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No. 775

THE ASSESSMENT OF SMOKE PRODUCTION BY BUILDING MATERIALS IN FIRES

3. The effect of relative humidity on measurements of smoke density

by

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THE ASSESSMENT OF SMOKE PRODUCTION BY BUILDING MATERIALS IN FIRES
3. THE EFFECT OF RELATIVE HUMIDITY ON MEASUREMENTS OF SMOKE DENSITY

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CORRECTION

Correction in Table 5, affecting Table 3, to be made as follows:

Table 5 (p.15) 2nd column, change 38.8 to 36.6
3rd column, change 4.4* to 2.2

Table 3 (p 7) 3rd column, change 0.406 to 0.450
5th column, change 22* to 10

p.8, 1st paragraph requires consequent amendment and extension as follows:

"It will be seen from Table 3 that the increase in relative humidity has increased the optical density of the smoke significantly for only one of the four possible board/mode of combustion combinations.

This result is consistent with the presence of significant HBC interaction (Table 2) and the absence of HC interaction. However, the absence of significant HB interaction suggests that the significance test adopted for the differences in Table 5 (Appendix 3) may be somewhat conservative and the difference for the chipboard under flaming conditions (corresponding to 10 per cent increase in optical density, Table 3 as amended) may in fact be significant."

THE CONCLUSIONS ARE NOT AFFECTED

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SUMMARY

It has been shown that the relative humidity of the ambient atmosphere can sometimes affect significantly the optical density of the smoke produced by materials in the fire propagation test apparatus.

Some control of the relative humidity in the test chamber will be necessary for the purposes of a standard test for smoke production.

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

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INTRODUCTION

A previous note[1] describes a proposed method for comparing the probable smoke production by different materials in fires by measuring the optical density of the smoke produced in a closed compartment when samples of material are burned under specified conditions. In the development of the method, the temperature of the compartment in which the smoke was collected was controlled closely (± 1 deg C) and the relative humidity did not vary widely.

However, it is known that the radius of combustion nuclei can depend markedly on the relative humidity of the atmosphere[2, 3]. Therefore, in proposing a method of smoke assessment based on measurement of optical density, it is important to determine the extent to which relative humidity needs to be controlled in order to keep this source of variation within reasonable limits. Otherwise, assessments for a given material might depend on extraneous factors such as the season of the year and the degree of artificial heating of the laboratory in which the test is carried out.

The dependence of particle radius on relative humidity has been calculated by Wright[2] from consideration of the vapour pressure equilibrium of spherical hygroscopic particles. For combustion nuclei in the atmosphere (Kew) having radii of order 10^{-6} cm*, the radius can increase by a factor of about 2 for an increase in relative humidity from 30 per cent to 90 per cent. As saturation is approached, the extent of the increase in radius becomes

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*Typically "smokes" have particles of size $< 10^{-4}$ cm (B.S.2955 : 1958, Glossary of terms relating to powders). Smokes from fires may include tarry pyrolysis products extending in size to visible droplets and also large flocs of soot.

greater. These effects are less for larger particles.

The effect on the optical density of smokes in general will depend on the particle size distribution, composition and concentration, and cannot readily be predicted by calculation.

This note describes an experimental investigation of the effect of relative humidity on the optical density of smoke measured under the condition of the proposed standard test[1].

EXPERIMENTAL

PRACTICAL

As previously[1], 228 mm square samples of board were burned in the Fire Propagation Test Apparatus[4] in a smoke-tight room of volume 33.7 m^3. The smoke produced was mixed with the air in the room with the aid of two fans and its optical density, over a path length of 1 m, was determined from measurements of the transmittance of a light beam focussed on a photoelectric cell.

The tests were carried out during late winter months when the absolute humidity of the atmosphere was low. Low levels of relative humidity (28 per cent) were therefore readily obtained in the test chamber by maintaining an elevated temperature of 25°C. High levels of relative humidity (86 per cent) were obtained by hanging wet hessian sacks in the test chamber.

