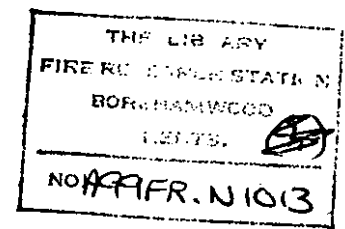# Fire Research Note
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THE ASSESSMENT OF SMOKE PRODUCTION BY BUILDING
MATERIALS IN FIRES

PART 4. LARGE SCALE TESTS WITH WALL LINING MATERIALS

by

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SUMMARY

Quantitative measurements have been made of the smoke production in vision obscuring terms of 5 materials, exposed both in the Fire Propagation Test Apparatus and also in much larger quantities (8 m^2) as the linings of a compartment containing a substantial fire, itself producing little or no smoke.

The range of smoke production was very large, extending over three orders of magnitude. Both methods gave similar values for the smoke production of materials producing much smoke, but for materials producing little smoke the large-scale tests registered less smoke than the Fire Propagation test method. Nevertheless there was a strong correlation between the values of smoke production from the two methods under the conditions examined.

THE ASSESSMENT OF SMOKE PRODUCTION BY BUILDING MATERIALS IN FIRES

PART 4.   LARGE SCALE TESTS WITH WALL LINING MATERIALS

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1.   INTRODUCTION

The role played by smoke in obscuring or blocking escape routes in buildings has led to investigations into methods for measuring the smoke production of material the earliest being those of Gross, Loftus and Robertson[1]. At the Fire Research Station the possibility of measuring smoke production from specimens exposed in the Fire Propagation Test Apparatus has been examined[2,3,4]. These methods were all based on the collection of the whole of the smoke produced by small specimens in board or sheet form. Gross et al[1] measured the optical density of the smoke accumulated in a test chamber of volume 0.5 m^3, from irradiated specimens 75 mm square. Bowes and Field[3] measured the optical density of smoke collected in a volume of 34 m^3 from specimens 190 mm square.

Heselden[5], however, has reported measurements of the smoke production of larger quantities of materials burnt under conditions approximating to those cf a large and well-ventilated fire. Samples of wood, foam rubber, polyurethane foam and expanded polystyrene were burned separately in loosely packed piles and kerosene was burned in a tray. As very large quantities of combustion gases were produced in these tests a different method had to be devised for measuring the production of smoke, entailing measurement of the flow rate and optical density of the hot smoke-laden gases given off by the fire.

For expanded polystyrene a discrepancy arose between the results of these large-scale tests and those of the Fire Propagation test[6], the former giving much more smoke per gram of polystyrene than the latter. This difference might have been due to a real difference between the smoke production of loose piles and of lining specimens or to some features inherent in the Fire Propagation test method.

An attempt has been made to resolve this discrepancy and obtain information on the relationship between small- and large-scale smoke tests for lining materials by measuring the smoke produced by various lining materials, including expanded

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polystyrene, burnt as linings under large fire conditions. These measurements have been compared with those for identical materials exposed to the Fire Propagation test.

2. MATERIALS TESTED

The materials chosen for this series of tests were selected initially from the range of materials graded as Class 0 under the B.S. 476 Fire Propagation test, Class 0 representing the range of materials for which the rate of heat release in fire is lowest. One additional material, from Class 4, was also used. The materials used are listed and described in Table 1.

The samples of plasterboard and wood fibre insulating board were coated with emulsion paint to represent a normal decorative finish.

The glass-reinforced polyester resin (GRP) had a polyester-based intumescent coating approximately 2 mm thick applied on one side only, intended to reduce the rate at which flame can spread over the surface.

The GRP samples were tested in three modes. In the first, the intumescent coating was exposed to the fire. In the second, the other side of the sample was exposed to the fire, but this was covered with two coats a fraction of a mm in thickness of a water-based polyvinylidene – chloride intumescent emulsion paint. In the third mode the unpainted surface of the samples was exposed to the igniting source.

Table 1

Materials tested

Material	Substrate	Surface coating	Sample thickness mm	Class [a]
Expanded polystyrene tiles [b]	Asbestos wood board [e]	None	7	O
Plasterboard [c]	None	Emulsion paint [f]	10	O
Heat resistant decorative laminate [k]	Asbestos wood board [e]	None	0.75	O
Wood fibre insulation board [d]	None	Emulsion paint [g]	13	4
Glass reinforced polyester resin (GRP)	None	Intumescent [h]	3	O
		Intumescent [j]	3	O
		None	3	O

(a)   Grade under Fire Propagation test

(b)   Tiles 305 mm x 305 mm glued over their entire near surface with a PVA-based adhesive

(c)   Standard grade

(d)   Untreated, (non fire-retardant)

(e)   6 mm in thickness and density of 1560 kg/m^3 (approx)

(f)   Two coats. Mean quantity of paint used 0.10 kg/m^2

(g)   The quantity of paint sprayed on to the surface of this material was governed by the absorption of each sample (a fixed shade of white was maintained). The mean quantity used however was 0.15 kg/m^2

(h)   A polyester-based intumescent coating 2 mm thick

(j)   A water-based polyvinylidene chloride emulsion a few tenths mm thick

(k)   Affixed to substrate by manufacturers

3.   BUILDING AND INSTRUMENTATION

For the large scale tests, a building already available as a test facility was used (Fig.1). It consisted of a large brick fire compartment[5] opening on to the side of a corridor 6 m wide, 3 m high and 12 m long in which instrumentation was installed. This represented at full size a short length of a covered shopping mall with shops opening on to it. For these experiments the open fronts of the 3 other compartments giving on to the corridor were filled in with hardboard screens. Variables such as temperature, rate of flow of gases and optical density were

monitored using the instrumentation previously described[5]. For these tests, the ceiling screen near the entrance to the corridor was removed so that the flow of hot, smoky gases would not be restricted, and measurement of the smoke production confused by accumulation or recirculation of smoke. To measure the rate of flow of hot gases, anemometer heads with metal vanes[5] were mounted on a vertical line half way down the centre of the corridor (at K, Fig.1). The doors at the end near M were fully open throughout each test.

At first the anemometers were mounted at various heights within the cool air layer so as to measure the rate of flow of air into the mall, approximately equal to the rate of flow of hot gases out. However, large fluctuations in response to external wind effects were found and for the majority of tests most of the anemometer heads were placed high up, in the hot gas layer. Although this meant that in a few cases the heads were exposed to gases hotter than the maximum temperature recommended by the manufacturers, in fact they were undamaged and continual maintenance and cleaning enabled the heads to function correctly. A closed-circuit television system was installed in the experimental building so that the tests could be observed remotely during the whole period of burning. The camera was maintained in position in the cold air layer near to the ground so that the smoke produced in the tests did not spoil the view of the fire.

4. REQUIREMENTS FOR BURNING CONDITIONS

Various attempts were made to find a suitable method for burning the samples so that the smoke production of each material might be monitored. In devising a suitable method the following requirements were considered:

Burning conditions

1. The samples should be exposed to an ignition source as linings, in sufficient quantity to represent a large-scale situation.

