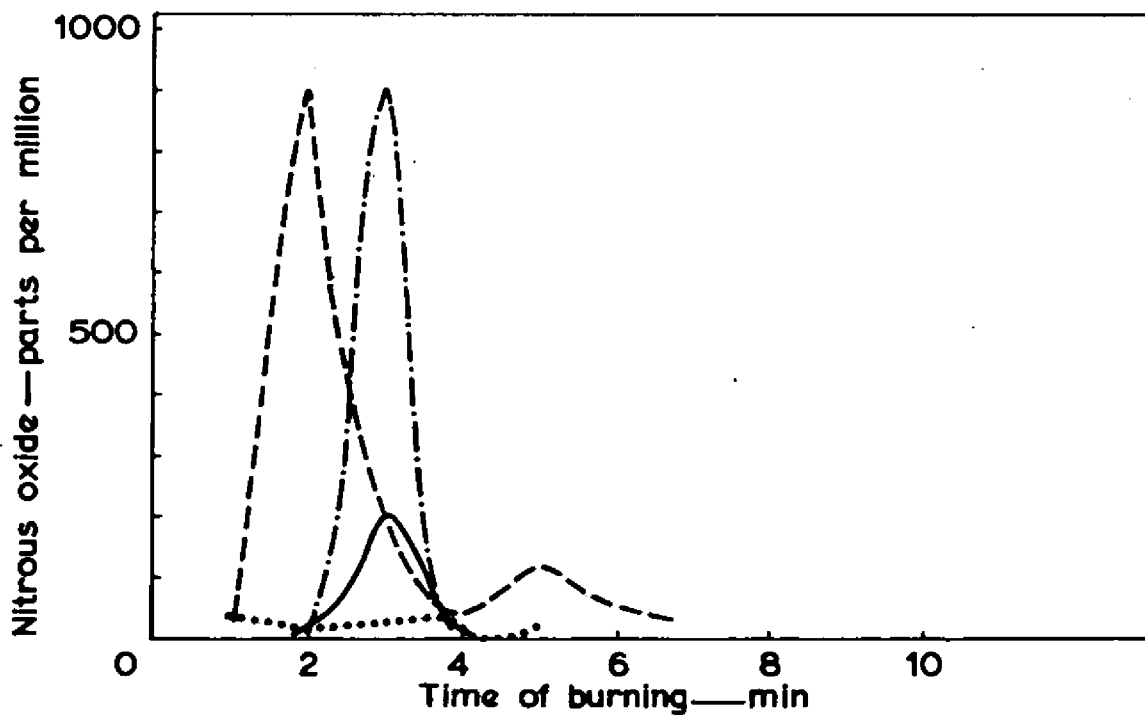
Figure 10   Nitrous gases in fire gases

——————   Standard polyether foam (A)
—·——·—   Standard foam with added flame retardant (B)
