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

1. Preliminary measurements of smoke production in the Fire Propagation Apparatus.

by

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SUMMARY

Tests have been made with a smoke measuring apparatus that can be attached to combustion chambers such as the Fire Propagation Test Apparatus. The results of tests with wood fibre insulating board and some plastics boards and sheets have indicated the salient factors that need to be met by a smoke measuring apparatus of this form for standard acceptance tests. These are the prevention of deposition of soot and consequent restriction of the smoke path, and adequate dilution and cooling of the smoke to ensure condensation of volatiles. It is also important that the material under test can be retained in the position where it is subjected to heat in the combustion chamber. The material under test should be subjected to a wide range of conditions of combustion to ensure that smoke measurements are made under conditions producing the densest smoke.

The extent to which the test, as developed so far, meets these factors is discussed, and the inherent limitations of the method are considered.



MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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## 1. Preliminary measurements of smoke production in the Fire Propagation Apparatus

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Increasing diversification in the combustible materials used for structural and finishing purposes in buildings, especially the introduction of materials based on plastics, may produce marked differences in the quantities and qualities of smoke and toxic products evolved during a fire. Cursory observation suggests that some of these materials produce smoke in quantities far in excess of those produced by traditional materials based on wood, and may seriously impair the chance of escape or rescue of the occupants of buildings involved in fire. There is therefore a need for a method of assessing the probable production of smoke and toxic matter when these materials are involved in fires, because of the effect of the smoke and gases on the visibility and toxicity of the atmosphere in escape routes. This note is concerned with the assessment of smoke; the question of toxicity is being considered elsewhere.

There is at present no accepted standard test in the United Kingdom for smoke from fires in building materials. As an initial approach to the problem of devising a suitable test, a request was received to examine the feasibility of measuring smoke production from samples undergoing test in the Fire Propagation Apparatus[1].

This note reports the results of some preliminary work undertaken with the objects of:

1. Devising a suitable method of measuring smoke produced during a test in the Fire Propagation Apparatus.
2. Determining the extent to which the standard operating conditions of the Fire Propagation Test are suitable for generating the full smoke producing potentialities of different building materials.
3. Determining the reproducibility likely to be attained.

### PROCEDURE

The following criteria were adopted for the design and operation of smoke measuring apparatus.

1. General

The light obscuring properties of the smoke is to be measured in terms of the attenuation of a light beam and the results expressed in terms of the optical density, because this can be related to visibility[2]. The luminous flux F after light of initial luminous flux $F_0$ has traversed a distance L of an attenuating medium is given by

$$F = F_0 e^{-kL} \qquad (1)$$

where k is a constant depending on the attenuating medium. The optical density D of length L of the medium is defined as

$$D = \mathrm{Log}_{10} \frac{F_o}{F} = \mathrm{Log}_{10} \frac{1}{T} = \frac{k}{2.303} L$$

where T is the transmittance through length L of the medium. Optical densities given in this note will be for a path length of one metre.

2. Preparation of sample

The smoke sampled from the Fire Propagation Apparatus is to be diluted to a known extent with clean cool air. This is desirable to ensure the condensation of the volatiles, including water, contributing to the smoke, and hence affecting its optical density(3). Further reasons for dilution include the approach to the practical condition of the dilution of smoke from a fire in a compartment as it disperses in a building and the avoidance of small transmittances which give small variations of optical density because of their logarithmic relation.

## APPARATUS

### General

The smoke measuring apparatus is shown diagrammatically in Fig. 1. It consists of a brass tube through which a mixture of smoke from the Fire Propagation Apparatus and clean air is drawn by means of a fan. The clean air is drawn from a place remote from the Fire Propagation Apparatus, to avoid contamination with smoke. The transmittance of the smoke bearing atmosphere in the tube is measured by a photometric system near the top of the brass tube.

### Smoke collecting and diluting system

Smoke is drawn into the large brass tube through a short, small diameter, tube inserted tightly into the cowl of the Fire Propagation Apparatus, Fig. 2. The ratio of smoke drawn from the apparatus and clean air is controlled by an orifice cap on the port admitting clean air. The flow of air through the air port and the smoke tube and their ratio, for a series of orifice caps is given in Table 1. The higher temperature of smoke entering the apparatus could alter this ratio.

TABLE 1

Ratio of Air to Smoke Entering the Smoke Measuring Apparatus

| Diameter of orifice cap cm | Diameter of smoke tube cm | Rate of flow through orifice cap ($R_1$) L/min | Rate of flow through smoke tube ($R_2$) L/min | $R_1/R_2$ |
|---|---|---|---|---|
| 3.49 | 0.49 | 264.7 | 4.69 | 56.9 |
| 3.18 | " | 220.6 | 5.36 | 41.2 |
| 2.54 | " | 141.0 | 6.52 | 21.6 |
| 1.75 | " | 66.7 | 7.76 | 8.6 |
| 1.27 | " | 35.3 | 8.33 | 4.2 |
| 0 | " | 0 | 8.33 | 0 |

All tests but one were made at a dilution ratio of 4.2

Photometric System

The photometric system adopted consisted of a potted selenium barrier cell (Megatron Ltd.) illuminated by a small electric lamp, the light from which traversed the tube through which the diluted smoke passed. A selenium barrier cell was chosen because such cells have a spectral response with the maximum at about the same wavelength as the human eye, although the decay in response on deviating from this wavelength is less rapid. The electric lamp was operated from a constant voltage supply system to minimise variation of luminous flux from the lamp. The photocell was connected in a circuit of external resistance of 100 ohms, stated by the makers of the photocell to give an output that varied linearly with the luminous flux falling on the photocell. A potentiometric recorder was connected across the 100 ohm resistance, so that the signal received by the recorder could be adjusted to an appropriate nearly full-scale deflection when the smoke tube was filled with clean air.