2. Conditions should be arranged so that after the ignition of each sample, as far as possible, flaming would spread over the entire surface exposed.

3. The ignition source should be as small as possible, (consistent with 2 above), so that little smoke would be consumed by the flame of the ignition source.

4. The fuel used as an ignition source should not itself produce smoke.

5. The fire should be well ventilated, so that considerably more air would be available than would be needed for complete combustion.

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Measurement requirements

1. The fire should be made large enough to permit satisfactory measurement of the flow rate of combustion gases.

2. The smoke should be sufficiently diluted to produce optical densities within the sensitive range of the smoke meters.

3. The results for any single material should be repeatable.

4. The procedure for each test should be identical in order that a direct comparison would be possible.

5. TEST CONDITIONS AND EXPERIMENTAL PROCEDURE

After a number of trials suitable test conditions were achieved. The conditions finally used were:

For each test 6 sheets 1.22 m x 1.14 m or 3 sheets 2.44 m x 1.14 m, ie 8.3 m^2 of the material tested were supported on a heavy steel frame so that they formed three sides of a box of dimensions 1.14 m x 1.14 m x 2.44 m high[*]. A ceiling of inert asbestos board with a layer of refractory mineral fibre felt stuck on the under surface (to prevent spalling) was placed over the top of the box, producing a structure like the end of a corridor (Fig.2).

Industrial methylated spirits (i.m.s.) containing 95% ethyl alcohol was used for ignition. This, like any other igniting source, probably consumed some smoke given off by the sample but had the overwhelming advantage of itself being smokeless (some of the materials produced such small quantities of smoke that this would have been unmeasurable if an igniting fuel producing much smoke had been used). 22.5 l (5 gals) of methylated spirits were burned in each test, of which 12.5 l (2.75 gals) was used for ignition, distributed in three trays of total area 1.02 m^2 (Fig.2). The remainder was burned in a fourth tray of area 0.82 m^2, placed a little way from the box, in order that the induced flow of gases would be large enough to measure and the smoke would be more diluted and its density easier to measure.

The procedure consisted of igniting the large tray outside the box 15 s before the smaller trays within the box so that a flow of air was induced well before any smoke was produced.

This simple arrangement overcame most of the problems arising from the requirements previously listed except that:

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[*]The total area exposed was 8 m^2

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a) large amounts of igniting fuel were required since the heat transfer from
   the clean alcohol flame to the samples was low (most of the heat produced
   by the poorly radiating flames was lost by convective transfer from the
   experimental box);

b) the test materials would not all continue to burn alone after the ignition
   source had burnt out.

6. RESULTS

   Not all the tests carried out appear in Tables 2, 3 and 4 as the first tests
were exploratory and in a few of the later ones there were failures of the measuring
systems.

   In every case the samples did not ignite within the first $\frac{1}{2}$ minute and yet
had finished burning before 5 minutes, the times being measured from ignition of
the small trays. The methylated spirits in the large tray outside the box burnt
for about thirteen minutes in all, so that there was no question of smoke being
trapped in the building and remaining unmeasured.

   The maximum output from the alcohol trays used for ignition (excluding the
large tray) was 0.9 MW, the mean value for a period of 13 minutes was 0.6 MW.
These values are high enough in relation to the enclosing compartment to represent
a severe fire condition. Despite this in several cases the samples burned only
where they were directly in contact with the flame, probably because flames from
burning alcohol are poor radiators.

   Although the area of sample exposed to the fire in each case was 8.0 m^2 the
area actually burning varied with each test.

   Of the samples tested, the fibre insulating board and the glass-reinforced
polyester were the only materials that burned over the whole area exposed. Both
materials burned at a high rate with vigorous flaming.

   The coatings applied to the glass-reinforced polyester had no effect on the
area burned in the fire but significantly affected the timing and extent of
combustion. The presence of the polyester-based intumescent coating appeared to
reduce the depth of burning and thus the quantity of material taking part in
combustion. (The coating, having intumesced, prevented access of oxygen from the
air to the material). The presence of the water-based intumescent coating delayed
ignition by about 1 minute. Thus since the build up of hot gas and flames was
also delayed, the depth of burning that resulted was less than that for the plain
samples, with no coating. The total heat output and total smoke production were
thus less than that for the plain samples, yet were greater than that for samples

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with the polyester-based intumescent coating.

The heat resistant laminate and plasterboard burned over most of the area exposed.

The material remaining at the end of one of the plasterboard tests is shown in Plate 1. This shows that the area of material actually burnt is hard to determine and therefore the smoke densities (Table 4) have been expressed in the first place in terms of the area of specimen actually exposed, even though in some cases not all of the specimens burned completely.

The polystyrene samples burned only over a very small area. The combustion occurred in places where the adhesion to the supporting asbestos failed. In parts where the tiles were well glued to the asbestos the polystyrene shrank back on to the supporting asbestos board to form molten globules. These globules would not burn, presumably because in this molten form, the heat was conducted rapidly to the asbestos, preventing heating up to ignition temperature.

Table 2 provides information on the ignition time, time to maximum burning rate and the duration of substantial burning.

Table 2

Burning data of the materials

Material	Test code	Time to ignition min s	Time to maximum burning rate min s	Duration of substantial burning min s	Flame size at peak burning
Expanded polystyrene	A B	Very little burning (see text) No times noted			Very small
Plasterboard	C	1 30	3 15	0 30	Very small
Heat resistant decorative laminate	F G	50 1 0	2 10 2 15	30 –	Very large
Wood fibre insulation board	H	30	45	2 30	Very large
Glass reinforced polyester resin (GRP)	I[a] J[b] K[c]	35 1 30 –	2 0 3 0 2 0	2 0 – –	Medium Large Large

(a) With an intumescent coating (polyester-based)

(b) With an intumescent coating (water-based)

(c) No coating

A dash implies no reliable observation or measurement

The hot smoky gases from the fire rose and flowed along underneath the ceiling of the fire compartment, into the corridor, along the length of the building and into the open air. The height of the corridor was 3.1 m and the smoky layer was maintained within the top 1 m or so. The division between the hot smoky layer and the inflowing cool air was fairly flat; the depth of hot gases could be assumed constant along the corridor and throughout each test. Three main variables were recorded at position K (Fig.1) throughout the test: temperature, rate of gas flow and optical density. Temperature and optical density measurements were made at half minute intervals and were recorded on paper tape using a 200-channel data logger. The temperature values of interest were those at position K , forming a vertical temperature profile from which the depth of the hot gas layer was obtained for each test.

The hot gas layer was taken as extending from the ceiling down to the level at which the temperature rise had fallen to one quarter of the maximum temperature rise in the hot gas layer (Fig.3). The derivation of this definition is empirical[12] but the layer depth is not too sensitive to its method of definition since it is in a region where temperature is changing rapidly.

The maximum temperature of the gases in the hot layer at K was, in most of the tests, in the region 100-150°C above ambient (Table 3).