— — — —·   High resilience (cold cure) foam (C)
··········   Special foam (D)
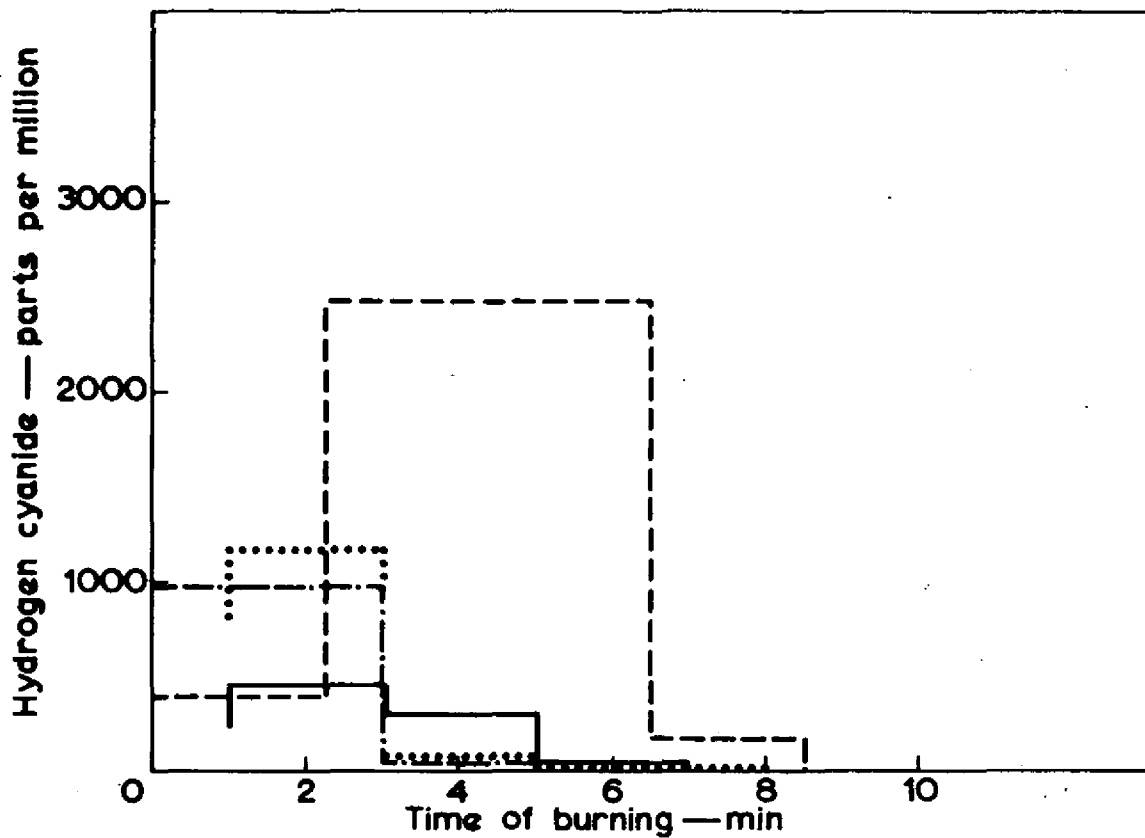
Figure 11   Hydrogen cyanide in fire gases