As the output of selenium photocells is affected by their temperature, a heat shield was placed between the Fire Propagation Apparatus and the photocell. However, it was found during tests that the output of the photocell was still affected, apparently by conduction through the brass smoke tube, and also by the chemical effects of some combustion products. An acceptable stability of the photocell was obtained by insulating it from the apparatus by means of a heat resistant plastic tube, and purging the space between the sensitive face of the photocell and a thin glass window in the plastic tube with a flow of cool air.

Diminution of the output from the photocell by the deposition of soot on the glass window or on the glass envelope of the electric lamp was avoided by the provision of narrow slots at the base of the attachment of photocell and bulb holders to the smoke tube. The small amounts of air drawn through these slots prevented soot deposition, but did not materially affect the length of the smoke path.

Modifications to the Fire Propagation Apparatus

The Fire Propagation Apparatus was modified to accept the smoke measuring apparatus by drilling a central hole in the top of the cowl into which the small tube of the smoke apparatus was a push fit, Fig. 2.

The effects of different conditions of combustion were examined first with the Fire Propagation Apparatus used with the test piece vertical as intended for incorporation in the British Standard 476. The only modification of the apparatus examined in these tests was a reduction in the area of the air vent at the bottom of the combustion chamber. Conditions of combustion were varied by using two levels of input of electrical energy, 0.6 and 1.5 kw, the latter being the standard condition, and two levels of town gas input: nil, and 0.53 kw, the latter being the standard condition.

Some difficulties arise in the testing of certain materials which either melt or delaminate in the standard Fire Propagation Apparatus. Materials which melt, such as thermoplastics, flow away from the radiant sources and on occasion block the jets of the town gas burner; also in melting they may sag and come into contact with the radiant electrical heating elements, affecting their output. Materials which delaminate, such as certain pressed building boards, may shed flakes which fall below the radiant sources, and may also bulge and come into contact with them. These effects were avoided or diminished by reorientating the Fire Propagation Apparatus, so that the test specimen was held horizontally. Modifications used in the present series of tests are illustrated in Figs 3A and B. The use of the apparatus with the specimen held horizontally avoided the loss of materials referred to above but did not completely prevent the upward bulging of the specimen. The tests were therefore made with the electrical radiant elements sheathed with thin transparent silica tubes to avoid contamination of the radiant elements by the material of the test pieces.

When the apparatus was reorientated in this manner, it was found that the form of gas burner and air vent used in the vertical apparatus, Fig. 3A, led to the loss of gases and flames through the vent; these were therefore repositioned and altered in shape, Fig. 3B, to avoid such losses.

## RESULTS

### Performance of Standard and Modified Fire Propagation Apparatus

The performance of the standard and modified versions of the Fire Propagation Apparatus were determined by trial runs in which pieces of asbestos board were subjected to the thermal test. The variation in flue temperature with time is shown in Fig. 4. Some differences were observed between the temperatures attained when the finished surface or the back surface were exposed to the sources of heat. All subsequent tests were therefore made with the finished surface of the test piece exposed, where there was a difference between the two surfaces of a specimen.

When the curves in Fig. 4 are brought to a common origin on the temperature scale, it is seen that the operation of the smoke apparatus reduced the temperature after twenty minutes by about 20°C, (the proposed specification limits are ± 15°C). The horizontally orientated Fire Propagation Apparatus gave a further reduction in the temperature at twenty minutes of about 20°C. The reduction of the thermal input to 0.6 kw electricity produced much lower final temperatures, the temperature rise after twenty minutes operation being 114°C and 90°C respectively for the vertically and horizontally orientated forms of the apparatus. It was also observed that there was a negligible difference in final temperatures between the apparatus operated with unprotected electrical elements and with the elements protected by silica sheaths.

### Experiments with Wood Fibre Insulating Board

Typical records of the transmittance and temperature during tests with the vertical and horizontal forms of the apparatus are given in Figs. 5 and 6 respectively. The results obtained from groups of five tests using wood fibre insulating board as the combustible material are given in Table 2; the table includes relevant information on the form of apparatus and energy input and mean values of the maximum optical density and the integrated optical density for the duration of test together with the coefficients of variation (C.V.) of these mean values. (The coefficient of variation is the standard deviation expressed as a percentage of the mean value of a sample). The integrated optical density was obtained by summing the optical densities for each minute of test. Smoke production sometimes occurred for periods longer than the specified Fire Propagation Test time of twenty minutes, particularly when the energy input was low; the longest time recorded was 46 min, for a test in the horizontally orientated apparatus with 0.6 kw electrical energy input in which no flaming combustion occurred.

The highest optical densities were obtained when the lowest energy input, 0.6 kw electricity, was used in the horizontally orientated Fire Propagation Apparatus. Loss of combustible material, which fell from the delaminating specimen during tests, probably contributed to the variation from the mean values, Table 2, obtained with the vertical apparatus. The emergence of flames and smoke from the ventilation slot probably accounted for some of the variation from the mean obtained in tests with the first form of the horizontally orientated apparatus, Fig. 3A. This loss was avoided by using the second form of apparatus, Fig. 3B. Also some variation was probably caused by differences in the burning of the individual test pieces. The last group of tests in Table 2 call for special comment; smouldering combustion only occurred in two of these tests; but in the remaining three tests the fumes ignited after a time and flaming combustion was established (Fig. 6). The results for individual tests in this group are given in Table 3. Although there are insufficient results to permit viable calculations of variance for each condition of combustion, there is an indication that the integrated optical density differed according to the mode of combustion in the tests. The maximum optical density was less likely to be affected, because maximum smoke evolution occurred before the vapours ignited.

The colour of the smoke emerging from the apparatus during tests at the lowest energy input, (0.6 kw electricity only) was whitish, but was a greyish white during the remaining tests. None of the tests produced black smoke, although small amounts of soot were deposited in the chimney of the Fire Propagation Apparatus during tests at the highest energy inputs.