Two methods were used to obtain the flow rate in the hot gases. This entailed either direct measurement of the rate of flow in the hot gas layer (tests C, D, G, H, I, J, K) or derivation of this quantity using measurements of rate of flow in the cool air layer and of the temperature rise of the hot gases; the former gave more satisfactory results. Maximum values of the rate of flow of hot gas are shown in Table 3. Readings obtained by using the direct measurements of flow rate in the hot gases and then reducing them to the corresponding flow in cold gases are compared with typical results obtained by direct measurement in the cold gases in Fig.4. The agreement is as satisfactory as can be expected since variations were recorded up to 100 per cent of the mean value of velocity from the measurements made in the cool air layer during steady burning. These values were recorded by scanning over four anemometers allowing 10 s for each channel with a 10 s interval between each scan. The results were then plotted and instantaneous cross-sectional velocities were determined. This method indicated fluctuations in instantaneous values of volume rate of flow of gas of up to ± 50 per cent, but the variation in an average over several minutes would be much smaller.

Figure 5 shows a typical vertical velocity profile.

Table 3

Properties of sample material fires
The figures in brackets are the times (in minutes) at
which the value of the parameter occurred

Material	Test code	Maximum temperature rise at K °C above ambient	Maximum volume rate of flow of hot gas at K m^3 s*	Maximum optical density/m at K	Maximum rate of smoke production at K $\frac{m^3}{m \quad s}$	Total heat flow past measuring point K $J \times 10^6$
Expanded polystyrene	A B	90 ($4\frac{1}{2}$) 103 ($4\frac{1}{2}$)	3.1 ($3\frac{1}{2}$) –	0.006 (4) 0.018($4\frac{1}{2}$)	0.57 (4) –	80 ––
Plasterboard	C D	113 ($3\frac{1}{2}$) 90 (4)	5.2 ($3\frac{1}{2}$) 5.4 (4)	0.006 (4) 0.006 (4)	1.64 (3) 2.03 (4)	170 160
Heat resistant decorative laminate	E F	139 (3) 145 ($2\frac{1}{2}$)	6.9 ($1\frac{1}{2}$) 11.0 (4)	0.099 (3) 0.150($1\frac{1}{2}$)	18.0 (3) 29.8 ($1\frac{1}{2}$)	– 260
Wood fibre insulation board	H	172 (3)	7.9 (2)	0.297 (1)	119 (1)	240
Glass-reinforced polyester resin (GRP)	I[a] J[b] K[c]	114 ($4\frac{1}{2}$) 155 (4) 168 (3)	6.0 ($4\frac{1}{2}$) 7.2 ($3\frac{1}{2}$) 6.8 (3)	3.37 (5) 3.33 ($3\frac{1}{2}$) 5.05 ($3\frac{1}{2}$)	1020 (5) 1507 ($3\frac{1}{2}$) 1990 ($3\frac{1}{2}$)	200 220 260
Control test (i.m.s.)	L	96 ($4\frac{1}{2}$)	4.2 ($3\frac{1}{2}$)	–	–	120[d]

(a) With an intumescent coating (polyester-based)

(b) With an extra intumescent coating (water based)

(c) No coating

(d) Owing to a substantial heat loss to the walls and ceiling this is
a quarter of the calculated output of fire (480×10^6 J)

*Not reduced to equivalent flow at ambient temperatures

The measurement of smoke production of the materials was made by continuously monitoring the smoke in the stream flowing away from the burning materials.

The optical density of the smoke was obtained from measurements of the attenuation of a light beam in passing a given distance through the smoky gas in the hot gas layer. The outputs from a receiver photocell and from a photocell designed to register changes in the output of the light source were monitored.

The optical density per metre, D', of the smoke layer was calculated from the

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attenuation of a light beam using the equation

$$D' = \frac{1}{d} \log_{10} \frac{I_o}{I}$$

where d is the path length (m), I_o is the output from the receiver photocell before the test and I is the output at a time t during the test corrected if necessary for any changes at the light source. Smoke meters with a 6 m path length were used when the concentration of smoke was thin, however longer paths would have increased the sensitivity of this measurement. Smoke meters with a short path ($\frac{1}{4}$ m) were used for dense smoke, but even these became somewhat insensitive at very high densities. A shorter path length instrument would, however, have been too sensitive to local variations.

Figure 6 shows a typical graph of optical density/m plotted against time, low values existing at the beginning and end of the test with a large peak for a brief interval about halfway through. Since readings were taken each half minute, the measurement system used was not ideal because such a large portion of the area under the graph (ie near the peak) is dependent on the accuracy of only a small number of readings.

The optical density/m is a useful parameter to characterise smoke since for a given type of smoke it is proportional to the mass concentration of smoke particles; furthermore it can be related to visibility[11]. (see fig.8).

The values of optical density/m vary greatly between the materials tested, the maximum value being approx. 1000 times larger than the minimum value (Table 3).

Comparisons between materials could be made using the measured values of optical density alone, but it is more meaningful to make a comparison in terms of total smoke production. The total quantity of smoke produced is in principle the product of smoke concentration and volume rate of flow of smoky gas integrated over the whole test period. However, for the present purpose it is more meaningful to obtain a measure of the total quantity of smoke expressed in vision-obscuring terms and this can be calculated directly from the optical densities and flow rates of gas without any knowledge of the constant of proportionality between mass concentration and optical density. One convenient measure of total quantity of smoke is the optical density/m that would eventually be obtained in a stirred enclosure of given volume supplied with all the smoke from the fire. This can be expressed[5] as an optical density/m produced in a volume of 1 m^3 by 1 g of fuel if the weight of fuel burned is known. Alternatively it can be expressed in terms of the area of specimen exposed or burned.

It is realised that the mode of formation of smoke is complex and may depend on reactions both within the solid or its char layer and in the vapour phase. Nevertheless it is of great practical importance to see how well results can be correlated in terms of the area of material exposed or burnt.

Thus we define:

$Dn(1)$ is the optical density/m obtained in a stirred volume of 1 m^3 by exposure to fire of 1 m^2 of material (not all the area of which necessarily burns or is affected by fire).

$Dn(2)$ is the optical density/m obtained in a stirred volume of 1 m^3 by exposure to fire of 1 m^2 of material which burns over the whole area exposed.

$Dn(3)$ is the optical density/m obtained in a stirred volume of 1m^3 by burning 1 kg of material.

$Dn(4)$ is the optical density 1 m obtained in a stirred volume of 1m^3 from 1m^2 of material, calculated from the results of the Fire Propagation Tests described in section 7.

These definitions have been formed for mathematical convenience, for example they could be used as an intermediate stage in the computation of a level of smoke density within a real building following the combustion of a certain quantity of lining material. It has to be assumed that the smoke production per unit area does not vary with area exposed and that the heat transfer rate in these fires is the same as that in the situation for which such calculations are being made.

To calculate a standard optical density, in this way, in a full-scale situation, it is necessary to integrate with respect to time, within the limits of duration of each test, the instantaneous rate of smoke production, which is the product of instantaneous values of optical density per metre path length and the volume rate of flow of the hot gases. The method of calculation is given in the Appendix and the results are shown in Table 4.

The standard optical densities were highly representative of the subjective visual conditions for each test. Thick, dense smoke created high optical densities (eg that of the glass-reinforced polyester where $Dn(1) = 500$ to 1000) whereas when only wisps of smoke were seen the standard optical densities were very small (eg for polystyrene and plasterboard $Dn(1) = 0.5$ to 1.0) as shown in Table 4. The table also gives values for the standard optical densities in terms of the estimated area burnt and the estimated mass of material burnt.