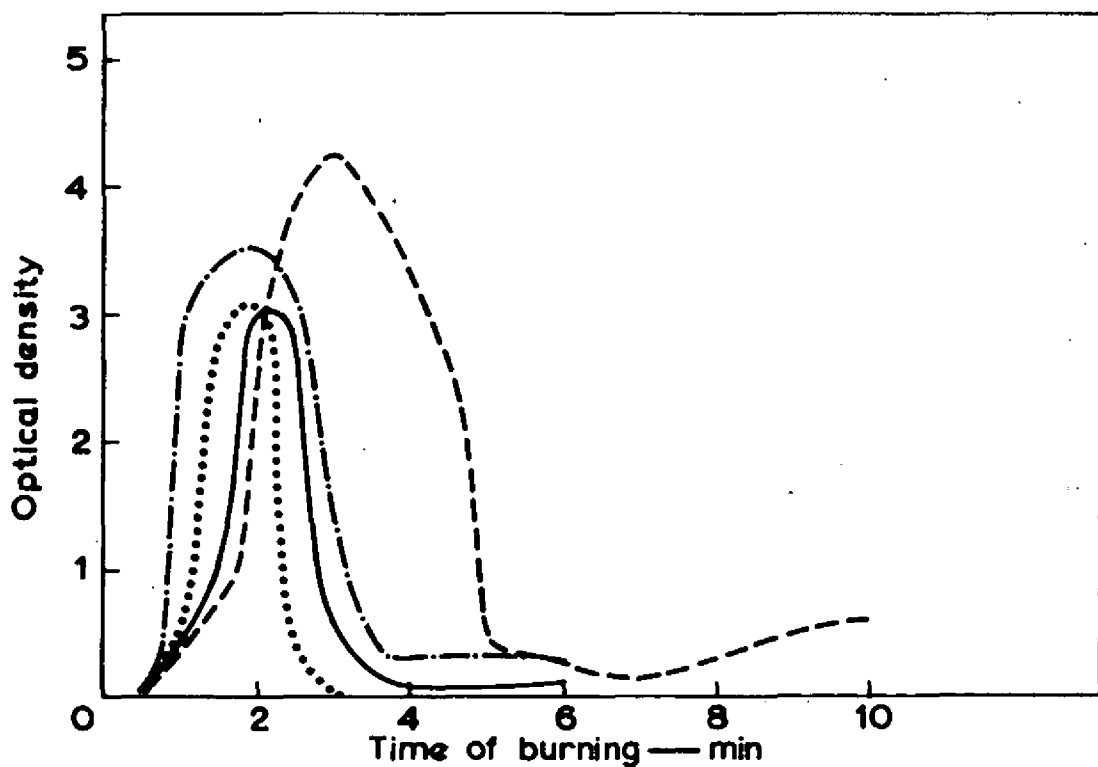
Figure 12   Optical density of smoke

———·—   Standard (polyether) foam
— — — —   High resilience (cold cure) foam
··········   Special foam
