# Fire Research Note
# No. 749

THE ASSESSMENT OF SMOKE PRODUCTION
BY BUILDING MATERIALS IN FIRES

2. Test method based on smoke accumulation in a compartment.

by

P. C. BOWES and P. FIELD.

March, 1969.

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F.R. Note No. 749
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# THE ASSESSMENT OF SMOKE PRODUCTION BY BUILDING MATERIALS IN FIRES

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SUMMARY

The measurement of the optical density of smoke produced by materials under test in the Fire Propagation Test Apparatus, and allowed to accumulate in a relatively large closed compartment, has been studied as a possible standard test for smoke production by building materials.

It is concluded that the procedure is suitable as a routine adjunct to the Fire Propagation Test without modification to the apparatus.

KEY WORDS: Smoke, Building materials, Fire Propagation Test.



MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
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# THE ASSESSMENT OF SMOKE PRODUCTION BY BUILDING MATERIALS IN FIRES

## 2. Test method based on smoke accumulation in a compartment

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## 1. INTRODUCTION

This note describes a further stage in the development of a test for assessing the probable smoke production by building materials in fires, based on measurement of the smoke produced by the materials when under test in the Fire Propagation Test Apparatus[1].

The initial approach to this problem[2] consisted of measuring the optical density of smoke from the chimney of the Fire Propagation Test Apparatus, the smoke being sampled continuously and diluted to a known extent with clean, cool air. This yielded the optical density of the diluted smoke as a function of time during the combustion of the material under test and provided a basis for comparing different materials. If desired, the instantaneous optical density could be integrated to yield a relative measure of the total smoke produced in a given period; no absolute measure was possible because the fraction of smoke sampled was not known. Smoke production was assessed in this way for a series of materials and for different modes of combustion in the Fire Propagation Test Apparatus.

In principle, this procedure appeared to be satisfactory as a comparative test of smoke production, but it was subject to a major practical difficulty in that the smoke-sampling became clogged with soot when some materials were tested. Further, even after dilution, the smoke and combustion gases were hot enough at the point of density measurement to necessitate an auxiliary cooling system for the photocell; at this point the equipment was, in fact, too hot to touch. It therefore seemed probable that the diluted combustion gases were well above their dew point and that altogether, the smoke was too hot and fresh, and likely to be changing in density too rapidly for it to be representative of the kind of smoke likely to be important in practice.

Essentially, it is desired to assess the contribution of different building materials to the smoke-logging of stairwells and corridors, and so to impeding escape, in parts of a building remote from the seat of fire; that is, where smoke is likely to be relatively well-mixed with air, cool and stable.

For these reasons it was decided to investigate an alternative method in which smoke from a material undergoing test in the Fire Propagation Test Apparatus was allowed to accumulate in a closed compartment. A compartment of relatively large volume was used with artificial stirring of the air, in order to facilitate mixing and cooling and so to obtain smoke in a state likely to be closer to practice.

In principle, the method was similar to the one adopted by Gross, Loftus and Robertson[3] (and, later, Gaskill and Veith[4]) who burned specimens of approximately 7.6 cm (3 in) square in a compartment 0.51 $m^3$ (18 $ft^3$) in volume. These authors expressed their results in terms of a specific optical density, $D_s$ defined as

$$D_s = D \frac{V}{AL} \tag{1}$$

where $D$ is the optical density of the smoke (i.e. the negative logarithm to base 10 of the fraction of incident light transmitted), measured over a distance $L$, that is produced from a sample of material with surface area $A$ exposed to a heat source in a compartment of volume $V$. They have suggested that $D_s$ will be a constant for a given material under given conditions of combustion, which should enable the optical density to be calculated for any other desired values of $V$, $A$ and $L$. It should be noted that, for this purpose, a given material in the form of boards of different thicknesses, would be classed as different materials.

In the test described in this paper, the conditions of combustion were those of the Fire Propagation Test Apparatus, operated both in the standard way[1] and in a non-standard way chosen to produce smouldering combustion, and the value of the dimensionless group $V/AL$ was about nine times larger than for the apparatus of Gross, Loftus and Robertson[3]. Some experimental factors have been assessed, and smoke densities have been measured for a range of different materials. Since this work is required as a possible basis for a standard, experimental arrangements and procedures are reported in detail.

It must be pointed out that this test is being proposed in the absence of adequate quantitative information on the factors which control the production of smoke by building materials in fires.

## 2. EXPERIMENTAL

### 2.1. APPARATUS

#### 2.1.1. Fire Propagation Test Apparatus

Two examples of the Fire Propagation Test Apparatus, constructed in accordance with B.S. 476 : Part 4[1], were used without modification.

Calibration runs, with asbestos board, were carried out as specified to confirm that the temperature/time curvesunder the standard conditions of operation were within the prescribed limits.

For smouldering combustion of the sample, the mode of operation was altered as described later.

#### 2.1.2. Smoke density measurement

Smoke density was measured in terms of the reduction in transmitted intensity of a light beam focussed on a photocell.

The arrangement of the light source and photocell receiver is shown diagrammatically in Fig. 1. A plane glass plate, set at $45^{\circ}$ in front of the light source ( $\sim$ 2 watts), reflected light on to a second photocell connected to compensate for variations in intensity of the light source during a test.

Although selenium barrier layer cells had been found satisfactory in the previous work[2], the opportunity was taken here to gain experience with another type. Cadmium sulphide photoconductive cells were used (ORP 12), the receiver and monitor cells being connected in a bridge energised by a constant voltage source as shown in Fig. 2. The out-of-balance voltage was measured by a potentiometric recorder. Low and high value variable resistances in the bridge provided coarse and

2.1.2. Smoke density measurement (cont'd)

fine adjustment for balancing at zero on the output recorder (chosen to correspond to full illumination) and at full-scale deflection (corresponding to complete obscuration). The light source was connected to a high-capacity lead storage-battery.

The optical system was arranged to measure obscuration in the horizontal direction and was mounted on a frame at about the centre of the test chamber (see below) with an optical path length of 1 m (3.3 ft).

Calibration with neutral density filters showed that the relation between the light intensity and the output e.m.f. was linear.

After a warming-up period of $\frac{1}{2}$ - 1 hr, the system was reasonably stable. Set-point drift during the period of a test amounted to about 1 per cent of full-scale deflection on the output recorder.

2.1.3. Test Chamber

The tests were carried out in a room as shown in plan in Fig. 3. The room was divided by a partition provided with a smoke-tight door (sealed with plastic foam strip) and two observation windows. The actual test chamber, in which the smoke was generated and measured, was approximately one half of the room as shown, the control equipment and recorders being housed in the other half. The volume of the test chamber was 33.7 $m^3$ (1200 $ft^3$).

The Fire Propagation Test Apparatus was placed on the floor of the chamber at one-third of a diagonal (see Fig. 3), and fans for mixing the air in the chamber were arranged on the other diagonal at distances of one-third. The fans, each with a free-air rating of 577 $m^3/h$ (340 $ft^3/min$), were mounted as shown in Fig. 4, so that they could be placed with their axes inclined to all the boundary surfaces of the test chamber. Efficient mixing was obtained with this arrangement, the plume of smoke from the Fire Propagation Test Apparatus being only rarely drawn directly across the light path (if this happened, the density record showed large transient changes).

The chamber was heated by electric tubular heaters controlled to maintain a temperature of 25°C (± 1 deg C) for all tests described in this Note, (see further in 3. Discussion).

2.1.3. Test Chamber (cont'd)

Smoke was cleared from the chamber after a test by opening a hatch in the roof and running the 1 h.p. fan mounted in the partition. During tests this fan was covered by a smoke-tight shutter.

## 2.2. CONDITIONING OF MATERIALS

Boards for test were cut to size, 228.6 mm (9 in) x 228.6 mm (9 in), and conditioned to 10–21 °C (50–70 °F) and 55–65 per cent relative humidity in the standard way[1] before test.

## 2.3. TEST PROCEDURE

### 2.3.1. Standard procedure

Tests carried out in accordance with the standard procedure for the Fire Propagation Test[1] allowed combustion of the test sample with production of flame. The conditions for these tests were (a) gas supplied to the burner to furnish 30 Btu/min (7560 cal/min), this being 1.83 l/min of local town gas, (b) electrical supply to heaters turned on at 1800 watts, 2 min 45 sec after ignition of gas jets and then reduced to 1500 watts at 5 min, at which it was kept constant for the remainder of the test.