The above humidity levels are the initial values. They will have been increased slightly by water vapour produced during combustion. Thus, the consumption of oxygen in the test chamber during tests was up to about 1 per cent by volume[1]. Assuming this was utilised in complete combustion, it may be estimated from combustion data for wood[5] that the water produced will have been sufficient to increase the pressure of water vapour by about 1.5 mm Hg. This could have raised the lower level of relative humidity to about 32 per cent and the upper level to 92 per cent.

Two materials were tested, namely wood-fibre insulating board and chipboard, both 12.7 mm in thickness. They were tested with two modes of combustion as before[1], i.e. combustion with flame under the standard conditions of operation of the Fire Propagation Test and under optimum conditions for smouldering combustion. These last conditions consisted of running the test without the gas flames and an initial power input of 1.5 kW to the heaters. After 1 minute the power input was reduced to 0.6 kW for the remainder of a test with wood-fibre insulating board and to 1.0 kW for a test with chipboard.

EXPERIMENTAL DESIGN

The investigation was conducted as a factorial experiment. The four factors tested, each at two levels, were as follows:-

Factor	Level	Symbol
Fire Propagation Test apparatus	No. 1	A_1
	No. 2	A_2
Material	Chipboard (12.7 mm)	B_1
	Wood-fibre insulating board (12.7 mm)	B_2
Mode of combustion	Standard (flame)	C_1
	Non-Standard (smouldering)	C_2
Relative humidity (Initial)	28 ± 7	H_1
	86 ± 1	H_2

The lower level of relative humidity was subject to variations in the absolute humidity of the outside atmosphere.

It was estimated that the sixteen tests of this 2^4 factorial experiment would be spread over a week or so. This introduced the possibility of day to day variation of uncontrolled factors, e.g. humidity of outside atmosphere (The earlier investigation[1] showed this to be negligible, but it so happened then that the outside humidity varied little). Further, because it was not possible to change the humidity level in the test chamber rapidly, it was convenient to maintain a given level for blocks of tests. For these reasons a split plot design was adopted in which groups of eight tests, comprising all combinations of the three factors A, B and C, were the whole plots and tests within whole plots were the split plots. The humidity levels were allotted to whole plots.

The split plots were grouped into blocks of 4 tests (or sub-plots) which could be carried out within periods of 24 hours (days) during which the humidity was kept at a given level. In order to avoid the risk of confounding, between blocks, some of the main effects and first order interactions of the split plot factors, the experiment was planned so as to confound the ABC interaction;

this was of little interest and, in fact, likely to be negligible. The design adopted is shown in Table 1. This design also confounds the between-block variance with the humidity in the whole plot, but the significance of this variance may nevertheless be determined approximately by comparison with the split plot error (see below).

TABLE 1

Split plot design with confounding

Plots	H_1		H_2	
Tests in a block \ Blocks (days)	1	2	3	4
1	A_2 B_1 C_1	A_1 B_1 C_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	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	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	A_2 B_2 C_2	A_1 B_2 C_2

The choice of block, and of tests within a block, was randomised subject to the restriction that it was impracticable to carry out consecutive tests on one apparatus (owing to the time required for cooling and cleaning between tests).

In order to provide degrees of freedom for the whole plot error, needed for testing the effect of humidity, the experiment was repeated once - giving a total of 32 tests.

Except for wood-fibre insulating board under standard conditions of operation of the test (flaming combustion possible), the dependent variable (or response to plot treatment) measured in the experiment was the minimum value of the optical transmittance of the smoke for a path length of 1 m (as previously[1]). The behaviour of the wood-fibre insulating board under standard conditions was unexpectedly complex (see Appendix 1) and the relevant transmittances were instead chosen as the values at a fixed time of 20 minutes for all tests containing the combination B_2 C_1, Table 1. These values were not minima but occurred where the transmittances were decreasing slowly. A possible inflationary effect due to variance associated with the rate of smoke production will therefore need to be taken into consideration where variances involving B_2 C_1 combinations are marginally significant.