—·——·——   Standard foam with added flame retardant
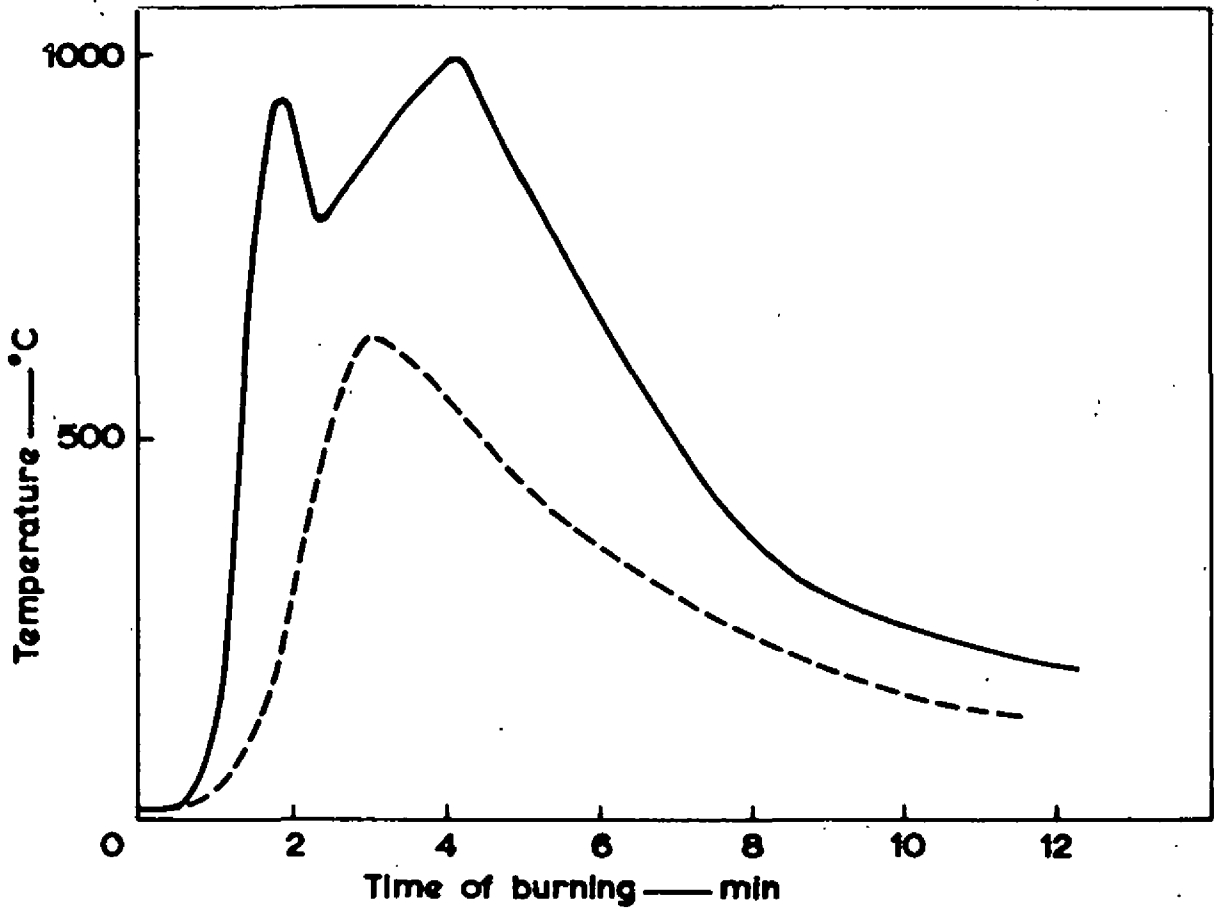
Figure 13   Fire gas temperatures; 100 cushion,(40kg), polyether foam test