Immediately before the test, the zero and full-scale settings of the light intensity recorder were adjusted, the zero corresponding to zero obscuration and the full-scale to 100 per cent obscuration (obtained by interposing a shutter in the light beam).

A test was continued until the obscuration had passed a maximum and begun to decrease. This usually required a test period of 20-25 min (20 min being the standard period for the Fire Propagation Test).

### 2.3.2. Non-standard Procedure

The non-standard operation of the test apparatus was aimed at obtaining smouldering combustion, or merely pyrolysis of the test specimen without ignition of the smoke and gaseous products. This was achieved by operating the test apparatus without the gas jets and reducing the power input to the electrical heaters. Preliminary tests were needed to determine the optimum power input for each material tested; this optimum being located to the nearest 100 watts. Under these conditions, the time required for the smoke obscuration to reach a maximum was commonly about 45 min (but see later).

2.3.2. Non-standard Procedure (cont'd)

The test apparatus was cleaned after each test. This was especially important after tests under non-standard conditions when, with smouldering combustion, tarry deposits were left on the inside of the specimen carrier which could produce smoke during a succeeding test under standard conditions.

2.3.3. Observations

The obscuration of the light beam during a test was obtained as a continuous record on a strip chart. A copy of a record, typical of the majority obtained in this work is shown in Fig. 5, for wood-fibre insulating board under smouldering conditions. The record shows greatest fluctuation in the intensity of transmitted light during the period of rapid increase in obscuration. However, the fluctuations rarely exceeded ± 2 per cent of full-scale deflection; this is an indication of efficient mixing. In the neighbourhood of the maximum obscuration, the smoke was relatively stable. Thus, 20 minutes after reaching a minimum in this test, the transmittance had increased by only 15 per cent; the rapid decay in density observed by Gross et al[3] was absent. Similar behaviour was obtained under the standard (flaming) conditions of test and with other materials.

At the end of a test the smoke was cleared and the zero setting of the recorder was checked both before and after cleaning the windows of the light-source and receiver photocell, and the full-scale deflection was checked. Except for one material (paper-filled phenol/formaldehyde board) there was no change in the zero reading before and after cleaning the windows, thus indicating that the deposition on the windows was negligible; for this one exception the deposit gave an obscuration of 2 per cent of full-scale. Both zero and full-scale deflections sometimes drifted by 1 or 2 per cent during a test. Since interest centred mainly on the maximum optical density, near the end of a test, the transmittance at any time during the test was calculated from the record trace as

$$\text{Transmittance, } T \text{ , } = \frac{\text{Final F.S.D. - Deflection at time t}}{\text{Final F.S.D. - Final zero}} \qquad (2)$$

2.3.3. Observations (cont'd)

For the one case in which there was a detectable deposit on the windows, the final F.S.D. and zero were taken as the values before the deposit was cleaned off; the calculated transmittance then applied only to smoke in suspension.

Observations of wet and dry bulb temperatures were made with a whirling hygrometer in the test chamber before each test in one of the main experimental blocks (see below).

## 2.4. TEST PROGRAMME AND RESULTS

### 2.4.1. Effects of operating variables

An initial programme of tests was carried out on the effects of some operating variables and possible interactions between them. Three variables were studied, each at two levels, as follows:-

1. Fire Propagation Test Apparatus. Possible variation between them.

    Two nominally identical apparatuses, each shown to satisfy the required temperature/time curve, were used and were designated $A_1$ and $A_2$ (see below).

2. Test materials

    $B_1$, paper-filled phenol/formaldehyde board (6.4 mm ($\frac{1}{4}$ in) thickness).

    $B_2$, wood-fibre insulating board (nominal 12.7 mm ($\frac{1}{2}$ in) thickness).

    $B_1$, although not a building board, was chosen as a convenient proving material of 'plastic' type which would not introduce complicating mechanical effects such as melting or collapse.

    $B_2$, was a convenient board of cellulosic type.

3. Test Procedure

    $C_1$, standard operating conditions[1], but continued for 25 minutes.

    $C_2$, non-standard conditions (45 min).

3. Test Procedure (cont'd)

Under the non-standard conditions, the electrical power was supplied at 1.2 kW for $1\frac{1}{4}$ min and then reduced to 0.6 kW for the remainder of the test. These conditions were chosen to produce optimum smouldering of the wood-fibre insulating board without flame and were used for both materials; they were not necessarily the optimum conditions for smouldering of the phenol/formaldehyde board.

It was possible to carry out only four tests in one day and there was, therefore, the possibility of day-to-day variation due to some uncontrolled factor such as relative humidity.

The tests were performed in accordance with the following design in which all possible eight combinations of A B C were carried out in two consecutive days (blocks). The A B C interaction was assumed to be unimportant and was confounded between the blocks.

Table 1

Experimental design

| DAYS (BLOCKS) / Tests on day | 1 | 2 |
|---|---|---|
| 1 | $A_2\ B_1\ C_1$ | $A_1\ B_1\ C_1$ |
| 2 | $A_1\ B_2\ C_1$ | $A_2\ B_2\ C_1$ |
| 3 | $A_1\ B_1\ C_2$ | $A_2\ B_1\ C_2$ |
| 4 | $A_2\ B_2\ C_2$ | $A_1\ B_2\ C_2$ |

The experiment was repeated three times, the starting block and the order of tests in each block being selected at random, subject to the limitation that the same apparatus was not used in consecutive tests (this was to allow for adequate cooling and cleaning after use). The total number of tests was 24.

The raw results are listed in Table 2 in terms of the minimum observed values of the transmittances calculated in accordance with equation (2) and expressed as percentages (the results, presented in

2.4.1. (cont'd)

this way, are not immediately informative but see below). The table also includes the relative humidities of the test chamber before each test and the time to the minimum transmittance.

Table 2

Effect of operating variables

| Day | Block No. | Test | Minimum Transmittance per cent (T x 100) * | Time to minimum min | Relative humidity per cent |
|---|---|---|---|---|---|
| 1 | 2 | $A_2\ B_2\ C_1$ | 89 | 25 | 35.5 |
| | 2 | $A_1\ B_2\ C_2$ | 35 | 42 | 33.0 |
| | 2 | $A_2\ B_1\ C_2$ | 96 | 45 | 33.0 |
| | 2 | $A_1\ B_1\ C_1$ | 6.0 | 23 | 33.0 |
| 2 | 1 | $A_2\ B_2\ C_2$ | 35 | 41.5 | 33.0 |
| | 1 | $A_1\ B_1\ C_2$ | 96 | 45 | 33.0 |
| | 1 | $A_2\ B_1\ C_1$ | 6.0 | 20 | 35.5 |
| | 1 | $A_1\ B_2\ C_1$ | 92 | 25 | 35.5 |
| 3 | 2 | $A_2\ B_1\ C_2$ | 82 | 45 | 38.0 |
| | 2 | $A_1\ B_1\ C_1$ | 8.0 | 20 | 35.5 |
| | 2 | $A_2\ B_2\ C_1$ | 89 | 25 | 41.0 |
| | 2 | $A_1\ B_2\ C_2$ | 33 | 40 | 38.0 |
| 4 | 1 | $A_1\ B_1\ C_2$ | 98 | 45 | 41.0 |
| | 1 | $A_2\ B_2\ C_2$ | 34 | 40 | 41.0 |
| | 1 | $A_1\ B_2\ C_1$ | 93 | 20 | 44.0 |
| | 1 | $A_2\ B_1\ C_1$ | 6.0 | 20 | 47.0 |
| 5 | 2 | $A_1\ B_2\ C_2$ | 35 | 41 | 44.0 |
| | 2 | $A_2\ B_1\ C_2$ | 98 | 45 | 41.0 |
| | 2 | $A_1\ B_1\ C_1$ | 5.0 | 22 | 44.0 |
| | 2 | $A_2\ B_2\ C_1$ | 87 | 25 | 44.0 |
| 6 | 1 | $A_1\ B_2\ C_1$ | 95 | 25 | 38.0 |
| | 1 | $A_2\ B_2\ C_2$ | 38 | 40 | 33.0 |
| | 1 | $A_1\ B_1\ C_2$ | 99 | 45 | 35.5 |
| | 1 | $A_2\ B_1\ C_1$ | 5.0 | 21 | 33.0 |

* Equation (2)

When the independent variable is a percentage, its distribution is not normal and it needs to be transformed for purposes of statistical analysis. The minimum transmittances were accordingly transformed to angles $\theta$, using the transformation, appropriate in this case,

$$\theta = \sin^{-1} \sqrt{T}$$

The analysis of variance for the transformed date is given in Table 3.