The reduction in the size of the air vent of the Fire Propagation Apparatus increased the maximum optical density, but reduced the integrated value. As the changes in optical density of the combustion products so produced were smaller than those produced by changes in the thermal energy input, and the orientation of the apparatus, this kind of modification was not proceeded with. The attenuation of light by smoke from the tests in the vertical apparatus at 0.6 kw electrical energy input only, over a distance of one metre, was a hundred times greater than the attenuation by smoke from the apparatus operated at the standard energy input of gas and electricity. When the Fire Propagation Apparatus was orientated horizontally and operated at the standard energy input conditions, the attenuation was three times greater than that obtained with the similarly

TABLE 2

Smoke Measurements with Wood Fibre Insulating Board

| Test Nos. | Orientation of apparatus | Energy Input kw | | Smoke measurements | | | |
|---|---|---|---|---|---|---|---|
| | | | | Maximum optical density | | Integrated optical density | |
| | | Gas | Electricity | Mean | C.V. | Mean | C.V. |
| 14-18* | Vertical | Nil | 0.6 | 4.98 | 7.4 | 13.6 | 13.8 |
| 19-23 | " | Nil | 0.6 | 2.99 | 6.0 | 16.42 | 8.1 |
| 24-28 | " | 0.53 | 1.5 | 1.08 | 29.0 | 2.18 | 12.9 |
| 60-65 | Horizontal, Fig. 3A | 0.53 | 1.5 | 3.14 | 15.9 | 11.20 | 18.4 |
| 79-83 | " " | Nil | 1.5 | 1.51 | 15.9 | 7.88 | 6.1 |
| 84-88 | " " | Nil | 0.6 | 5.54 | 6.7 | 33.0 | 6.6 |
| 92-96 | " Fig. 3B | 0.53 | 1.5 | 1.96 | 16.0 | 8.78 | 6.3 |
| 98-102 | " " | Nil | 0.6 | 4.64 | 6.0 | 34.94 | 11.8 |

*Tests with restricted air vent; area reduced to 1.6 $cm^2$

TABLE 3

Smoke Measurements with Wood Fibre Insulating Board
Horizontal Fire Propagation Apparatus;
energy input 0.6 kw electricity only

| Test No. | Smoke measurements | | Maximum flue temperature °C | Ignition of fumes |
|---|---|---|---|---|
| | Maximum optical density | Integrated optical density | | |
| 98 | 4.96 | 40.12 | 207 | No |
| 99 | 4.77 | 32.64 | 299 | Yes |
| 100 | 4.27 | 38.6 | 191 | No |
| 101 | 4.77 | 31.08 | 272 | Yes |
| 102 | 4.44 | 32.26 | 251 | Yes |

operated vertical apparatus, and one thousand times greater when operated at an energy input of 0.6 kw electricity only.

The integrated optical density was very much greater, for all variations from the standard form and operation, than for the standard form and operation of the Fire Propagation Apparatus.

The smoke generated in the above tests did not block the small diameter smoke tube. Although provision was made to heat this tube to prevent condensation, it was not found necessary to heat the tube for the thermal conditions tested. The soot deposited during the tests at high energy input did not block the tube, but the tube was lightly tapped during the tests to prevent blockage.

## Experiments with plastics boards and sheets

Tests were made using the vertical form of apparatus with poly (vinyl chloride) sheet of 1.5 and 3 mm thickness, poly (methyl methacrylate) sheet of 6 mm thickness and expanded polystyrene board of 25 mm thickness.

The smoke from the poly (vinyl chloride) sheet increased the output from the photocell when it was operated with its sensitive face protected only by the air leak which prevented soot from entering the side tubes. An exploratory test with poly (methyl methacrylate) sheet gave a similar result, but this may have been due to residual contamination from previous tests with poly (vinyl chloride). No such effect was observed with the polystyrene board. This increase in sensitivity of the photocell was avoided by placing a glass window some distance from the face of the photocell and purging the space so formed with clean air.

The results obtained with polystyrene board prior to the above modification of the smoke apparatus and those obtained with poly (vinyl chloride) after modification are given in Table 4. The mean maximum optical density obtained with polystyrene board is not much greater than that obtained with wood fibre insulating board, but the weight of combustible matter is much less. (Weight of wood fibre insulating board test piece 160 g, weight of polystyrene board test piece 20 g). The test piece ignited immediately the town gas was ignited, melting and sagging to the bottom of the Fire Propagation Apparatus in a few seconds, and giving off black sooty smoke.

The mean maximum optical density obtained with the poly (vinyl chloride) sheet was from 10 to 12 units greater than was obtained with wood fibre insulating board. In these tests the smoke tube became partially blocked with black soot, but this was cleared readily by lightly tapping the smoke tube. However, because of this, integration of the optical density would give unreliable results, and this calculation was not made. It was observed

TABLE 4

Smoke Measurement with Plastics. Vertical Fire Propagation Apparatus; energy input 0.53 kw gas and 1.5 kw electricity

| Test No. | Material | Smoke measurements | |
|---|---|---|---|
| | | Maximum optical density | Integrated optical density |
| 30 | 25 mm Polystyrene | 0.91 | 6.26 |
| 31 | " " | 1.47 | 5.26 |
| 32 | " " | 1.82 | 9.14 |
| 33 | " " | 1.24 | 6.50 |
| 34 | " " | 1.35 | 6.04 |
| 35 | " " | 0.75 | 6.54 |
| 50 | 3 mm Poly(vinyl chloride) | 11.85 | Not calculated |
| 51 | 1.5 mm " | 13.06 | " " |
| 52 | 1.5 mm " | 11.80 | " " |

during these tests that the sheet plastic softened and swelled and approached very closely to the electrical heating elements.