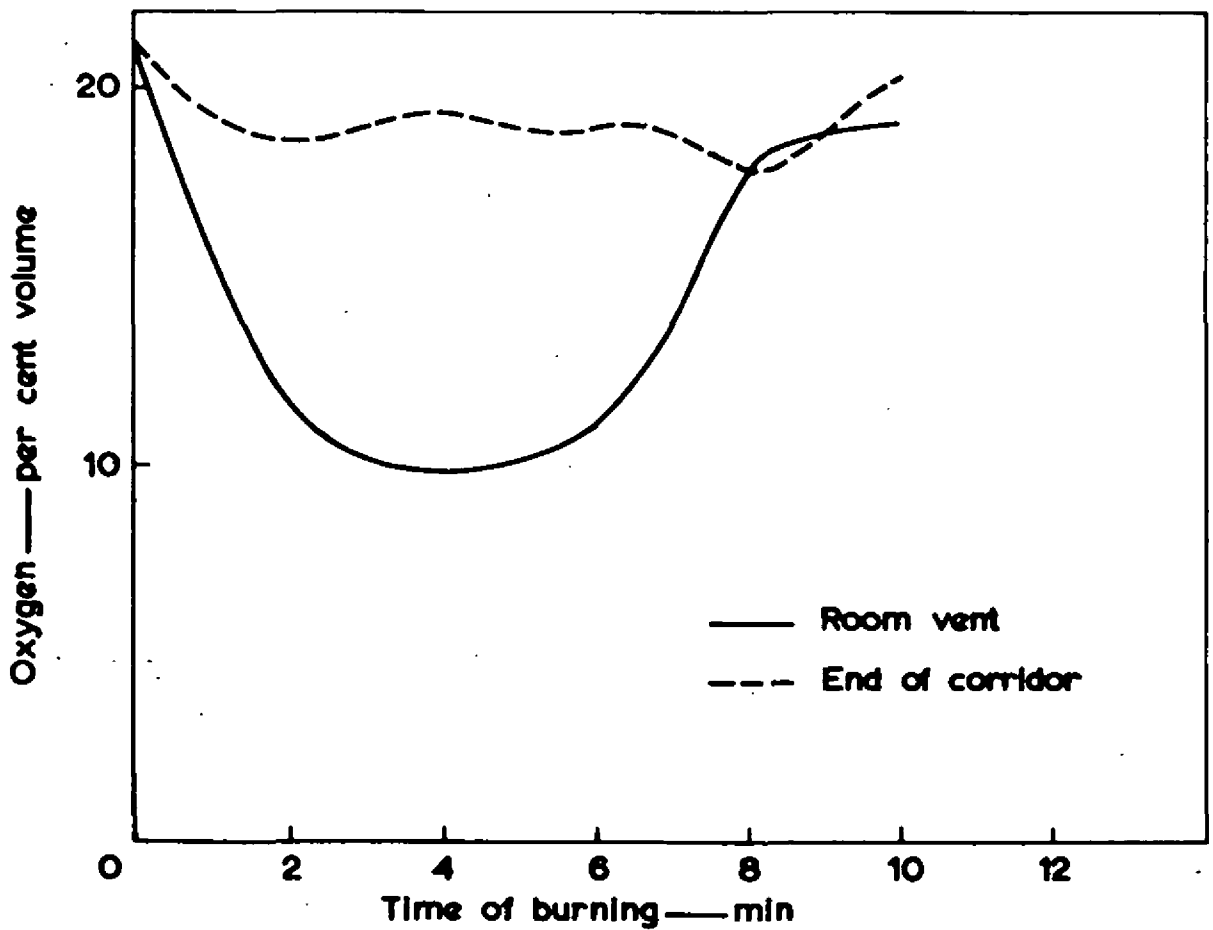
Figure 14   Oxygen in fire gases; 40 kg foam test
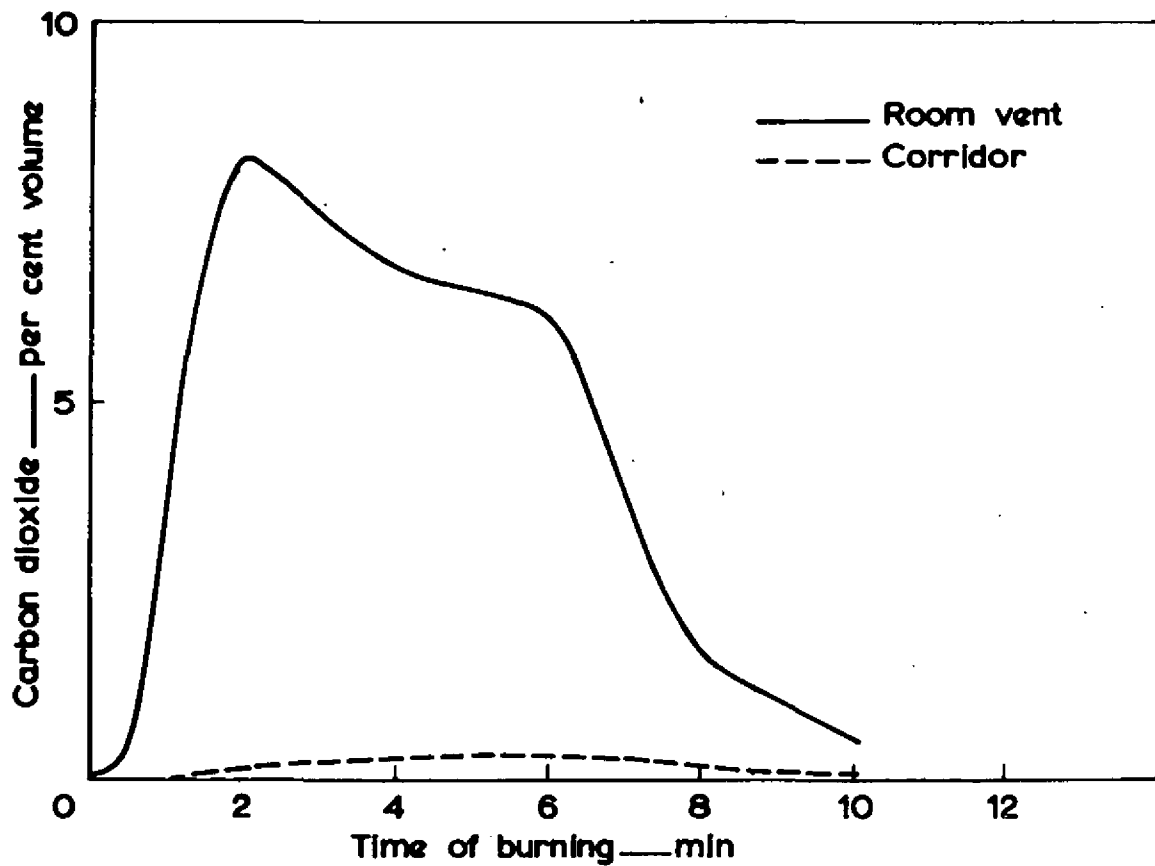
Figure 15   Carbon dioxide in fire gases; 100 cushions