Table 3

Analysis of variance

| Source of variance | Sum of squares | Degrees of freedom | Mean sum of squares | Variance ratio |
|---|---|---|---|---|
| A | 49.6 | 1 | 49.6 | 4.0 |
| B | 419.2 | 1 | 419.2 | 33.7 |
| C | 1,144.0 | 1 | 1,144.0 | 92.0 |
| AB | 3.2 | 1 | 3.2 | 0.25 |
| BC | 15,055.1 | 1 | 15,055.1 | 1,211.2 |
| AC | 0.01 | 1 | 0.01 | $< 10^{-4}$ |
| Days | 88.1 | 5 | 17.6 | 1.42 |
| Error | 149.2 | 12 | 12.4 | - |

It may be concluded from this table that the day-to-day variation in this series of tests and the AB and AC interactions, were quite insignificant. The probability of the variance ratio for the variation between apparatuses (factor A) is slightly in excess of 0.05, and is high enough for this variation to be ignored in the present series of tests. However, if this test method is widely adopted, it would be worthwhile checking this source of variation further - especially, perhaps, between different laboratories. Otherwise, as expected, the major effective variables are the test material and the mode of operation of the test. These show strong interaction, i.e. the relative behaviour of different materials in the test depends strongly on whether the comparison is made under flaming or smouldering conditions.

2.4.1. (cont'd)

Grouping the results for the two apparatuses, the average results for minimum transmittance and maximum optical density for the six tests on each material in the two modes of test, are as given in Table 4.

Table 4

Summary of results

| Material | Mode of combustion | Minimum transmittance of smoke per cent | | Maximum optical density per metre | |
|---|---|---|---|---|---|
| Wood fibre insulating board | Flaming | 91 | (+ 2.7)* (- 3.5) | 0.041 | (+ 0.017) (- 0.013) |
| | Smouldering | 35 | (+ 5.4) (- 5.0) | 0.46 | (+ 0.06) (- 0.07) |
| Paper-filled phenol/formaldehyde | Flaming | 6 | (+ 2.9) (- 2.4) | 1.22 | (+ 0.22) (- 0.17) |
| | Smouldering | 96 | (+ 2.0) (- 2.8) | 0.019 | (+ 0.012) (- 0.009) |

* The figures in brackets give the upper and lower 95 per cent confidence limits.

The principal conclusion from Table 4 is that, as indicated in the analysis of variance, there can be a large difference in the smoke production by a given material under the two modes of combustion; and, at least for the fixed condition for smouldering in these tests, the direction of this difference can be opposite for two different materials.

Further points noted were:-

(1) The relative humidity did not vary widely during these tests (Table 2).

(2) The time for the transmittance to reach a minimum was 20-25 minutes for the standard conditions of test and 40-45 min for the smouldering conditions (Table 2).

2.4.2. Smoke production by different building boards

In order to explore the capabilities of the test and the range of smoke densities likely to be encountered in practice, a number of building boards, chosen to include traditional and non-traditional materials, were tested under both standard and non-standard conditions.

The standard conditions of test were as described under 2.3.1. In the non-standard tests, the initial power input was 1.5 kW and this was reduced after 1 min to the optimum level for smouldering for each material determined as under 2.3.2. For some materials in non-standard tests, the time for the transmittance to reach a minimum was up to 1 hour.

The results are given in Table 5 in terms of the mean values of minimum transmittances with upper and lower 95 per cent confidence limits (calculated via the angular transforms as in 2.4.1 above) and the corresponding optical densities. Entries in the table have been rounded to two significant figures and, as far as possible, confidence limits indicated by a single difference (rounded to one significant figure)*. The materials are tabulated in order of increasing optical density of the smoke produced under standard conditions. The optimum power input for smouldering combustion is indicated for each material.

The optical densities given in the table have been converted to visibility of, say, an illuminated exit sign, using the relationship plotted in Fig. 6. This relationship[5] is based on available published data for visibilities of lamps and illuminated figures in smokes of different kinds; the data (not shown here) falls within ± 20 per cent of the line in Fig. 6.

A sample of expanded polystyrene (density 0.02, thickness 10.8 mm) was tested, but this melted during test and gave no measurable smoke. The densest smoke, black and brown in colour, was obtained from the glass-fibre reinforced polyester board. After the series of tests with PVC, the metal of the test apparatus was corroded, and the refractory cement was softened sufficiently to necessitate repair before further use.

*Since the transmittances are not normally distributed, the upper and lower confidence limits are not symmetrical with respect to the means. Here, however, where the limits have been drastically rounded off, the assymetry disappears in all but a few cases where the errors are large; in these cases the upper and lower limits are indicated separately in the table.

2.4.2. (cont'd)

Table 5 - Part 1

Smoke production by different building boards

| Board | Density g/cm$^3$ | Thickness mm | Standard (Flaming) No. of tests | Standard (Flaming) Transmittance per cent | Standard (Flaming) Optical density per metre | Standard (Flaming) Visibility m | Non-standard (Smouldering) No. of tests | Non-standard (Smouldering) Optimum power watts | Non-standard (Smouldering) Transmittance per cent | Non-standard (Smouldering) Optical density per metre | Non-standard (Smouldering) Visibility m |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Plasterboard 0.6, 8.3, 0.6* | 0.82 | 9.5 | 3 | 91 $\pm$ 2 | 0.041 $\pm$0.008 | 17 $\pm$ 3 | 3 | 1000 | 90 $\pm$ 1 | 0.046 $\pm$0.006 | 15 $\pm$ 2 |
| Wood-fibre insulating board | 0.25 | 12.7 | 6 | 91 $^{+3}_{-4}$ | 0.041 $^{+0.02}_{-0.01}$ | 17 $^{+6}_{-4}$ | 6 | 600 | 35 $\pm$ 5 | 0.46 $^{+0.06}_{-0.07}$ | 2.5 $^{+0.4}_{-0.2}$ |
| Phenol/formaldehyde faced hardboard 0.4, 3.3, 0.3 | 1.30 | 4.0 | 4 | 66 $\pm$ 2 | 0.18 $^{+0.02}_{-0.01}$ | 5.2 $\pm$ 0.3 | 4 | 1000 | 41 $\pm$ 3 | 0.39 $\pm$0.03 | 2.9 $\pm$ 0.2 |
| Polyurethane foam sandwich 0.1, 0.4, 12.0, 0.5 | 0.08 | 13.0 | 4 | 62 $^{+9}_{-12}$ | 0.21 $^{+0.09}_{-0.06}$ | 4.8 $\pm$ 1.3 | 4 | 1200 | 55 $\pm$ 5 | 0.26 $\pm$0.04 | 3.9 $\pm$ 0.5 |
| Birch plywood | 0.69 | 6.4 | 4 | 58 $\pm$ 3 | 0.24 $\pm$0.02 | 4.3 $\pm$ 0.3 | 3 | 900 | 29 $\pm$ 4 | 0.55 $\pm$0.06 | 2.3 $\pm$ 0.2 |
| Hardboard | 0.86 | 3.7 | 5 | 57 $\pm$ 7 | 0.25 $\pm$0.05 | 4.1 $\pm$ 0.7 | 4 | 900 | 28 $\pm$ 2 | 0.56 $\pm$0.04 | 2.2 $\pm$ 0.1 |

* Where a board consists of several layers, the thickness of each layer is given here in mm. The nature of each layer is not always positively identified.