Tests were continued with the horizontally orientated Fire Propagation Apparatus, to avoid losses of molten plastics and reduce the approach of the heated specimen to the electrical heating elements. The results obtained with expanded polystyrene board 25 mm thickness and flexible expanded polyurethane sheet 19 mm thickness are given in Table 5. Two values of maximum optical density are given for one of the tests with expanded polyurethane sheet. The smaller value is that of the smoke produced in the early stage of the test, while the test piece was melting and collapsing; the vapours from the test piece ignited 6 min afterwards, giving a rapid increase in smoke density, to the larger value, for a short time. The second test piece did not ignite, the optical density being similar to that obtained from the first test piece prior to ignition.

TABLE 5

Smoke Measurements with Plastics

Horizontal Fire Propagation Apparatus;
energy input 0.53 kw town gas and 1.5 kw electricity

| Test No. | Material | Maximum optical density | Comment |
|---|---|---|---|
| 55 | 25 mm expanded polystyrene | 5.9 | Actual dilution ratio 8.6. Optical density calculated for dilution ratio 4.2. Specimen ignited. |
| 56 | " " | 5.5 | Specimen ignited |
| 57 | " " | 6.2 | " " |
| 58 | 19 mm foamed polyurethane | 1.94<br>0.29 | Second peak after flaming<br>First peak before flaming |
| 59 | " " | 0.29 | First peak, no flaming |

The results for tests 55, 56 and 57 suggest that the differences in dilution used do not materially affect calculations of optical density.

Tests were then made using a paper filled phenol-formaldehyde resin sheet of 6 mm thickness. During tests under the standard thermal condition in the horizontal apparatus, copious amounts of dense sooty black smoke were formed, which could not be dislodged from the chimney of the Fire Propagation Apparatus or the smoke tube. The small diameter smoke tube was reduced in length to 1 mm in an attempt to prevent soot deposition obstructing the transfer of smoke from the chimney to the smoke measuring apparatus but without success. No meaningful measurements of smoke density were therefore possible.

## DISCUSSION

The present work was undertaken to examine the feasibility of using the Fire Propagation Apparatus as the basis of a standard smoke test; this depends on finding appropriate means of transferring smoke from the Fire Propagation Apparatus to a suitable smoke measuring device. Such a test should make fair assessments of the smoke producing potential of building materials in fires and hence should be capable of operating over a range of conditions of burning embracing those occurring during fire incidents. This is important because different materials may generate their most dense smoke under different conditions of burning. For example, in the present tests wood fibre insulating board generated dense smoke when it smouldered in a low temperature environment, whereas under the same conditions expanded polystyrene vaporised, producing little obscuration. However, in higher temperature environments, when ignition had occurred, the smoke from the burning polystyrene was much denser than that from wood fibre insulating board. The burning conditions of test pieces in the Fire Propagation Apparatus can be varied by using different inputs of electrical energy and town gas to vary thermal conditions.

The work reported here has shown that, provided the range of thermal conditions is extended to ensure, on the one hand, smouldering of materials without ignition, and on the other, more vigorous burning than at present attained, the Fire Propagation Apparatus may be a suitable combustion chamber for the measurement of smoke production. The method of measuring smoke appears to be satisfactory, but the method of sampling requires further study in order, firstly, to prevent soot deposition affecting optical measurements, and secondly, to reduce the temperature of smoke at the point of measurement to the levels found in practical situations. The reproducibility attained (Table 2) is probably sufficient for the acceptance testing of materials.

If the materials at risk are the wall linings of escape routes, it may be desirable to operate the Fire Propagation Apparatus with the test piece of material vertical. In this case some mechanical retention of the test piece would be necessary, for example by wire gauze.

The results of standard tests should be indicative of conditions likely to arise in fires in buildings. These could range from the passage of smoke through the escape route without retention, to the complete retention of smoke in the escape route. The first condition is indicated by the direct readings of optical density, and the maximum optical density as given herein would be a suitable measurement. The condition arising from the complete retention of smoke in an escape route is indicated by the integrated optical density given herein, because optical density is directly related to the number of particles and their diameter[3]. Thus, provided that the smoke at the point of measurement is cool and all condensible matter has been condensed, the integrated optical density is a measure of the total particulate matter at maximum particle diameter but with minimal aggregation, from which the optical density in a fixed volume could be calculated.

An alternative approach would be the adoption of an apparatus in which a specimen of material was burnt in an enclosed space, the optical density of the atmosphere in the space being recorded continuously[4, 5]. With this kind of measurement, the rate of smoke production is given by the slope of the curve for optical density with time, and the maximum rate by the maximum slope. The maximum value of optical density recorded indicates the maximum obscuration obtained from the totally retained smoke under the experimental conditions.

Correlation of the results obtained with either form of apparatus with the conditions arising in fires in buildings would require the performance of some full-scale tests on appropriate building materials, with sufficient instrumentation to measure the thermal conditions to which the materials are subjected.

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(4) GROSS, D., LOFTUS, J. J. and ROBERTSON, A. F. "A method for measuring smoke from burning building materials." Paper presented at the 69th Annual Meeting of the American Society for Testing and Materials. Atlantic City, N.J., U.S.A.

(5) "A method of measuring smoke density." N.F.P.A. Quarterly, Jan. 1964.