The outstanding feature of Table 4 is the enormous range over which the standard optical densities lie. The materials that have been tested cover a range of standard optical density per square metre of exposed sample, greater than three orders of magnitude.

Table 4

Standard optical densities of the sample materials

Dn(1) - Standard optical density (S.O.D.) per unit area of specimen exposed (m^{-2})
Dn(2) - S.O.D. per unit area burned (involved in combustion) (m^{-2})
Dn(3) - S.O.D. per unit mass burned (involved in combustion) (kg^{-1})
Dn(4) - S.O.D. per unit area burned in Fire Propagation tests (m^{-2})

Material	Test code	Dn(1)	Dn(2)	Dn(3)	Dn(4)
Expanded polystyrene	A B	0.50 0.70	3.8 -	30 -	43 $(22)^d$
Plasterboard	C D	0.90 1.0	1.0 -	3.3 -	63
Heat resistant decorative laminate	E F G	4.2 4.6 5.4	4.8 4.9 -	2.6 3.7 -	68
Wood fibre insulation board	H	34	34	9.5	270* 101**
Glass reinforced polyester resin (GRP)	I^a J^b K^c	220 415 620	220 415 620	47 87 130	775 960 920

*Mean of 3 tests obtained in 1972

**Mean of 6 tests obtained in 1975 for a nominally identical material

(a) With an intumescent coating (polyester based)

(b) With an extra intumescent coating (water based)

(c) No coating

(d) Value from Fire Research Note 856 (ie 1 in thick, 14 g reduced to 7.5 mm thick and 5.88 g)

7. THE FIRE PROPAGATION TEST METHOD

Two different techniques are possible for making quantitative measurements of the smoke production of materials in vision-obscuring terms. The first, adopted for these tests, was the method of continuously monitoring the smoke flowing away from the sample materials. The second, adopted in the Fire Propagation test, is to collect all the smoke produced by the sample in a fixed volume, stir it well, and measure the obscuration produced. In both cases, optical density is measured by means of the attenuation of a beam of light passing a known distance through the smoky gases. The measurements necessary for the first method are extensive and are

laborious to use. The second method has much to recommend it but is impossible to apply to more than very small quantities of material. Whilst not invalidating the method this means that it may be more difficult to ensure that the conditions of exposure of the specimen adequately represent a fire situation.

In the Fire Propagation test, samples of specimens of standard size 228 mm x 228 mm were used, of which an area 190 mm x 190 mm was subjected to a standard procedure of heating and ignition[6]. The smoke given off by the sample was collected in a closed room of volume 18.8 m^3, and mixed uniformly by fans. The optical density was monitored throughout the duration of the test. The path length of the smoke meter was 0.5 m. The standard optical densities were obtained from the peak values of optical density, obtained by the GRP in 18 minutes and by the other materials in 20 minutes.

The results from the Fire Propagation Test Method (Table 4) have been taken as the mean of three similar tests (except for samples of glass-reinforced polyester with intumescent coatings). The tests in each case were found to be reasonably repeatable. In a sense the results are more reliable than those of the large-scale tests since the density of smoke is the only variable that has to be measured on the small scale. Variations from test to test are not, on the whole, systematic and thus demonstrate the real variability in smoke production.

8. COMPARISON OF LARGE AND SMALL-SCALE EXPERIMENTS

The smoke production of the materials tested, expressed in terms of their ability to obscure vision within a volume collecting smoke covered a very large range, the polystyrene producing optically very thin smoke and the glass-reinforced polyester larger volumes of thick black smoke. The total quantity of smoke was found to be independent of the total heat output of each material (compare Tables 3 and 4), for example the decorative laminate burned vigorously giving off little smoke, whereas the glass-reinforced plastic burned only steadily giving off very large quantities of smoke.

Standard optical densities, ie the optical densities/m in a stirred volume of 1 m^3, have been obtained from both the large scale and the Fire Propagation test data, each being expressed in terms of the smoke produced from unit area (1 m^2) of material exposed. These are compared in Table 4, where it is seen that the results for the two types of exposure are by no means in agreement.

Figure 7 shows the results given by the Fire Propagation test method plotted against the results from the present large scale tests.

The relationship between Dn(1) and Dn(4) is represented by the equation:

$$Dn(1) = 0.0006 \ Dn(4)^{2.0}$$

with a correlation coefficient of 0.98. The relationship between Dn(2) and Dn(4) can be written as:

$$Dn(2) = 0.0039 \ Dn(4)^{1.7}$$

with a correlation coefficient of 0.95.

From the above equations it can be seen that there is a highly systematic correlation, although there is not 1:1 correspondence nor even a linear relationshi between the two methods.

The deviation from the ideal 1:1 relationship is greatest for the low smoke producing materials.

Thus whilst the results from the Fire Propagation test are similar to those of large scale experiments for materials which produce much smoke, the results are too large, or the results from the large-scale experiments too small, for materials which produce little smoke. This discrepancy may be due to a preheating or a restriction of ventilation that occurs in the Fire Propagation test or perhap to the consumption of a greater proportion of smoke by the alcohol fuel used for ignition in the large scale tests. Some, but by no means all, of this difference arises because a rather small proportion of material was actually burnt in the large scale tests with polystyrene. In Test 9 only about $\frac{1}{8}$ or so of the sample appeared to have burned and Dn(2) is much nearer than is Dn(1) to the value of Dn(4).

However the value of the Standard Optical Density/m of 1 g of polystyrene found by inserting the above estimates for the proportion burnt (0.03) is still much lower than the values obtained for burning piles of expanded polystyrene pieces[5] (0.6 to 0.9) indicating a real difference between the smoke production of polystyrene as a lining and as piles of pieces.

Some smoke from the polystyrene may well have been consumed in the flames of the igniting alcohol, or (virtually the same thing) the alcohol flames may have modified the combustion of the polystyrene so that less smoke was produced, but since polystyrene will only burn at all as a lining if it is exposed to contact from large flames, for practical purposes this difference can be regarded solely as a difference between smoke production of polystyrene burnt as linings and as a pile of pieces.

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9. CONCLUSIONS

1. The measurement of smoke production by a material is generally easier experimentally if all the smoke is collected in a given volume rather than continuously monitored in a flowing gas layer. However, the former method can only be used for small quantities of material, and whilst perhaps it is the natural choice for a test method, it gives an impression that smoke production is capable of more precise definition than is justified in practice.

2. The range of optical densities measured, for the materials used in these experiments, was very large, covering three orders of magnitude. Glass-reinforced polyester resin produced the most and polystyrene the least smoke.

3. The large-scale tests and the Fire Propagation test method both gave broadly similar values for the smoke production of the materials producing most smoke, but for the materials producing little smoke the different methods gave very different results, the large-scale tests registering less smoke than the Fire Propagation test method. A small part of this discrepancy was removed by calculating smoke production in terms of the material actually burnt rather than the material exposed.