RESULTS

ANALYSIS OF VARIANCE

As previously explained[1], the analysis of variance is performed on the angular transforms of the percentage transmittances. The analysis is shown in Table 2 (The original results are given in Appendix II).

TABLE 2.

Analysis of variance

Source of variance	Sum of squares	Degrees of freedom	Mean sum of squares	Variance ratio
Blocks (Days)	68.6	7	9.8	1.8[1]
Replication	2.3	1	2.3	0.7
Humidity	50.0	1	50.0	15.3*
Whole plot error	16.3	5	3.26	
A	14.1	1	14.1	2.6
B	4108.7	1	4108.7	750 *
C	4704.5	1	4704.5	860 *
AB	2.4	1	2.4	0.4
AC	17.1	1	17.1	3.1
BC	432.2	1	432.2	78.8*
HA	2.1	1	2.1	0.4
HB	10.6	1	10.6	1.9
HC	9.1	1	9.1	1.7
HAB	2.6	1	2.6	0.5
HAC	5.7	1	5.7	1.0
HBC	29.2	1	29.2	5.3*
Split plot error	65.8	12	5.48	
Total		31		

[1] Compared with split plot error (see text above).

* Significant at 5 per cent level.

The analysis shows that the effect of relative humidity on the optical transmittance of smoke is highly significant, and this conclusion has not been affected by possible between-block variance.

As expected[1], the split-plot analysis shows the board (B), mode of combustion (C) and their interaction (BC) to be highly significant factors. The main results of interest in this part of the analysis, however, are the interactions with humidity, all of which are unimportant except HBC which is just significant (chance value 4.8). This last implies that the effect of relative humidity on the optical transmittances (and hence, optical density) of the smoke from different boards depends on the mode of combustion. This conclusion is weakened by the possible presence of a rate variance in the results for wood-fibre insulating board under standard conditions.

EFFECT OF RELATIVE HUMIDITY

The actual magnitude of the effect of increasing the relative humidity in the test chamber is shown in Table 3 in terms of the maximum optical density of the smoke produced by the two boards under the two modes of combustion (except for wood-fibre insulating board under standard conditions). The optical densities shown, calculated as the negative logarithms to base 10 of the transmittances, are derived from transmittances corresponding to mean values of the angular transforms of the observed transmittances for four tests each at each level of relative humidity (pooling A_1 and A_2).

TABLE 3

Effect of relative humidity on the maximum optical density of smokes produced in the fire propagation test apparatus.

Source of smoke	Mode of combustion \ Relative humidity	28 per cent	86 per cent	Increase in optical density per cent
Chipboard (12.7 mm)	With flame	0.406	0.495	22*
	smouldering	0.979	1.00	2
Wood-fibre insulating board (12.7 mm)	With flame[1]	0.079	0.084	6
	smouldering	0.438	0.587	34*

[1]Values at 20 minutes.

*Significant (see Appendix 3).

It will be seen from Table 3 that the increase in relative humidity has increased the optical density of the smoke significantly for only two of the four possible board/mode-of-combustion combinations.

CONCLUSIONS

Depending both on the material under test and on the mode of combustion, the relative humidity of the ambient atmosphere can sometimes affect significantly the optical density of the smoke produced by materials in the fire propagation test apparatus.

On the basis of Wright's model for the effect, this result implies that the hygroscopic properties of smokes depend both on the original material and on the mode of combustion. It is also possible that the combustion process itself is affected by changes in humidity.

For the materials and modes of combustion tested here, the optical density of the smokes was increased by amounts varying between zero and 34 per cent on increasing the relative humidity from about 30 per cent to about 90 per cent. The increase may well be greater for other materials.

Accordingly, it is concluded that some control of the ambient relative humidity is necessary for the purposes of a standard test for smoke production.