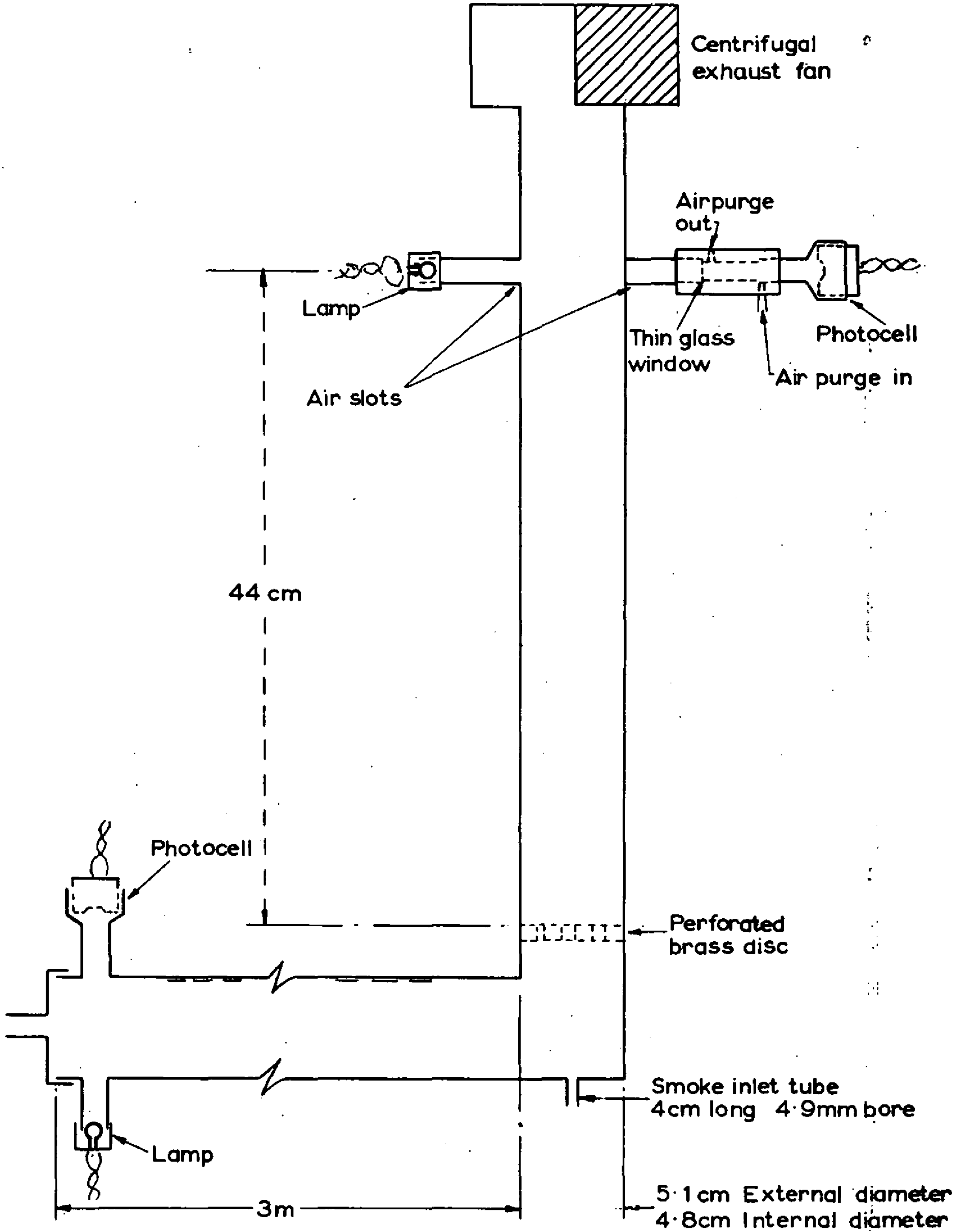


FIG. 1. SMOKE MEASURING APPARATUS

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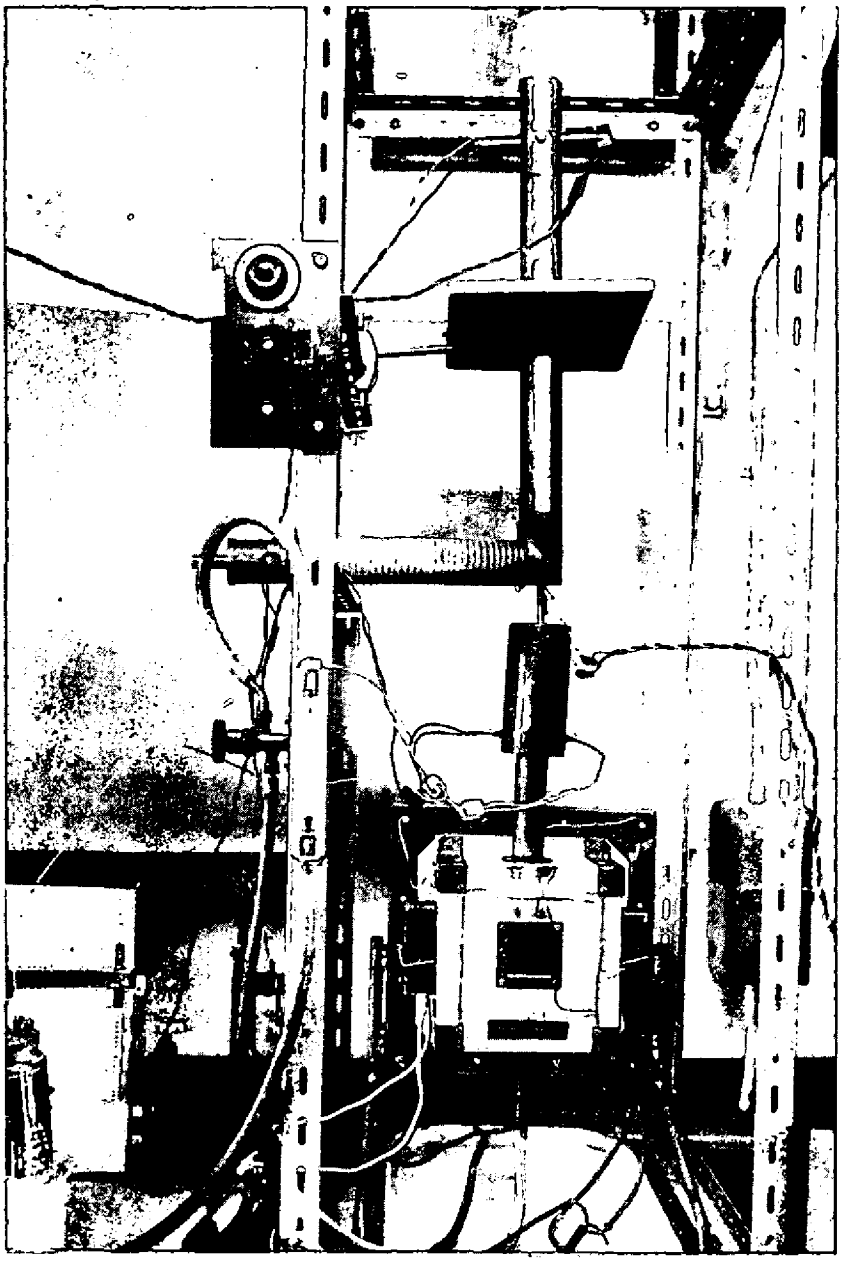