4. Both methods graded the materials in the same order in terms of smoke production.

5. A strong correlation exists between the values of $Dn(1)$ and $Dn(4)$ defined in section 6. The relationship is a simple power law which approximates to a square law:-

$$\text{ie } Dn(1) \propto Dn(4)^2$$

6. Subject to confirmation from possible future tests, the confidence shown in the existence of a definite relationship between $Dn(1)$ and $Dn(4)$ suggests that the Fire Propagation test method may be a suitable standard for the determination of smoke production from interior wall lining materials.

10. ACKNOWLEDGMENTS

11. REFERENCES

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APPENDIX

Let v be the volume rate of flow of smoky gases through a cross-section of the mall, at temperature T $^{\circ}K$ at time t

D be the optical density of the smoky gases (assumed uniform over the whole cross section) measured over a path length l_1

Beer's law gives:

$$I = I_o e^{-bcl_1}$$

where I/I_o is the fraction of light transmitted over a path length l_1 through the smoke, b is assumed constant for smoke from a particular fuel and c is the smoke concentration (mass/unit volume).

The optical density $D = \log_{10} (I_o/I) = \dfrac{bcl_1}{2.303}$

The mass of smoke passing the cross section in a time interval dt is then

$$cv \, dt = \frac{D}{l_1} \cdot \frac{2.303}{b} \cdot v \, dt \qquad ,$$

The total mass of smoke passing over the whole period of a test lasting a time t_f is

$$M = \frac{2.303}{l_1 b} \int_o^{t_f} D v \, dt$$

If this smoke is imagined to be collected without loss in a volume V, and then to be well stirred, the concentration of smoke will be M/V and the optical density for a path length of l_2 will be:

$$\frac{b M l_2}{2.303 \, V} = \frac{l_2}{l_1 V} \int_o^{t_f} D v \, dt$$

If the area of specimen exposed is A, the standard optical density $Dn(1)$ is obtained by inserting $l_2 = 1$ m, $V = 1$ m^3 , and A . Thus

$$Dn(1) = \frac{1}{A \, l_1} \int_o^{t_f} D v \, dt$$

If v is obtained by measuring the volume rate of flow of air towards the fire v_o, at temperature T_o $^{\circ}K$ then

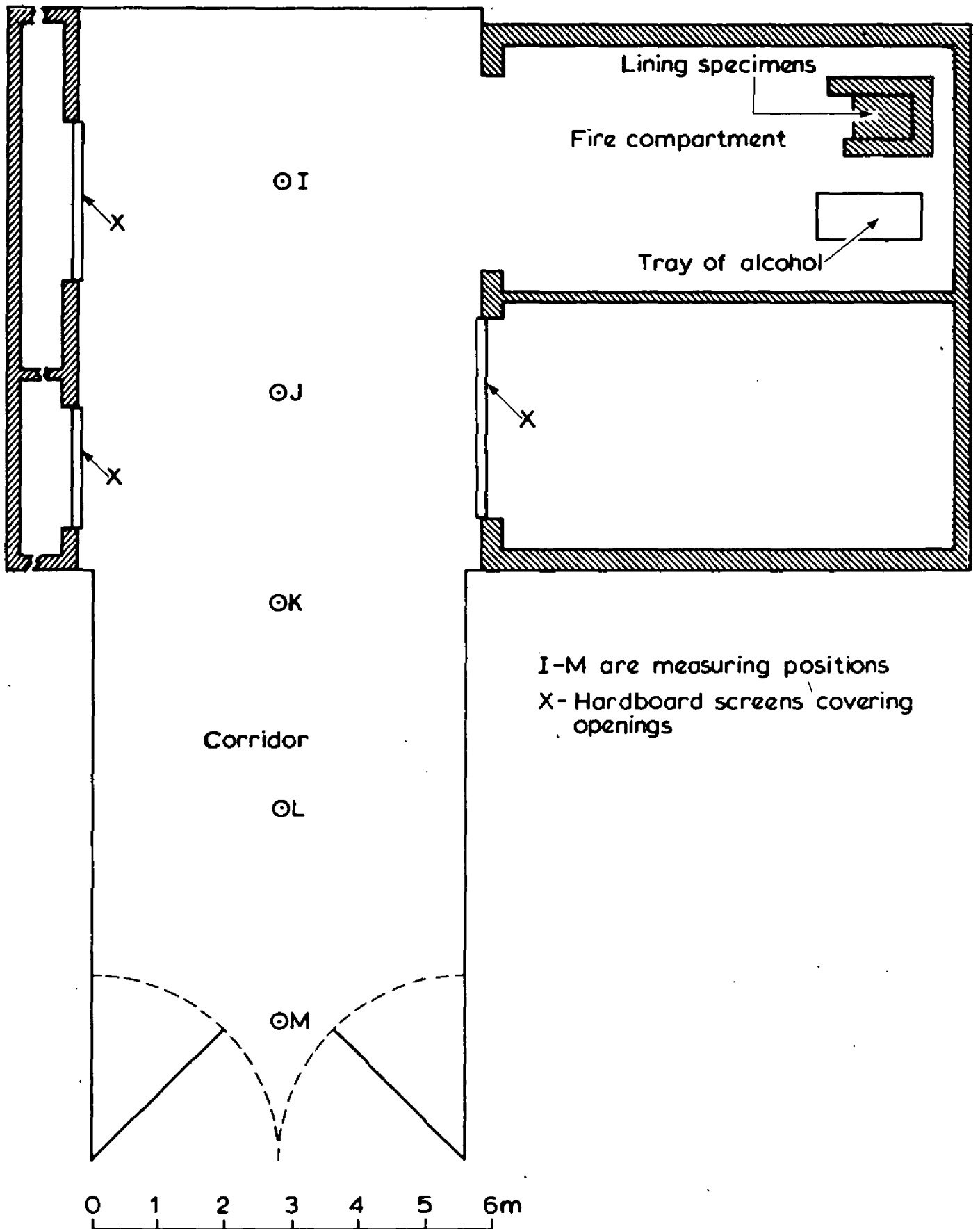$$Dn(1) = \frac{1}{A l_1 \, T_o} \int_o^{t_f} D v_o \, T \, dt$$