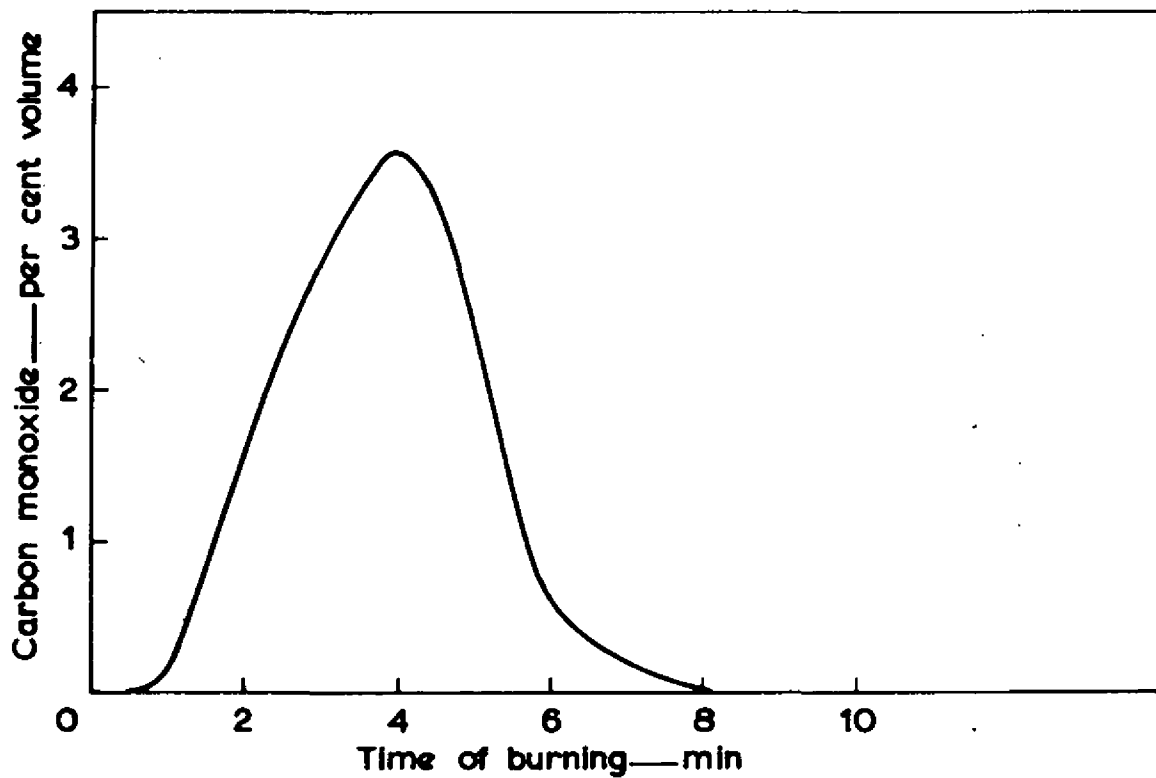   (40 kg) polyether foam test

Figure 16   Carbon monoxide in fire gases; 100
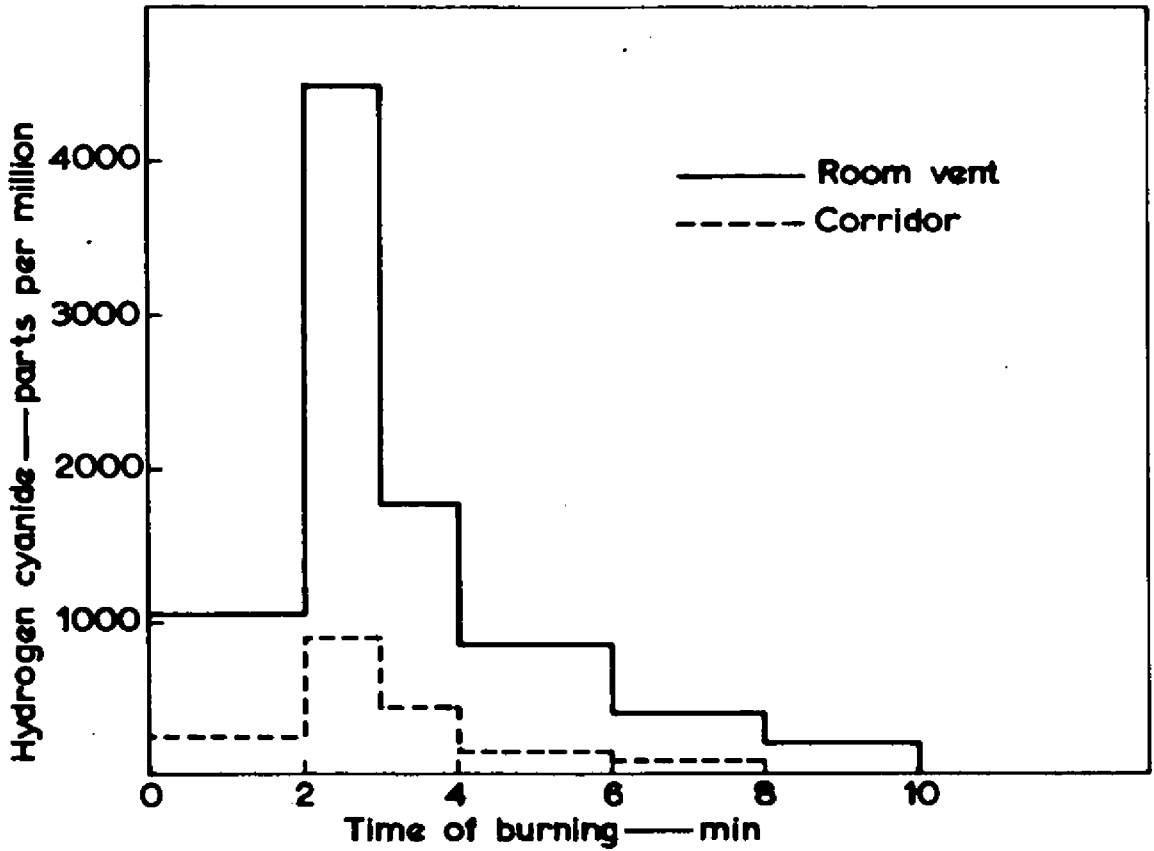   cushions (40 kg) polyether foam