FIRE PROPAGATION APPARATUS WITH
SMOKE APPARATUS ATTACHED

FIG. 2.

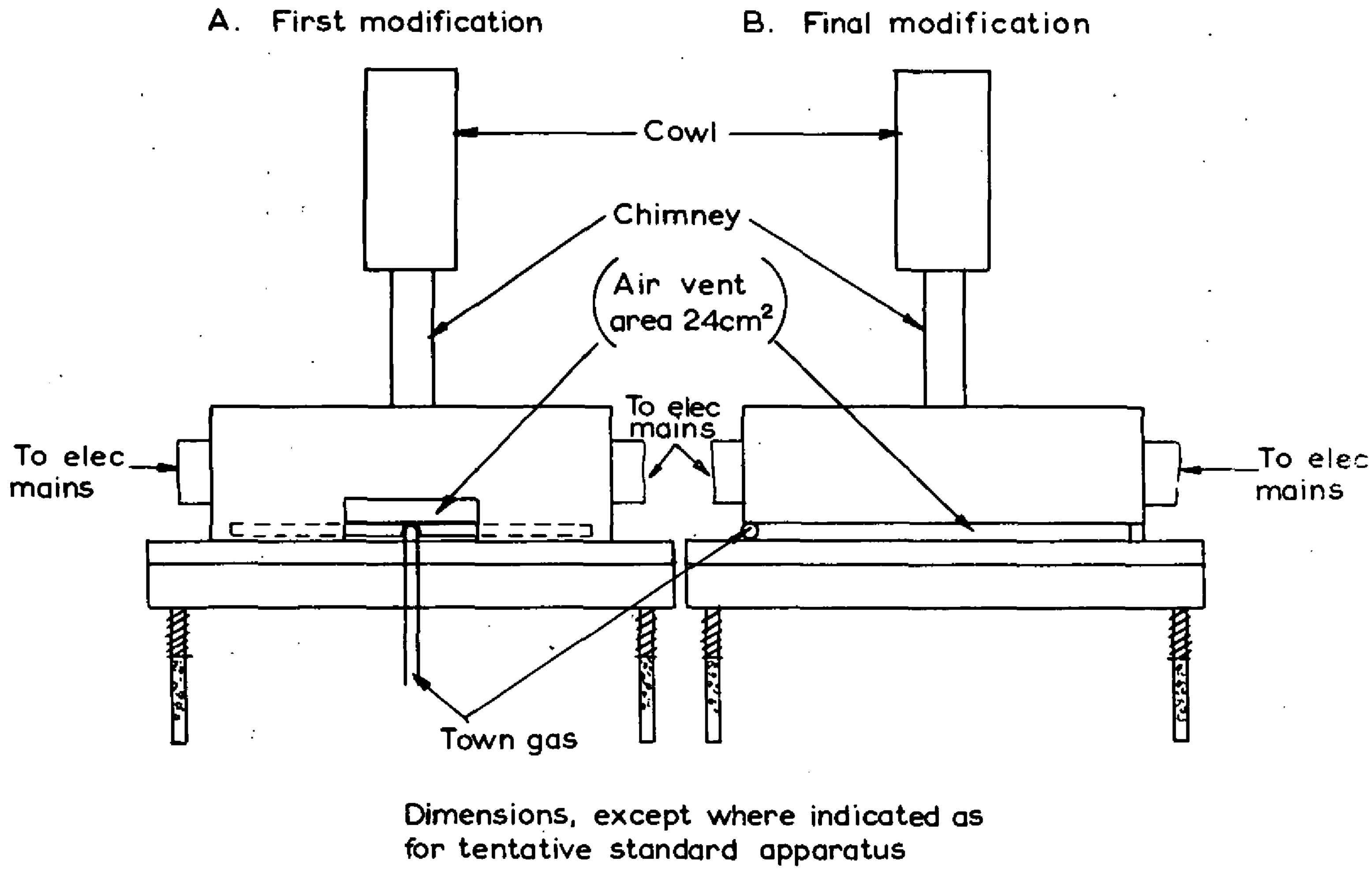


FIG. 3. MODIFICATIONS OF FIRE PROPAGATION APPARATUS. HORIZONTAL ORIENTATION

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