Figure 1 Plan of experimental building

Ceiling asbestos with
refractory felt lining

Linings on 3 walls

Trays
containing
alcohol

0   1m
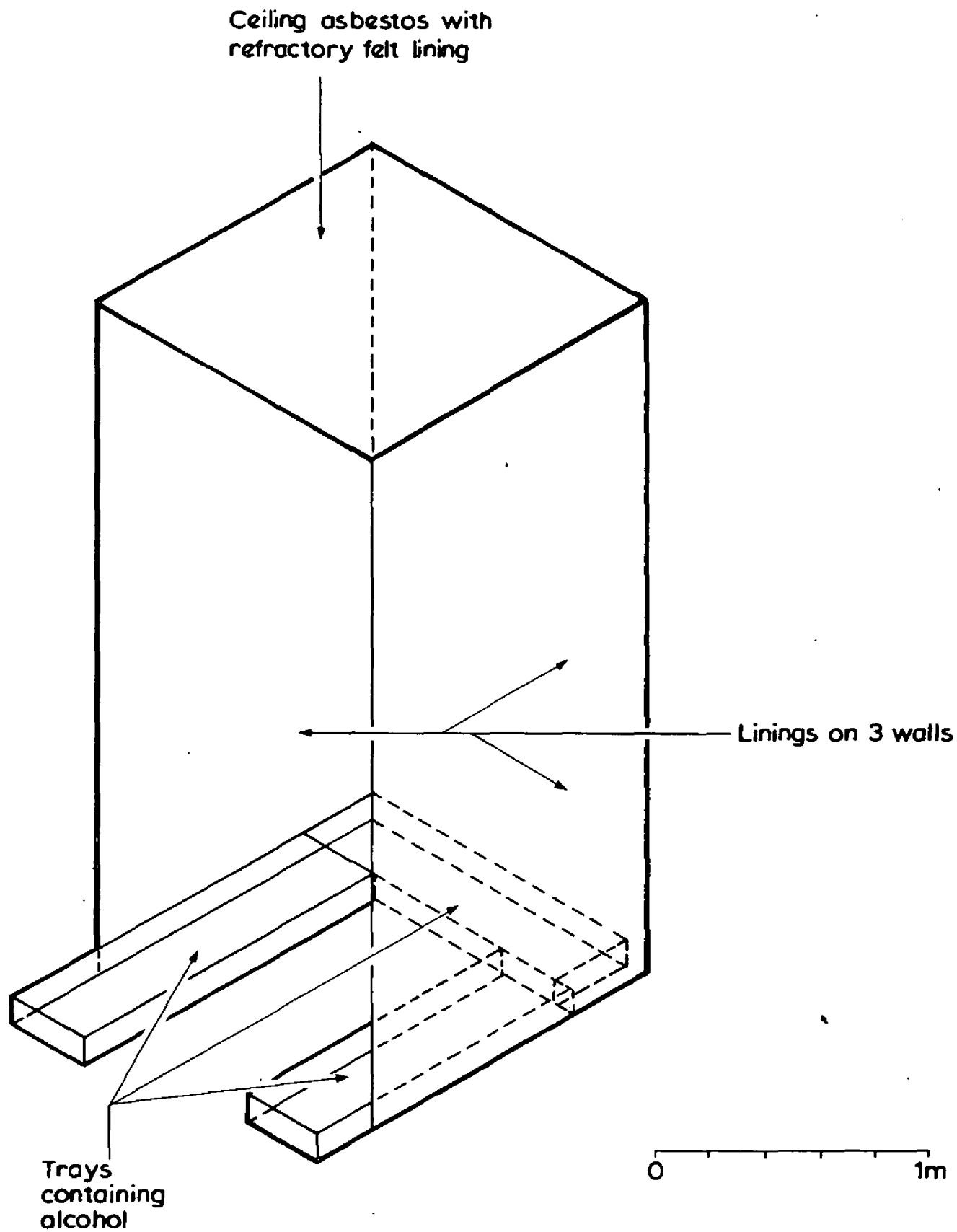
Figure 2 Isometric view of box containing lining specimens

Figure 3 Temperature profile and layer depth
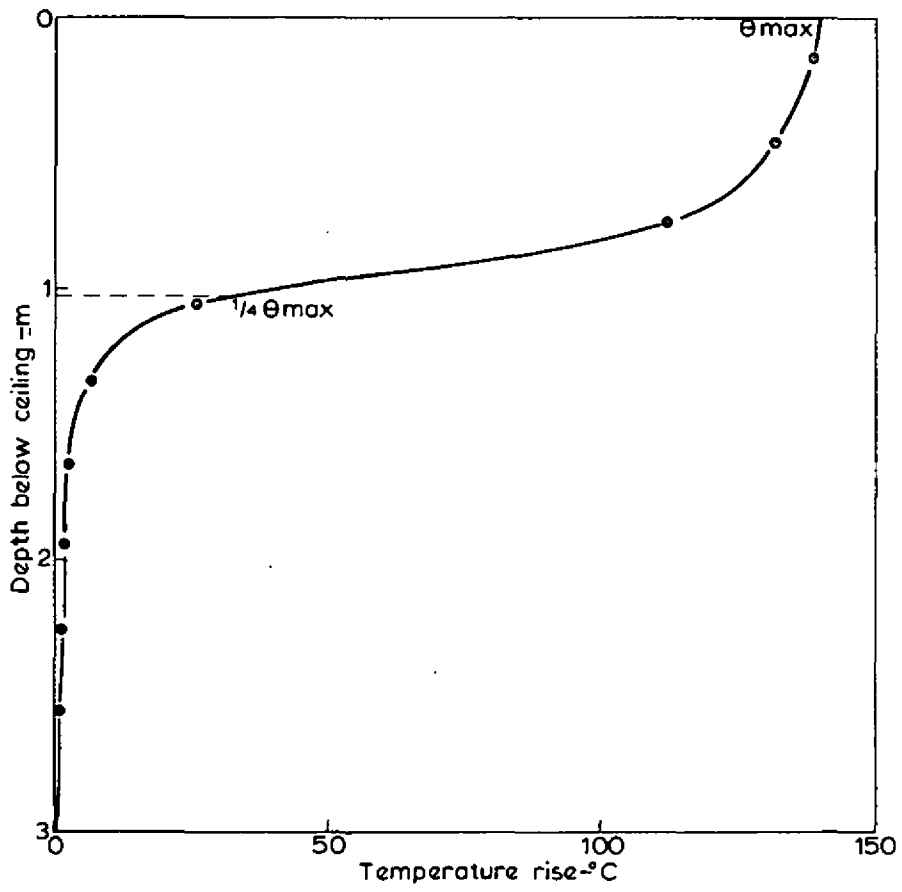