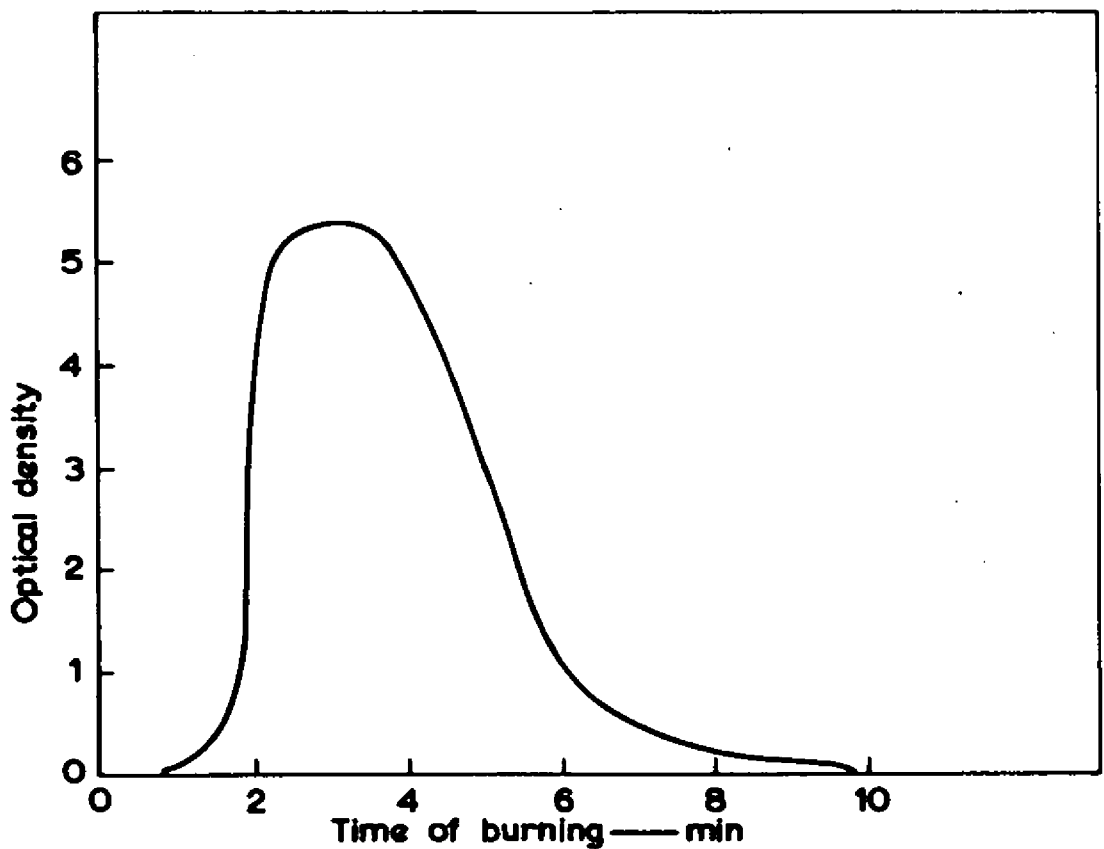Figure 17 Hydrogen cyanide in fire gases; 100 cushions (40kg) polyether foam

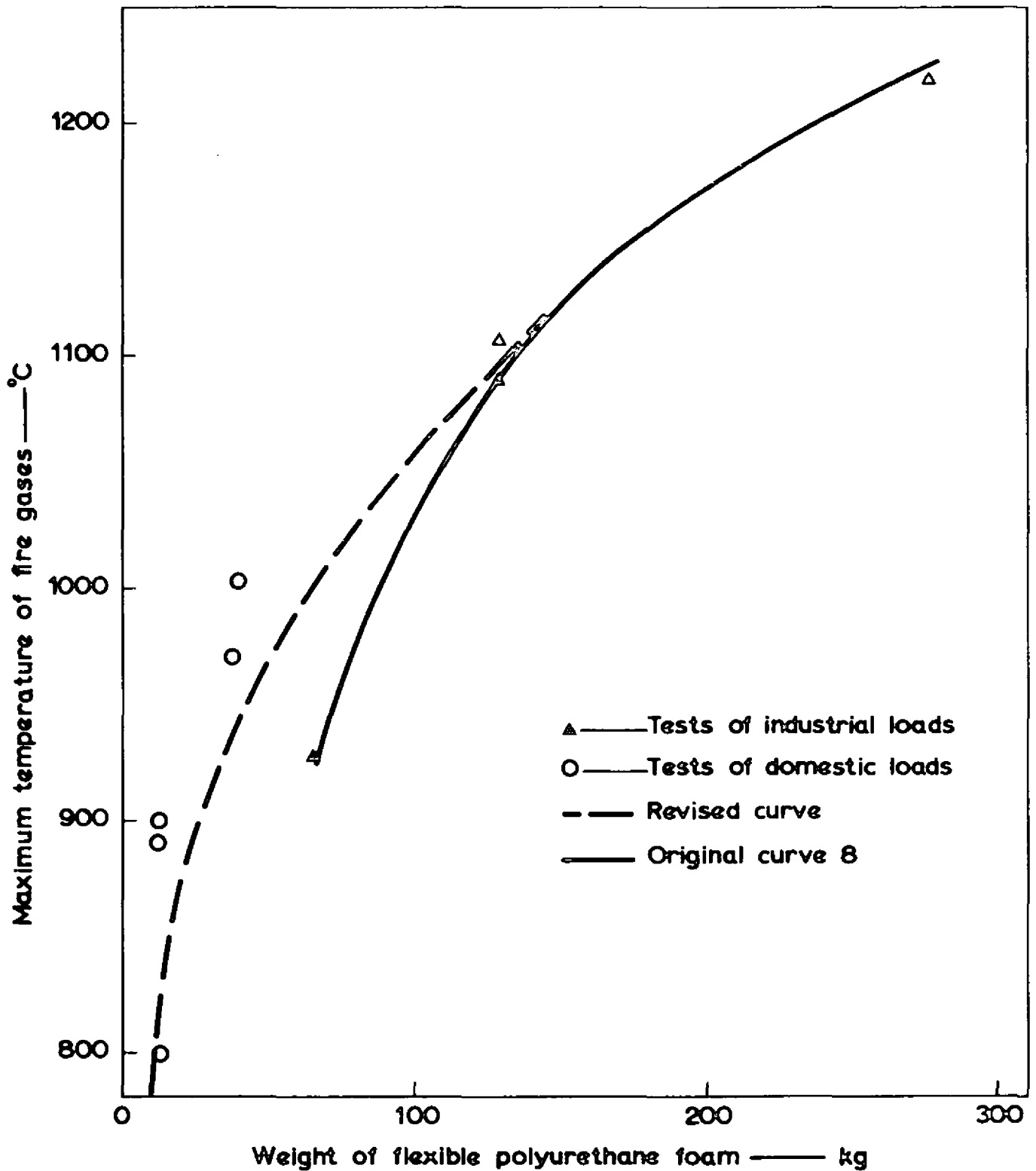Figure 18 Smoke density; 100 cushions (40kg) polyether foam

Figure 19 Relation between fire load of flexible polyurethane foam and maximum temperature of gases at compartment opening