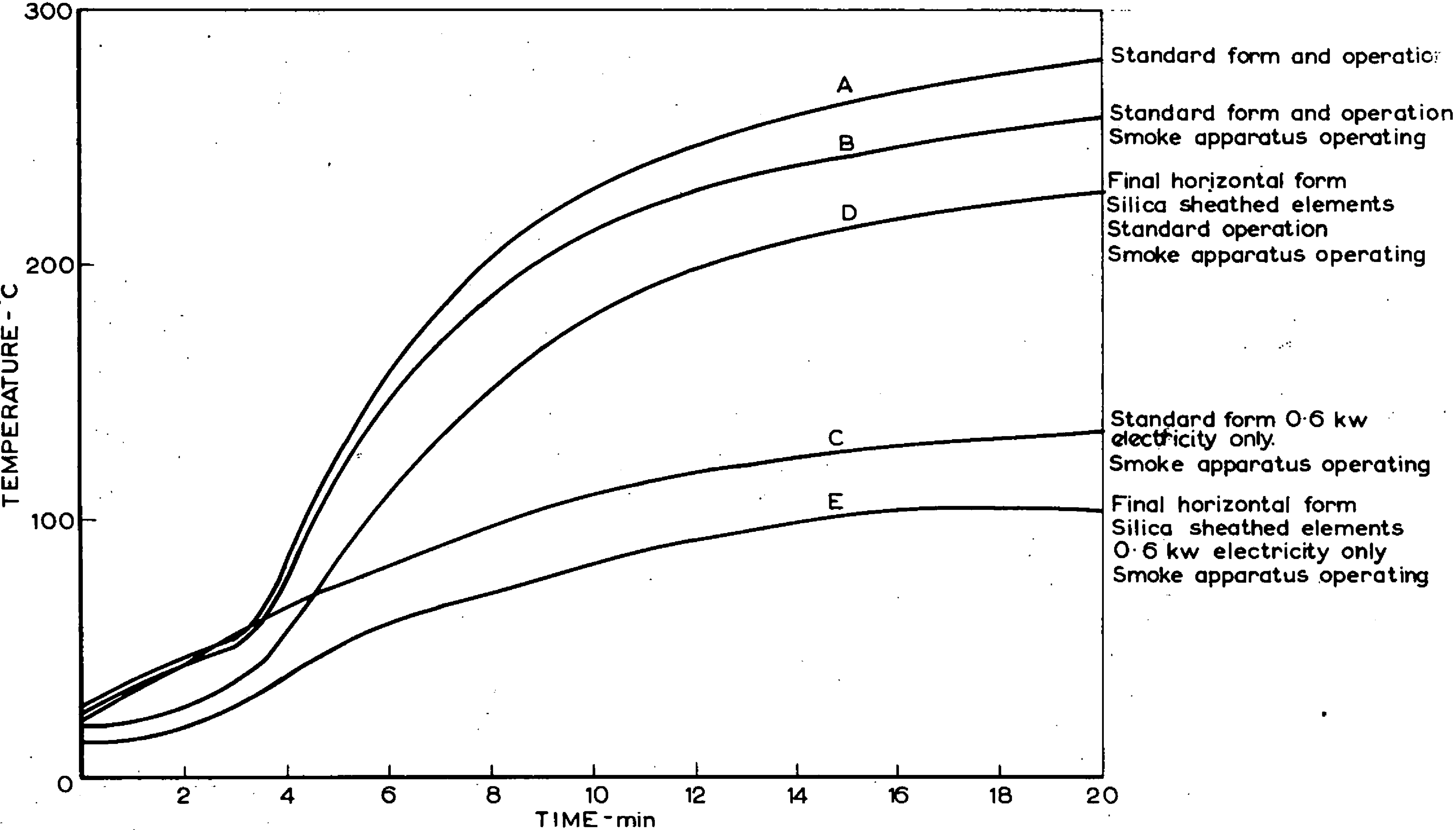


FIG.4. EFFECT OF ENERGY INPUT AND ORIENTATION OF FIRE PROPAGATION APPARATUS ON FLUE TEMPERATURES

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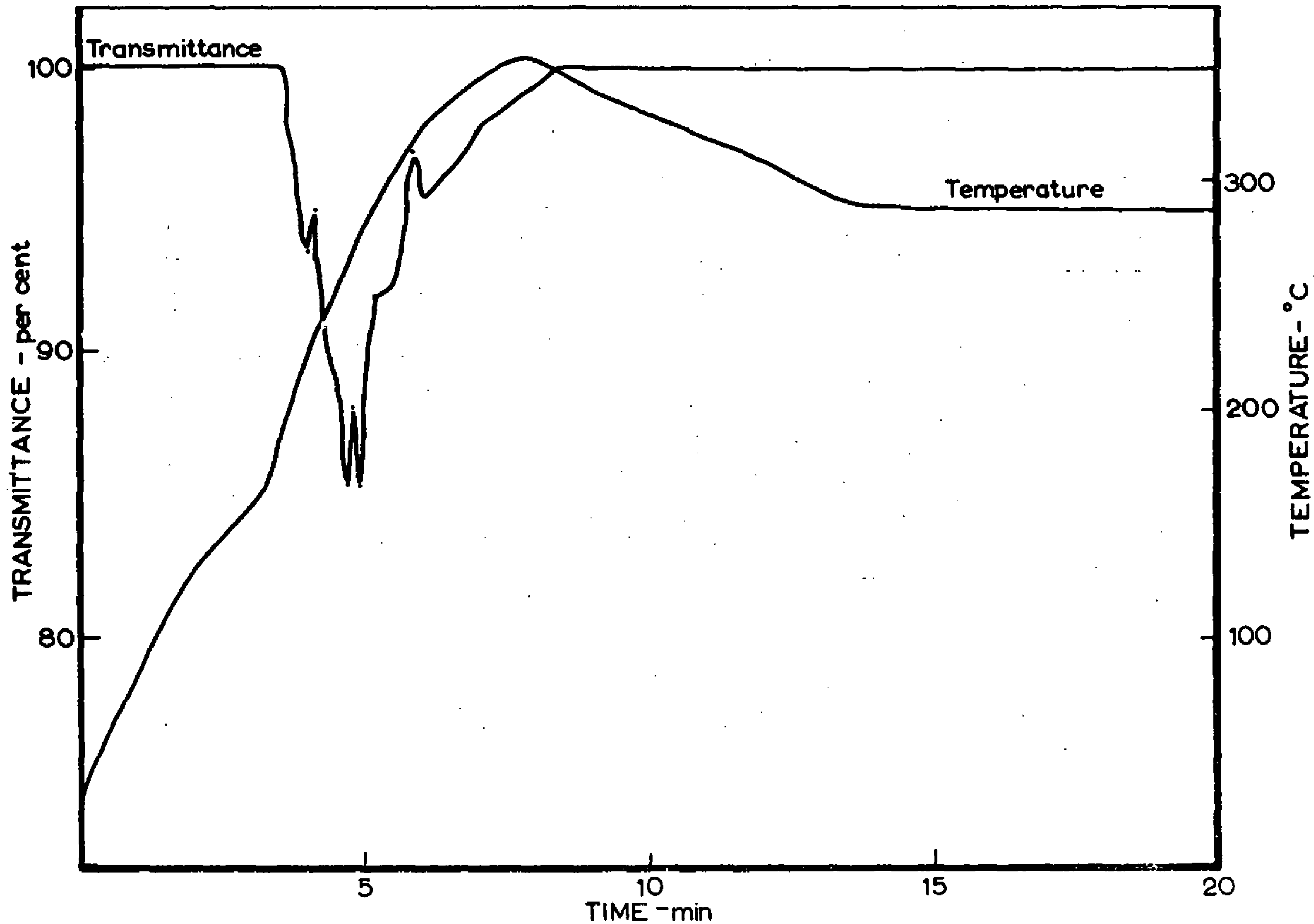