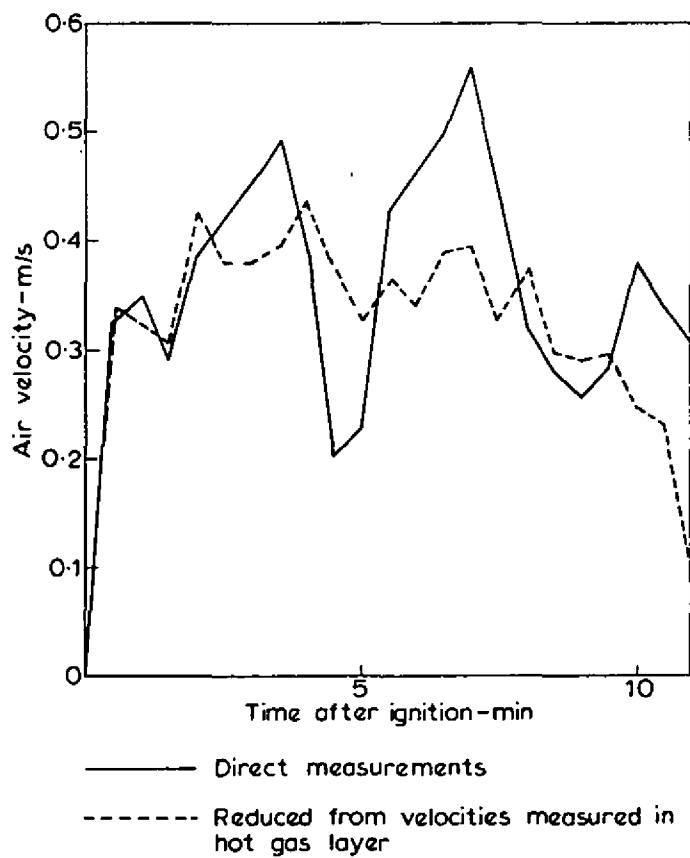Direct measurements

------- Reduced from velocities measured in hot gas layer

Figure 4 Mean velocity of inflowing cool air layer
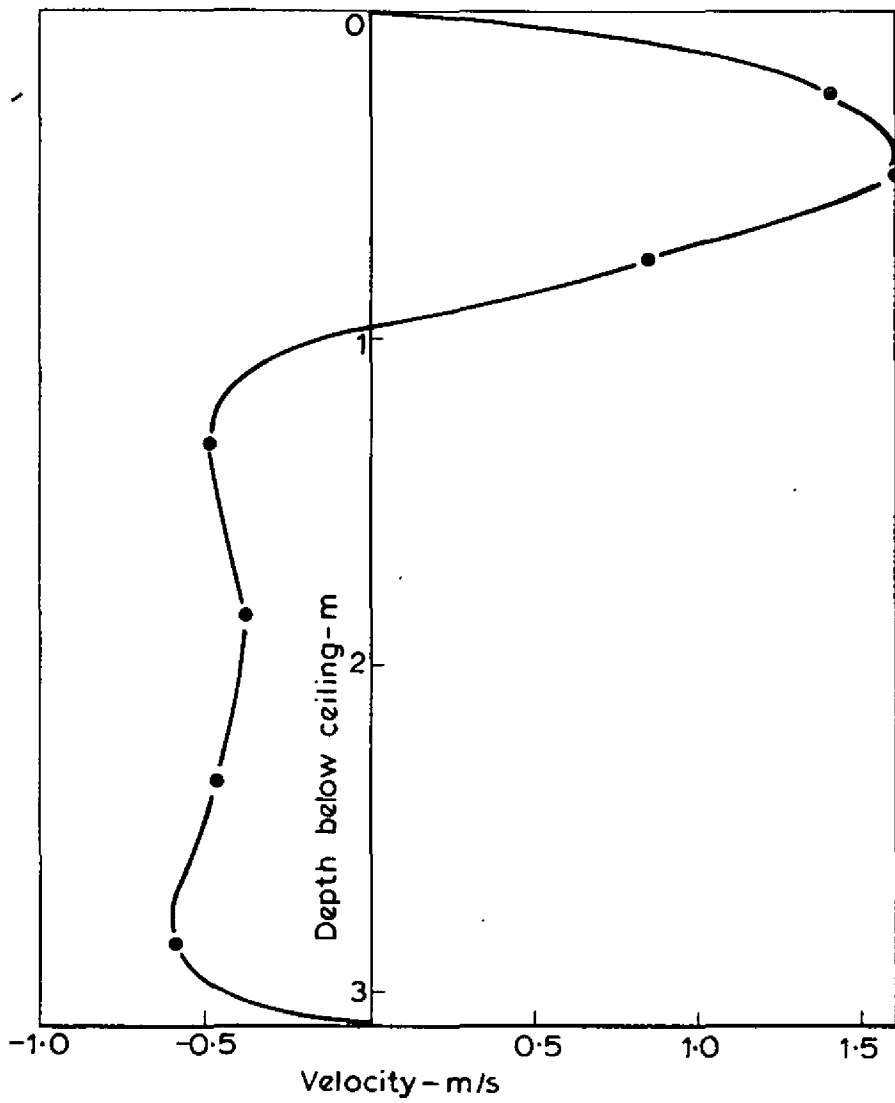
Figure 5 Vertical velocity profile (test C)
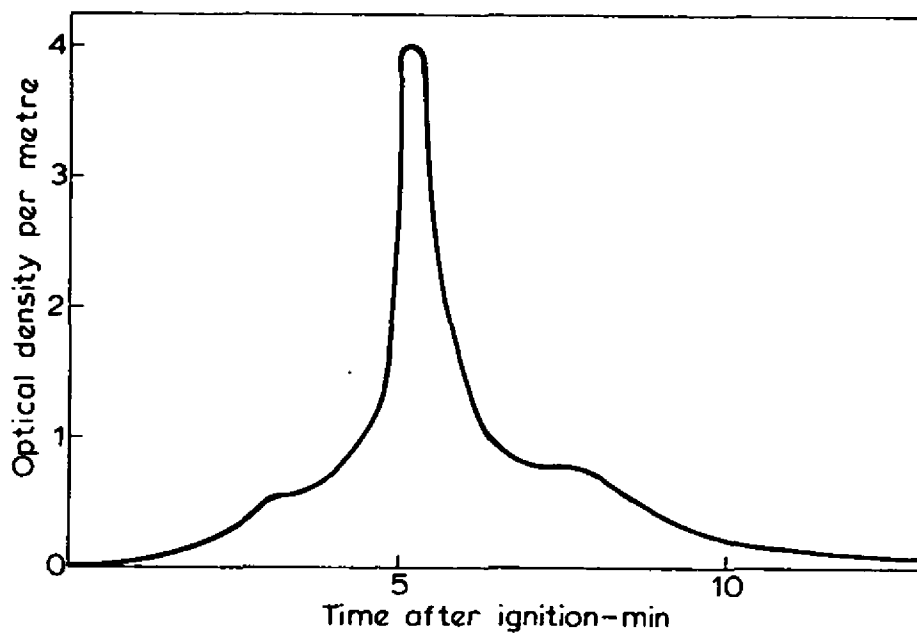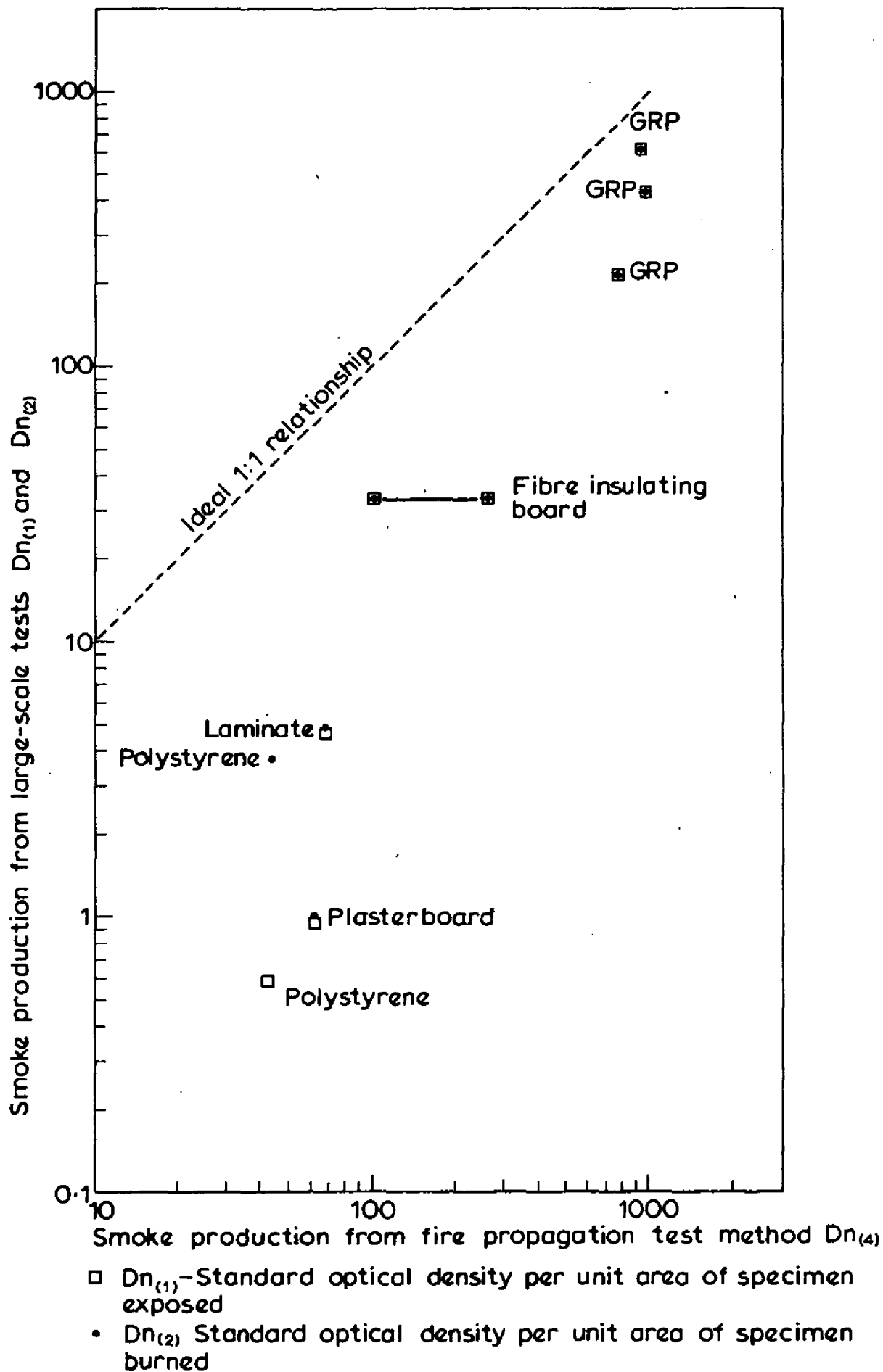