It is suggested that it will be sufficient to control the relative humidity to within the range 55 - 65 per cent as is at present required for the conditioning of materials for test in the Fire Propagation Test[4]. By simple proportion, this would restrict the effect on the optical density of smoke, at least for the materials tested here, to a maximum of about ±3 per cent about the mean. Since the effect of relative humidity on particle size is not linear[2, 3] the effect, on the optical density, in the range 60 ±5 per cent relative humidity, is likely to be less than the above estimate of ±3 per cent.

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APPENDIX I

SMOKE GENERATION BY WOOD-FIBRE INSULATING BOARD

Seven of the eight tests with wood-fibre insulating board under the standard conditions of operation of the Fire Propagation Test Apparatus (combustion with flame, $B_2 C_1$ type) gave photometer records of the form shown in Fig 1. (Note that increasing deflection implies decreasing transmittance).

In these tests smoke evolution took place in two stages. Between about 12 and 15 minutes the record shows a steady level corresponding to a transmittance of 90 per cent followed by an increase to a second steady transmittance of 76 per cent. The eighth record showed a continuous decrease to the lower level of transmittance. The first level of transmittance corresponds to the value previously reported for wood-fibre insulating board under flaming conditions[1] but the second level has not been previously observed.

Re-examination of all previous records showed that in all but two cases the transmittance had either definitely passed through a minimum or reached a steady value of about 90 per cent at 20 - 25 minutes in tests of the $B_2 C_1$ type. In the two exceptions there was evidence, previously overlooked, of a further decrease in transmittance after 20 - 25 minutes.

The pieces of wood-fibre insulating board used in the two series of tests were cut from different sheets but, otherwise the reason for the different behaviour is not known. It is possible, however, that the second stage of smoke evolution corresponds to the initiation of smouldering combustion in the residue of unburned material normally left where the specimen is clamped between the back-plate and the front face of the combustion chamber of the fire propagation test apparatus. If this is so, the result implies that the ease with which this smouldering may be initiated can vary widely between batches of wood-fibre insulating board. This effect will need to be taken into consideration in the specification of a standard smoke test.

For the present series, the effect necessitated an arbitrary choice of the smoke level to be used for the combinations involving $B_2 C_1$ in the analysis of variance. It was desired to include a high level of transmittance, as previously obtained with wood-fibre insulating board under standard conditions, but there was here a missing value for this level at the lower humidity ($H_1 B_2 C_1$). A compromise was affected by choosing the value of the transmittance at 20 minutes, although this possibly introduced a rate variance (see text).

Mean values for the optical density at the two levels produced by wood-fibre insulating board under standard conditions are given in Table 4.

TABLE 4

Optical density of smoke from wood-fibre insulating board.
(Standard mode of operation of fire propagation test)

Relative humidity per cent \ Optical density	Lower level	Upper level
28	0.042	0.106
86	0.044	0.143

It will be seen that the effect of relative humidity on the lower level of optical density is small, as in Table 3 on page 7, and the conclusions of the main investigation are not affected. The effect of relative humidity on the upper level of optical density is comparable with that observed for smouldering combustion (Table 3) and accords with the view that the upper level of density is associated with smouldering of the board residues.

APPENDIX 2

EXPERIMENTAL RESULTS

Replicate	Plot	Block	Sub-plot	R.H. per cent	Transmittance per cent
1	H_1	2	$A_2\ B_2\ C_1$	38	87.8
			$A_1\ B_1\ C_1$	37	29.0
			$A_2\ B_1\ C_2$	32	11.9
			$A_1\ B_2\ C_2$	34	34.1
	H_2	3	$A_2\ B_2\ C_2$	85	26.4
			$A_1\ B_1\ C_2$	85	10.8
			$A_2\ B_1\ C_1$	86	28.6
			$A_1\ B_2\ C_1$	86	83.9
	H_1	1	$A_2\ B_1\ C_1$	32	41.3
			$A_1\ B_1\ C_2$	30	9.8
			$A_2\ B_2\ C_2$	30	35.2
			$A_1\ B_2\ C_1$	30	82.2
	H_2	4	$A_1\ B_1\ C_1$	86	31.2
			$A_2\ B_1\ C_2$	85	9.7
			$A_1\ B_2\ C_2$	87	20.9
			$A_2\ B_2\ C_1$	85	81.1
2	H_2	4	$A_1\ B_2\ C_2$	87	30.4
			$A_2\ B_1\ C_2$	85	10.0
			$A_1\ B_1\ C_1$	88	29.1
			$A_2\ B_2\ C_1$	85	84.4
	H_1	1	$A_1\ B_1\ C_2$	20	9.8
			$A_2\ B_2\ C_2$	20	34.1
			$A_1\ B_2\ C_1$	33	78.9
			$A_2\ B_1\ C_1$	33	36.9