2.4.2. (cont'd)

Table 5 - Part 2

Smoke production by different building boards

| Board | Density g/cm$^3$ | Thickness mm | Standard (Flaming) No. of tests | Standard (Flaming) Transmittance per cent | Standard (Flaming) Optical density per metre | Standard (Flaming) Visibility m | Non-standard (Smouldering) No. of tests | Non-standard (Smouldering) Optimum power watts | Non-standard (Smouldering) Transmittance per cent | Non-standard (Smouldering) Optical density per metre | Non-standard (Smouldering) Visibility m |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Melamine faced hardboard 0.4, 2.5, 0.3 | 1.35 | 3.2 | 4 | 55 ± 7 | 0.26 ±0.06 | 4.0 ± 0.8 | 4 | 1000 | 47 ± 3 | 0.33 ±0.03 | 3.3 ± 0.2 |
| PVC-faced hardboard 0.5, 5.2 | 1.03 | 5.7 | 4 | 42 ± 2 | 0.37 ±0.02 | 3.0 ± 0.2 | 3 | 900 | 54 ± 2 | 0.27 ±0.02 | 3.8 ± 0.2 |
| Rigid PVC | 1.56 | 1.6 | 3 | 39 ± 5 | 0.41 ±0.06 | 2.8 ± 0.3 | 3 | 1000 | 42 ± 5 | 0.38 ±0.05 | 3.0 ± 0.3 |
| Chipboard | 0.64 | 12.7 | 4 | 38 ± 2 | 0.43 ±0.02 | 2.7 ± 0.1 | 4 | 1000 | 11 ± 2 | 0.94 ±0.06 | 1.5 ± 0.1 |
| Glass-fibre reinforced polyester (flame retardant) | 1.80 | 3.3 | 3 | 25* 0.3* | 0.60 1.52 | 2.1 1.0 | 3 | 1200 | 14 ± 1 | 0.86 ±0.03 | 1.6 ± 0.1 |

* Owing to large scatter of results for this board under standard conditions, entries are given here only as upper and lower 95 per cent confidence limits.

2.4.2. (cont'd)

The data in Table 5 can be most readily appreciated in terms of the estimates of visibility. Excluding the three examples of visibilities of 15 m or more (plasterboard and wood fibre-insulating board undergoing flaming combustion) it will be seen that the range of visibilities lay between about 1 m and 5 m. Broadly speaking, this represents the difference between the ability to distinguish an exit sign across the width of a corridor and at an appreciable distance down the length of a corridor (the "15 ft dash" corresponds to a visibility of 4.6 m). To this extent, the smoke dilution achieved in these tests may be regarded as realistic.

Except for the PVC-faced hardboard and rigid PVC, smoke production under optimum conditions for smouldering (or simply pyrolysis) was greater than under the standard conditions of test with flame. In all but one example (wood fibre insulating board), however, the increase in optical density (or decrease in visibility) was less than a factor of 2.

The repeatability of the results was generally satisfactory. Thus, in terms of the angular transforms of the transmittances, standard deviations were usually less than 5 per cent of the means. Reference to Table 5 will show that, as a result, the 95 per cent confidence limits for optical densities and estimated visibilities were usually within 20 per cent of the means. The most important exceptions were the tests on the glass-fibre reinforced polyester under flaming conditions. The high variability in these tests was probably a consequence of the fire retardant treatment since it was observed that flames appeared only intermittently as brief flashes.

2.4.3. Effect of dilution

The effect of the degree of dilution on the optical density of the smoke was determined in an experiment in which smoke produced in a given test was allowed to accumulate either in the test chamber, as above, or in the whole room (Fig. 3). In this latter case, tests were conducted with the door in the central partition open and with the 1 h.p. fan in operation to obtain the necessary mixing. Operating controls were moved outside the room. It was necessary in these tests to provide a screen to protect the Fire Propagation Test Apparatus from the direct influence of

2.4.3. Effect of dilution (cont'd)

the 1 h.p. fan. Two boards were tested under the two modes of operation of the Test Apparatus and the experimental design was as in Table 1, where the symbols now have the meaning given below:

| Factor | Level | Symbol |
|---|---|---|
| Room volume | 33.7 $m^3$ | $A_1$ |
| | 63.6 $m^3$ | $A_2$ |
| Material | Chipboard | $B_1$ |
| | Wood-fibre board | $B_2$ |
| Operating conditions | Standard | $C_1$ |
| | Non-standard | $C_2$ |

The non-standard conditions of operation were the optimum for smouldering of each material as given in 2.4.2. The experiment was repeated three times.

It will be noted that $A_2/A_1 = 1.9$ and, if equation (1) is to be applicable, we should find that the increase in volume reduces the maximum optical densities in the same ratio.

The analysis of variance of the results is given in Table 6 and the mean values of the maximum optical density for each ABC combination, with their 95 per cent confidence limits, in Table 7. Table 7 also includes the ratios of the maximum optical densities with and without dilution. There appears to be no satisfactory test of significance for these ratios, but a simulation procedure has confirmed that they are the best estimates obtainable from the data.

2.4.3. (cont'd)

Table 6

Analysis of variance
(angular transforms of transmittances)

| Source of variance | Sum of squares | Degrees of freedom | Mean sum of squares | Variance ratio |
|---|---|---|---|---|
| A | 1,371.1 | 1 | 1,371 | 46 * |
| B | 2,739.3 | 1 | 2,739 | 91 * |
| C | 3,021.1 | 1 | 3,021 | 101 * |
| AB | 498.0 | 1 | 498 | 17 * |
| BC | 303.4 | 1 | 303 | 10 * |
| AC | 104.8 | 1 | 105 | 3.5 |
| Days | 38.9 | 5 | 7.8 | 0.3 |
| Error | 359.8 | 12 | 30.0 | - |
| Total | - | 23 | - | - |

* significant

An important result in Table 6 is that the AC interaction is not significant at the 5 per cent level. The most likely source of this interaction was disturbance of the combustion conditions in the Fire Propagation Test Apparatus by the operation of the 1 h.p. fan when both halves of the room were in use. It may be concluded that there was no such disturbance.

2.4.3. (cont'd)

Table 7

Effect of dilution

| Board | Room volume | Standard (flaming) | | | Non-standard (smouldering) | | |
|---|---|---|---|---|---|---|---|
| | | No. of tests | Optical density per metre | Density ratio | No. of tests | Optical density per metre | Density ratio |
| Chipboard | X 1 | 3 | $0.44^{+0.16}_{-0.12}$ | 2.2 | 3 | $0.92^{+0.34}_{-0.24}$ | 2.4 |
| | X 1.9 | 3 | $0.20^{+0.10}_{-0.07}$ | | 3 | $0.38^{+0.15}_{-0.11}$ | |
| Wood-fibre insulating board | X 1 | 3 | $0.048^{+0.043}_{-0.029}$ | 2.0 | 3 | $0.49^{+0.17}_{-0.13}$ | 2.9 |
| | X 1.9 | 3 | $0.024^{+0.030}_{-0.018}$ | | 3 | $0.17^{+0.09}_{-0.06}$ | |

2.4.3. (cont'd)

The density ratios in Table 7 are somewhat higher than the expected value of 1.9, the excess being greater for smouldering combustion than for flaming. Thus increasing the volume of the test chamber reduces the optical density of the smoke to a greater extent than expected from straightforward dilution.

2.4.4. Concentrations of oxygen and carbon monoxide

In order that the conditions of combustion can be clearly defined, it is desirable that the smoke test chamber should be large enough to ensure that the combustion is not significantly affected by oxygen depletion during the course of a test. Checks of oxygen concentration were therefore carried out at the end of tests on the chipboard, which represented the greatest weight of combustible tested, and these showed that the concentration did not fall below 19.8 per cent in this work (air 21 per cent).

As a guide to the relation between smoke density and carbon monoxide levels, a few spot tests were made with Draeger tubes. Carbon monoxide concentrations of 0.06 to 0.08 per cent (600 to 800 p.p.m.) were observed during the initial block of tests with wood-fibre insulating board and paper-filled phenol/formaldehyde (section 2.4.1.) and 0.05 per cent in the above tests with chipboard. Thus, at smoke densities corresponding to visibilities as low as 1.5 m (4.9 ft), the concentration of carbon monoxide can be well below the level regarded as dangerous for an exposure of 1 hr (i.e. about 0.1 per cent).