Figure 6 Optical density at position K (test I)
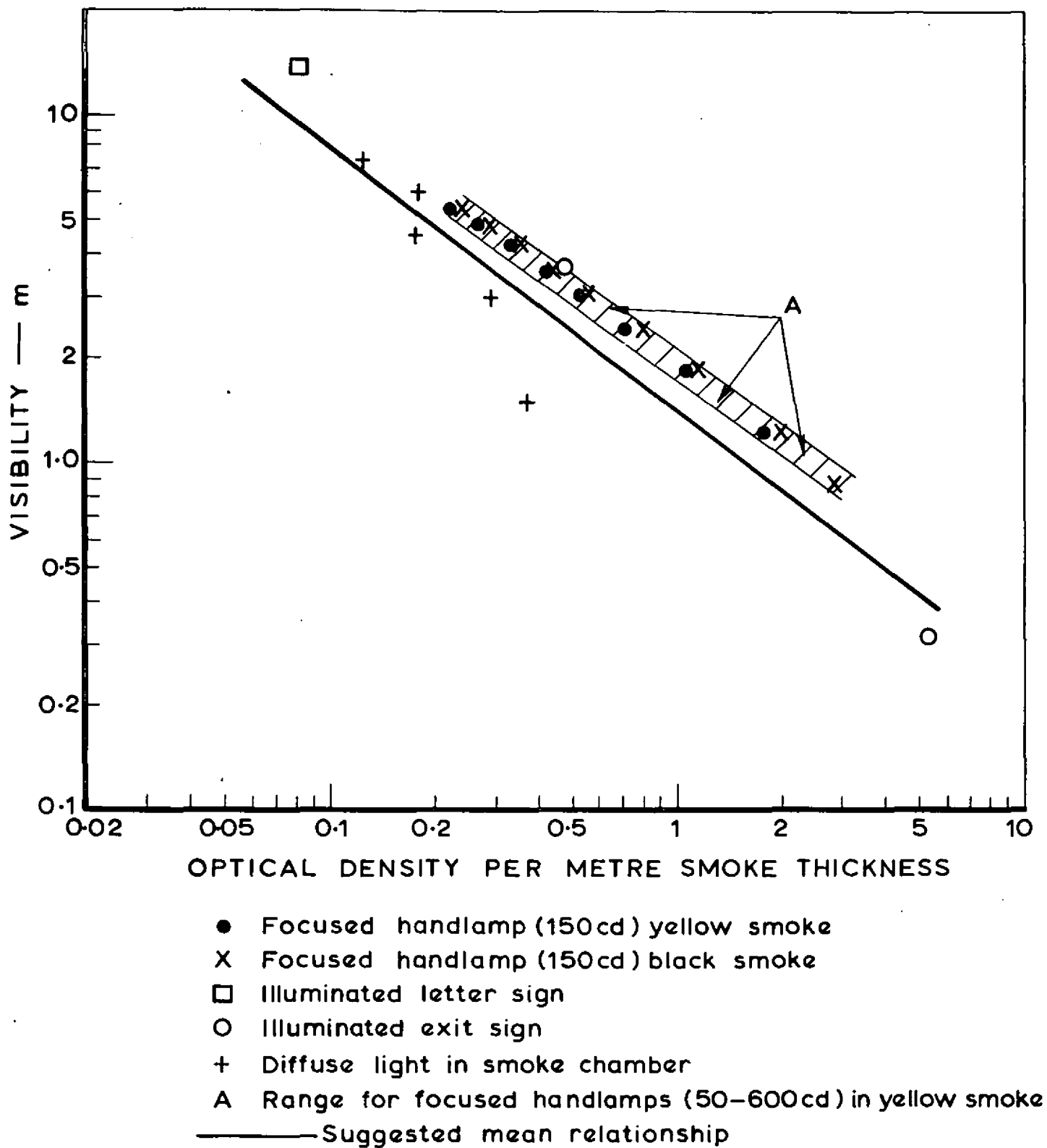
Figure 7 Comparison of large and small-scale results

● Focused handlamp (150 cd) yellow smoke
X Focused handlamp (150 cd) black smoke
□ Illuminated letter sign
O Illuminated exit sign
+ Diffuse light in smoke chamber
A Range for focused handlamps (50-600 cd) in yellow smoke
————Suggested mean relationship

FIG 8   RELATIONSHIP BETWEEN VISIBILITY AND OPTICAL
DENSITY OF SMOKE FROM FIRES
(TAKEN FROM D J RASBASH[11])

PLATE 1. MATERIAL REMAINING AFTER A TEST WITH PLASTERBOARD