FIG. 5. LIGHT TRANSMITTANCE, TEST No 27 VERTICAL APPARATUS STANDARD CONDITIONS

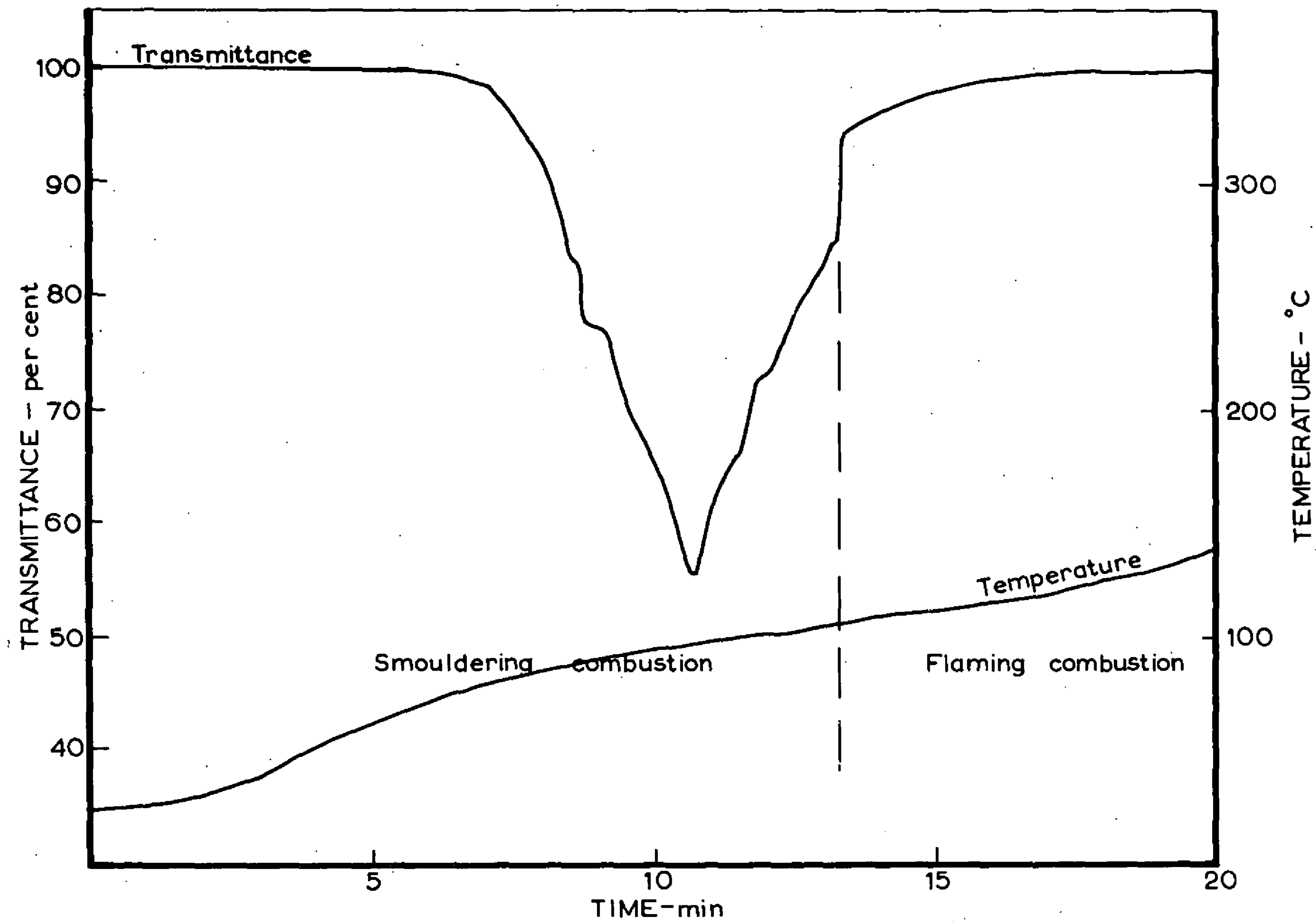


FIG. 6. LIGHT TRANSMITTANCE TEST No 101 HORIZONTAL APPARATUS
0·6 KW ELECTRICITY ONLY