# 3. DISCUSSION

## 3.1. EVALUATION OF TEST

Some comparison is possible with the results obtained by Stark and Hassan[2] using the smoke-sampling procedure on the Fire Propagation Test Apparatus. Thus, in tests lasting 20 minutes, the total flow of air and smoke past the density measuring point in their apparatus was about 0.75 $m^3$ (assuming an average gas temperature of about 80°C), and the integrated optical densities per metre for this volume, obtained from wood-fibre insulating board, were 2.2 for flaming combustion under standard conditions and 16.4 for smouldering combustion (conditions as in the present work). Allowing simply for dilution

3.1. (cont'd)

to the volume of the test chamber used in the present work, 33.7 $m^3$, these values correspond to optical densities of 0.048 and 0.35 respectively, which are comparable with the values of 0.041 - 0.048 and 0.46 - 0.49 ~~[illegible]~~ reported here for the corresponding modes of combustion (Tables 1 and 7). The good agreement between the results for flaming combustion suggests that, in fact, Stark and Hassan were sampling a high proportion of the smoke produced; their lower value for smouldering combustion is doubtless largely a consequence of their test, and the integration interval (20 min), not extending to the density maximum which, in the present work, occurred at 45 min.

The exposed area of the specimen in the Fire Propagation Apparatus is 0.0364 $m^2$, hence the value of the factor **V/AL** is 930 for the test equipment in the present work. The maximum specific optical density for smoke produced from wood-fibre insulating board under smouldering conditions, calculated from equation (1), is thus 428 - 456. The value reported by Gross et al[3] is 376 (V/AL = 96), i.e. about 13 per cent less. This can be regarded as reasonable agreement.

For flaming combustion there is a larger discrepancy between the results obtained here and those of Gross et al[3], the values for the maximum specific optical densities being respectively 38 - 45 and 146 (ref.3). This difference probably arises from a difference in the conditions for flaming combustion in the two tests. Thus, in the present work, the ratio of the maximum optical densities for smoke from smouldering and flaming combustion of wood-fibre insulating board is about 10, while for the results of Gross et al, the ratio is 2.6 which suggests less complete combustion of pyrolysis products under flaming conditions in their apparatus than in the Fire Propagation Test Apparatus.

It thus appears that, for comparable modes of combustion, measurements of smoke production employing different procedures, and on different scales, are capable of giving comparable results for a given material. This is subject to the limitation on scale imposed by the requirement that the oxygen concentration must not be allowed to become low enough to modify the combustion.

3.1. (cont'd)

The observations on the effect of dilution of the smoke are in agreement with those of Gross et al (whose results cover a wider range of optical densities) in showing that optical density is not strictly proportional to dilution. However, the effect of dilution appears to be sufficiently predictable to allow, at the least, considerable flexibility in the specification of the dimensions of test equipment.

It happened that, although uncontrolled, the relative humidity in the test chamber lay within narrow limits during at least part of this investigation. Since, however, the particle size of smoke can vary appreciably with relative humidity[6], it is possible that measurements of smoke production might show an unacceptable seasonal, or even shorter period, variation depending markedly on whether the test chamber is artificially heated or not. This is to be investigated further.

## 3.2. SMOKE RATING OF MATERIALS

The purpose of this test is to rate materials in order of smoke producing potentiality and so to assess their acceptability for use in different parts of a building from the point of view of the contribution they are likely to make to the total smoke production during a fire. This applies especially to the early stages of a fire in a building when escape routes should remain open as long as possible.

It is not appropriate here to attempt to define a smoke production index and acceptance limits, but it is desirable to summarise some of the factors which need to be taken into consideration in doing this.

### 3.2.1. Relation to fire growth

Fires commonly start in the contents of compartments in buildings and the amount of smoke accumulating within a compartment or spreading through open doors, etc., to the rest of the building will depend, in the earliest stages of a fire, on the amount and nature of the contents rather than on structural materials or decorative finishes of the compartment. These will contribute to smoke production at a later stage - almost certainly long after the compartment of origin has become untenable.

3.2.1. (cont'd)

Smoke production by structural materials and decorative finishes in the compartment of origin will be especially important during the spread of fire in a building if the fire in the compartment reaches an advanced stage before breaking out. When a fire breaks out of a compartment it becomes, in effect, a large source and combustible structural materials and finishes in adjacent corridors, landings, etc. will be rapidly involved; thus, they may be expected to make an almost immediate contribution to the total smoke production. The importance of this contribution will need to be assessed in relation to the smoke production by the already large compartment fire.

Thus, generalising, it is suggested that the acceptable level of smoke production by a given building material will need to depend on its position in the building in relation to the probable sequence of fire development in the building. Where significant involvement depends on the existence of an already large fire in other materials, this level can be correspondingly high.

Because they tend to be involved relatively late in the development of a fire, flooring materials might be permitted a higher level of smoke production than wall or ceiling linings.

Positive measures of smoke control in buildings such as smoke stop doors, ventilation and pressurisation will clearly modify acceptance levels for smoke production.

3.2.2. Mode of combustion

Evidence is being obtained[7] that the performance of a material in the Fire Propagation Test[1] can, in certain cases, give a valid indication of its contribution to the early stages of the development of a fire in a building. It is not safe, however, to conclude that smoke production by a material in the Test Apparatus under standard conditions will also run parallel to smoke production in practice. Depending on the proximity to the seat of the fire and on the air supply, and also on factors such as fire retardant treatments of materials, materials may be expected to contribute smoke as a result of simple pyrolysis, smouldering combustion, or flaming combustion, at different stages during the growth of a fire in a building.

3.2.2. (cont'd)

For these reasons it is desirable that the smoke rating of materials should include their behaviour under, at least, both smouldering and flaming combustion.

3.2.3. Smoke production index

The first requirement of a smoke index is that it shall give a measure of the smoke production potential of a material. For this purpose, the maximum optical density of smoke measured under cumulative conditions, as in this work, is appropriate - preferably converted to specific optical density as defined by Gross et al[3] (equation (1) above).

In considerations of smoke movement and dilution in buildings it is desirable to have also a measure of source strength, i.e. rate of production of smoke for different materials. The relevance of measurements based on the Fire Propagation Test Apparatus for this purpose, however, is uncertain.

Detailed analysis of the rates of smoke accumulation measured in this work has not been made at this stage. For present purposes it is sufficient to note that widely different maximum optical densities for different materials, were reached in similar times; i.e. 20-25 min for flaming combustion and 40-60 min for smouldering combustion. Broadly, therefore, the only information provided here is that high rates of smoke production are closely associated with high maxima, i.e. high smoke potentials.

The same result is evident in the data obtained by Gross et al[3], but in their apparatus a greater discrimination was obtained between different materials. Thus, at a given level for maximum optical density, maximum rates of increase of optical density varied between different materials by a factor of up to about 4. Inspection of the results obtained so far reveals no effect of comparable magnitude in the present work.

The rate of combustion and smoke generation under the conditions of these tests may be expected to be governed by the heat flux to the test material and the way this is modified by the combustion chamber during a test.

3.2.3. (cont'd)

Discounting the pilot flame, the applied heat flux to the specimen in the furnace used by Gross et al. was 2.5 $W/cm^2$. Under standard conditions of operation, this value is exceeded in the Fire Propagation Test Apparatus after about 5 min, the value at 20 min being about 5 $W/cm^2$ (heat transfer to asbestos wood)[8]. As the test material burns, however, the heat flux in the relatively enclosed combustion chamber of the Fire Propagation Test Apparatus can rise to much higher values (as yet, not measured) as the temperature rises. It is therefore possible that, in this apparatus, the rate of smoke generation is governed more by the properties of the combustion chamber than under the more "open" conditions of test used by Gross et al, differences between materials being correspondingly obscured.

For these reasons, it is suggested that, initially, the appropriate index of smoke production for a test based on the Fire Propagation Test Apparatus, is simply the maximum specific optical density.

A more detailed analysis of the observed rates can be made later if the feasibility of a rate index is considered to merit further study.

## 4. CONCLUSIONS

1. The cumulative method of assessing smoke production by materials under test in the Fire Propagation Test Apparatus is simple and could be used as a routine adjunct to the Fire Propagation Test itself without modification of the apparatus.

2. The principal requirement is a reasonably smoke-tight room with facilities for fan-stirring of the air and clearance of the smoke at the end of a test.

3. The relation of optical density to dilution is sufficiently linear to justify limited use of the specific optical density proposed by Gross, Loftus and Robertson. This allows flexibility in the choice of dimensions for the test equipment and provides a basis for estimating the practical significance of the measurements. The room volume used in this work with the Fire Propagation Test Apparatus (i.e. 33.7 $m^3$ (1200 $ft^3$)) resulted in smoke densities which were realistic in terms of visibility and is considered to be about right for purposes of a standard.

4. The factors needing to be most precisely specified are those controlling the combustion of the test specimen.

5. Repeatability of tests was satisfactory and comparable with that achieved by other workers[2, 3]; 95 per cent confidence limits for optical densities in 3-6 tests were usually within 20 per cent of the means.

6. The appropriate index of smoke production for a material in this test is considered to be the maximum value of the specific optical density.

7. Reproducibility between different laboratories using this test method is likely to be good, but should be checked.

## 5. ACKNOWLEDGEMENT

The authors are indebted to Mr. G. Ramachandran of the Statistics and Economics Section of the Fire Research Station for the experimental designs and for advice on the analysis.

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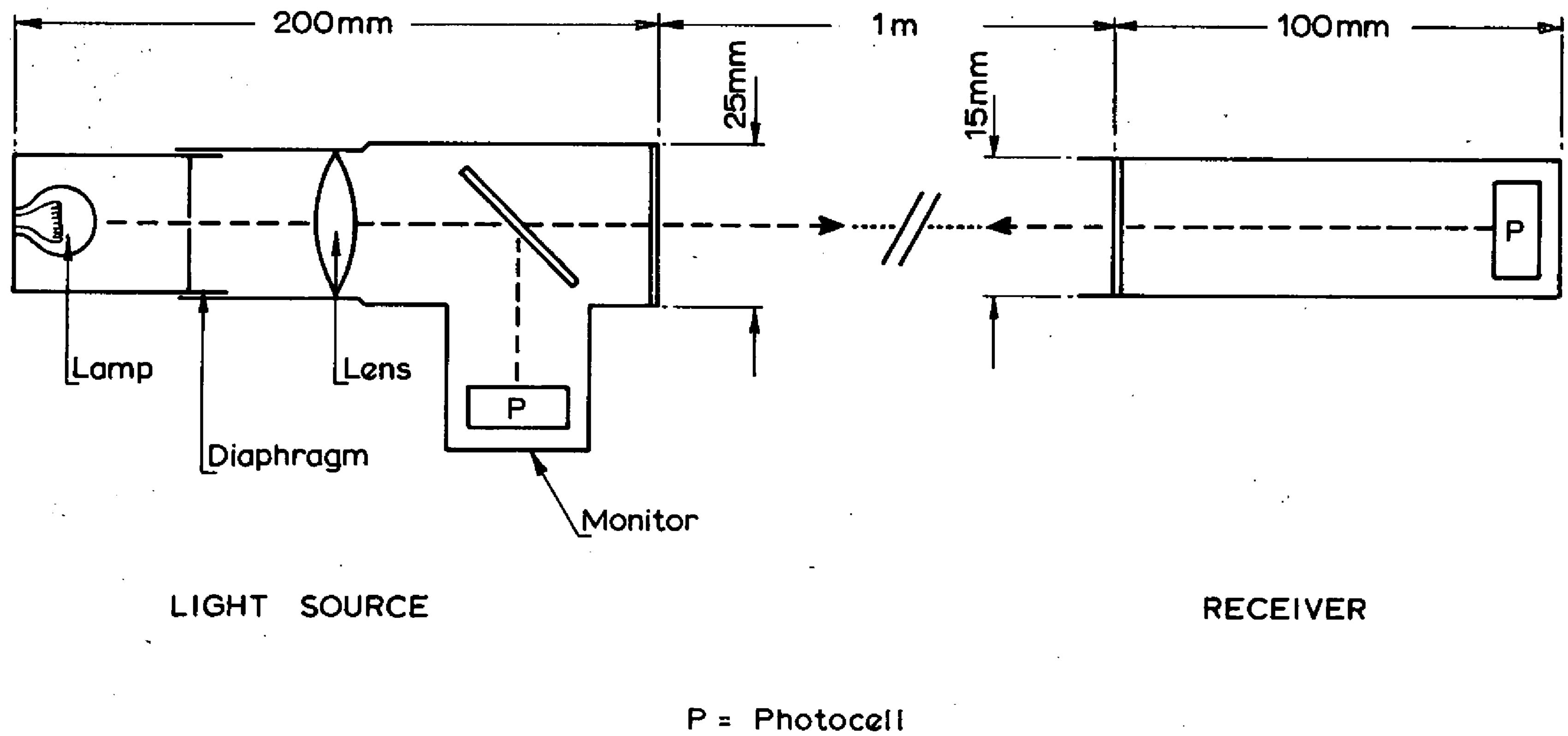



FIG. 1. OPTICAL SYSTEM FOR TRANSMITTANCE MEASUREMENTS

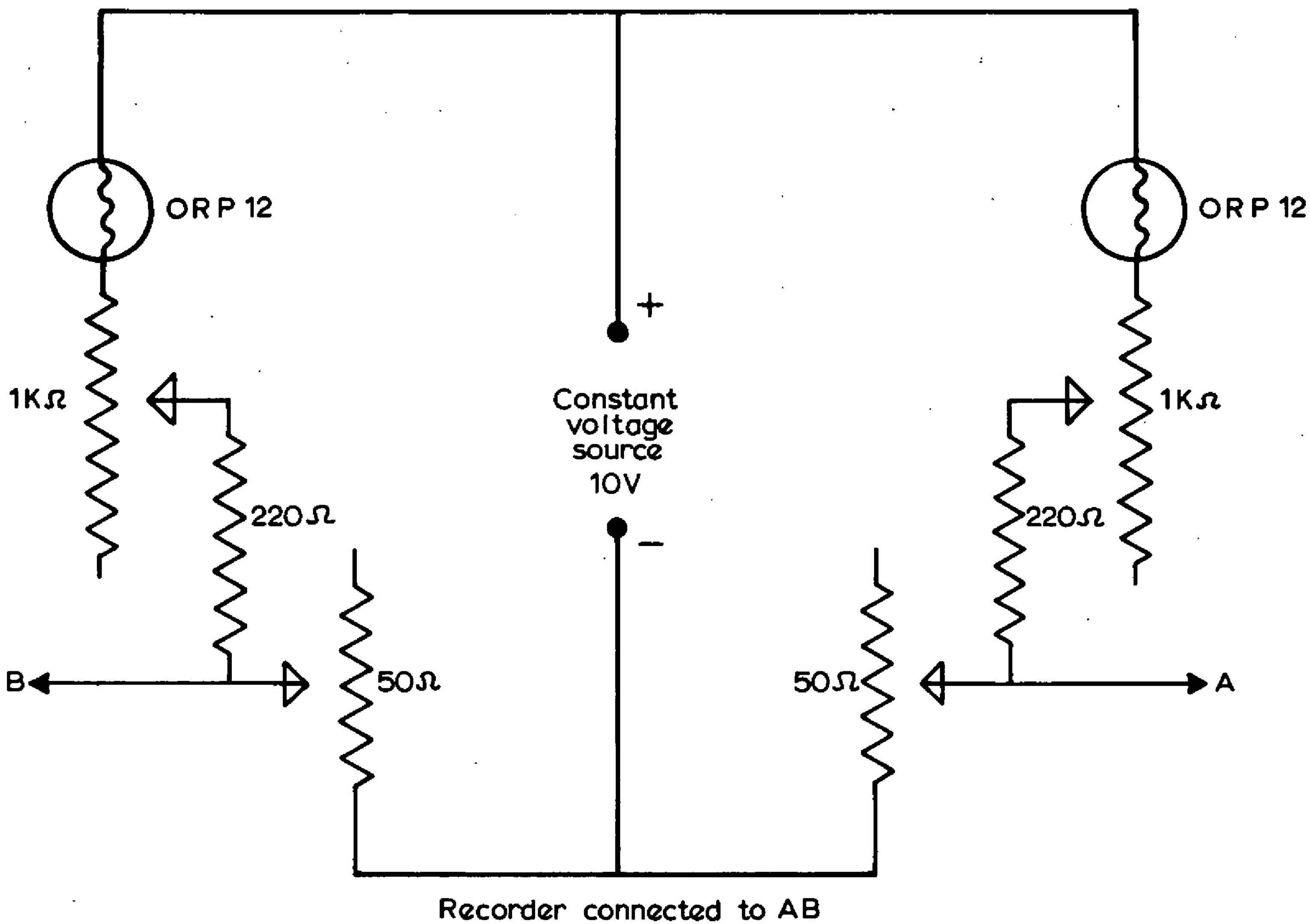
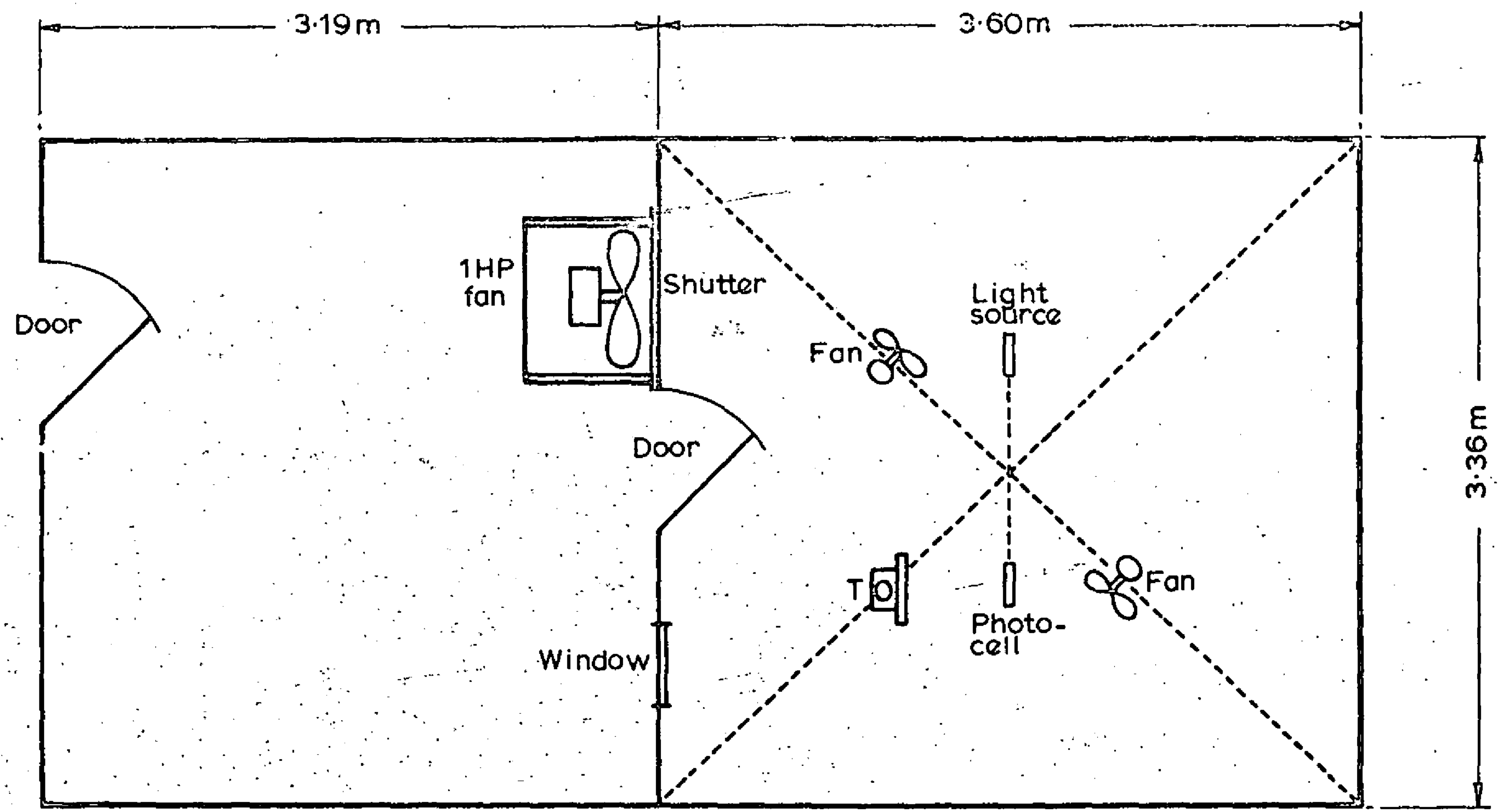



FIG. 2. PHOTOCELL BRIDGE




Height 2·79m T = Fire propagation test apparatus

FIG. 3. TEST CHAMBER GENERAL ARRANGEMENT (PLAN)

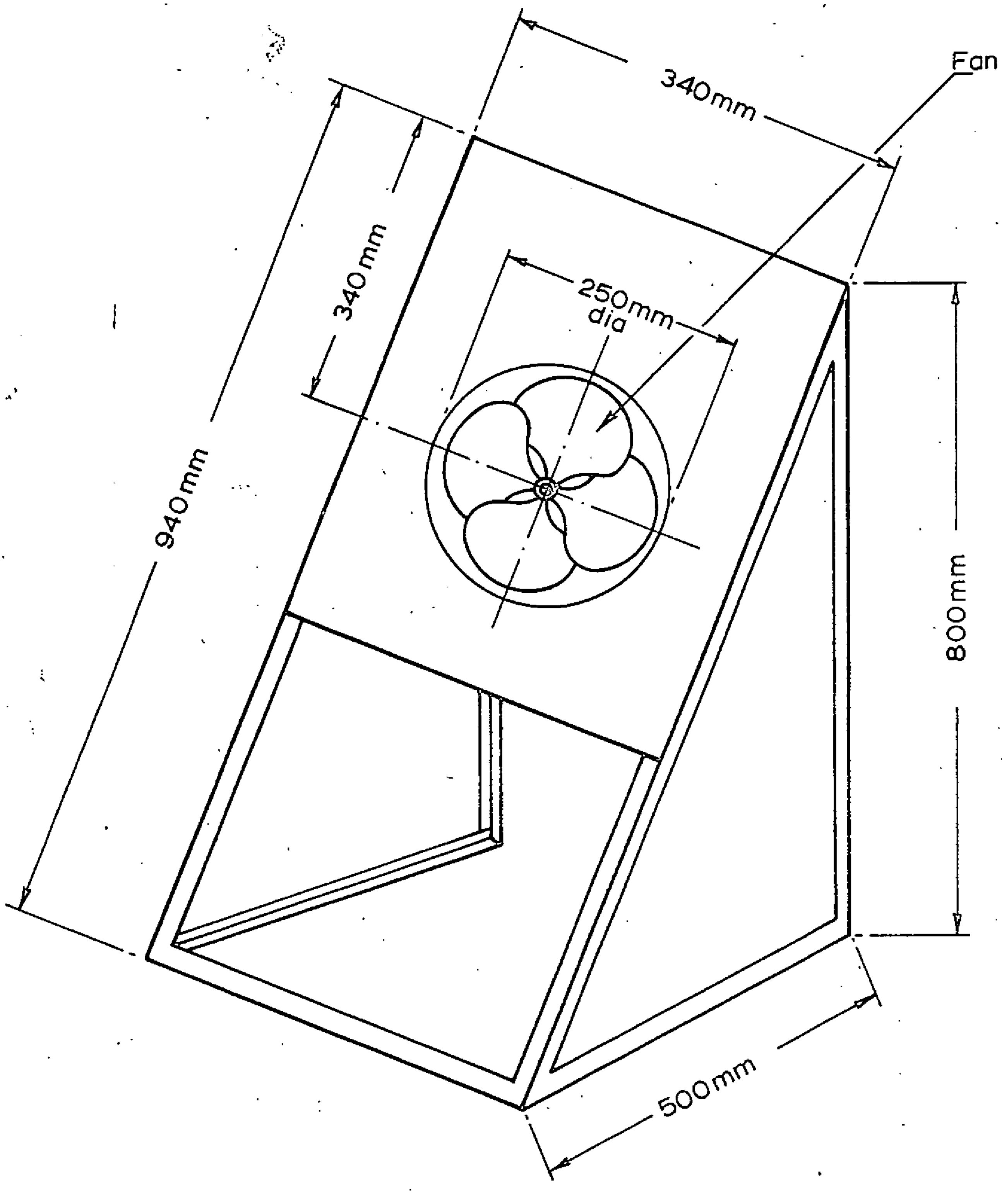



FIG. 4. FAN MOUNTING

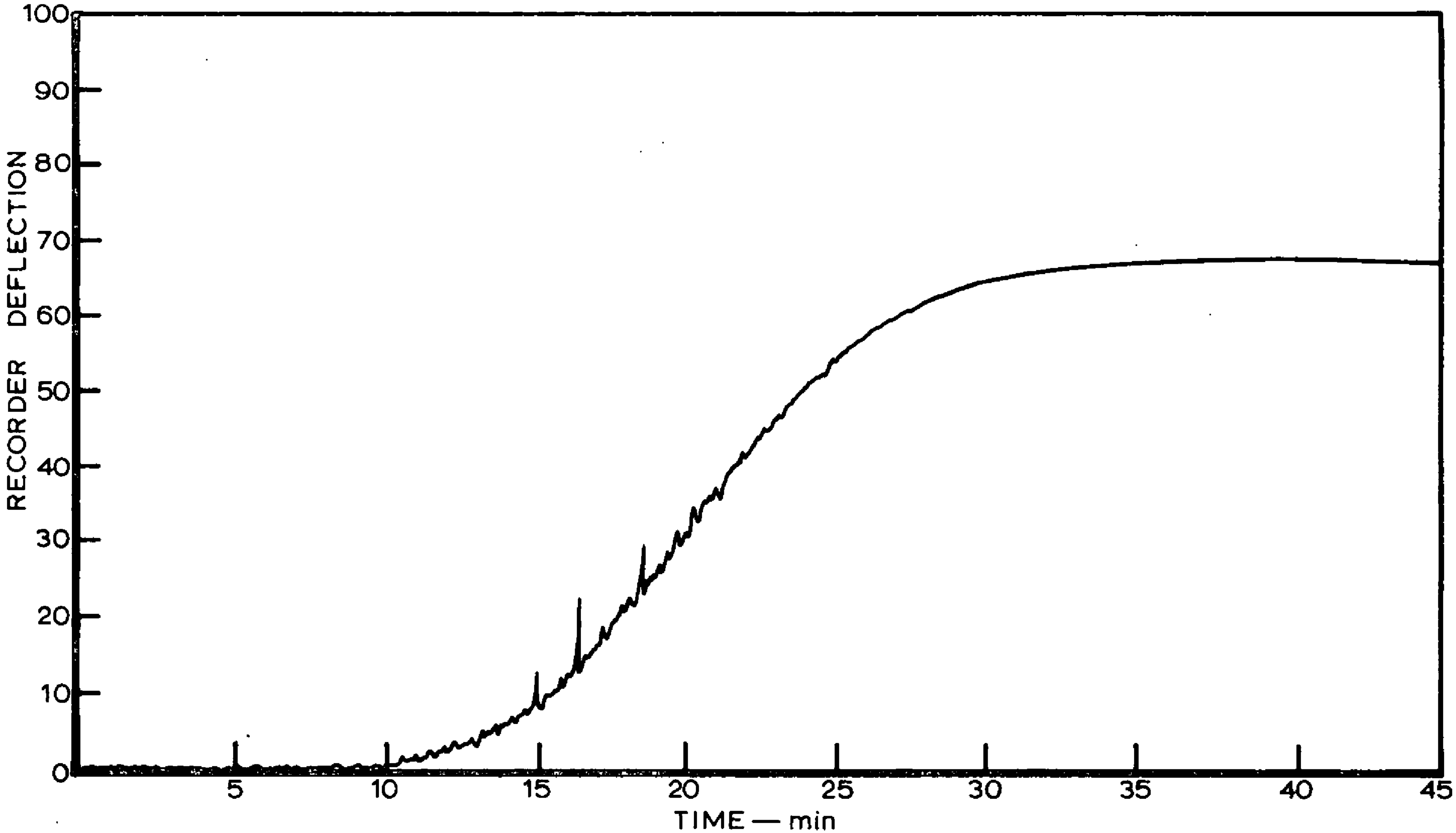
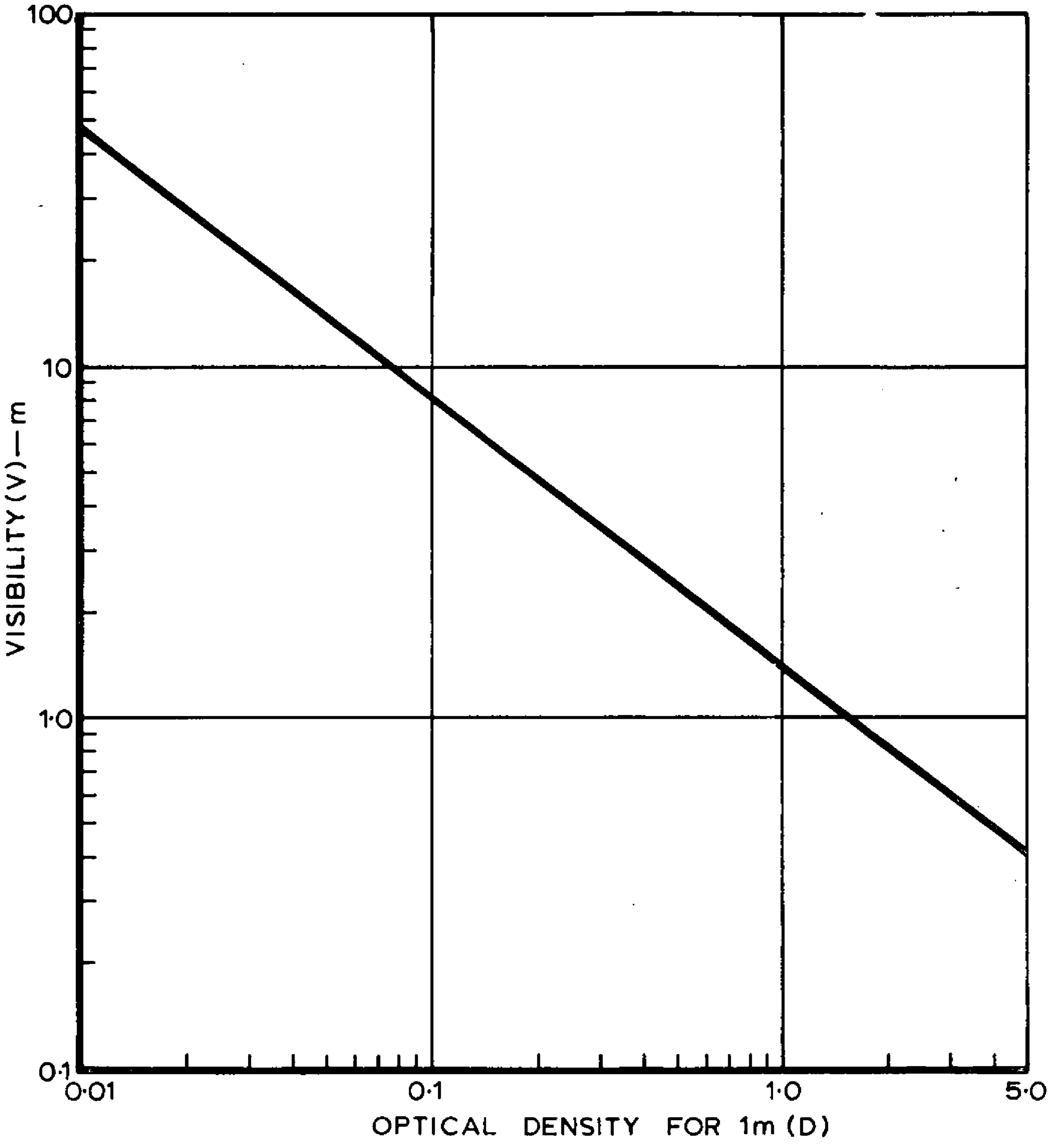



FIG. 5. TYPICAL RECORDER TRACE




$$V = \frac{1{\cdot}40}{D^{0{\cdot}767}}$$

FIG. 6. RELATION BETWEEN VISIBILITY AND OPTICAL DENSITY OF SMOKE (REF. 5)