Replicate	Plot	Block	Sub-plot	R.H. per cent	Transmittance per cent
	H_2	3	A_1 B_2 C_1	86	80.0
			A_2 B_2 C_2	87	26.4
			A_1 B_1 C_2	86	9.2
			A_2 B_1 C_1	85	39.1
	H_1	2	A_1 B_1 C_1	20	35.2
			A_2 B_2 C_1	20	83.9
			A_1 B_2 C_2	18	42.8
			A_2 B_1 C_2	20	10.4

APPENDIX 3

TEST OF SIGNIFICANCE

In Table 3 each of the interaction effects $B_1 C_1$, $B_1 C_2$, $B_2 C_1$ and $B_2 C_2$ have been compared at the two levels H_1 and H_2 of humidity which is a whole plot factor. Such a comparison has an error variance depending on both the whole plot error and the split plot error. The difference between the means of, say, $H_1 B_1 C_1$ and $H_2 B_1 C_1$ has the variance δ_d^2 given by

$$\frac{2}{r\ s\ d} \left[dW + (s - d) E \right] \qquad (1)$$

where

r = number of replications = 2

s = number of split plot treatments = 8

d = number of split plot treatments on which the means $H_1 B_1 C_1$ and $H_2 B_1 C_1$ are based = 2, (A_1 and A_2)

W = mean sum of squares for whole plot error = 3.26

E = mean sum of squares for split plot error = 5.48

For the comparison under consideration an exact test of significance does not appear to be available in the literature. However, the following test would be approximately valid. It is based on the Behrens-Fisher test[6] for the difference of two means for which the errors are due to different causes.

Expression (1) for δ_d^2 could be rewritten as $(S_1^2 + S_2^2)$ where

$$S_1^2 = \frac{2\ W}{r\ s} = \frac{3.26}{8} = 0.4075 \text{ and}$$

$$S_2^2 = \frac{2\ (s - d)}{rsd} E = \frac{5.48 \times 12}{32} = 2.055$$

$$\tan \theta = \frac{S_1}{S_2} = 0.44 \quad \theta = 23^{\circ}\ 48^{1}$$

$$\delta_d = \sqrt{S_1^2 + S_2^2} = 1.57$$

The degrees of freedom for W and E are 5 and 12. The tabulated values (d) for $n_1 = 5$, $n_2 = 12$ and $\theta = 23^{\circ} 48^{1}$ are about 2.233 for the 5 per cent level of significance and 3.107 for the 1 per cent level. The corresponding critical differences CD ($= d.\sigma_{\alpha}$) are 3.506 for the 5 per cent level and 4.878 for the 1 per cent level. The observed difference is judged to be significant if it exceeds the critical difference. The test is applicable only to the means based on the angular transforms of the percentage transmittances.

These mean transforms and their differences, corresponding to the data in Table 3, are given in Table 5 below.

TABLE 5

Mean angular transforms for effect of humidity

Variable	Mean transform	Difference ($H_1 - H_2$)
H_1 B_1 C_1	38.8	
H_2 B_1 C_1	34.4	4.4*
H_1 B_1 C_2	18.9	
H_2 B_1 C_2	18.4	0.5
H_1 B_2 C_1	65.9	
H_2 B_2 C_1	65.2	0.7
H_1 B_2 C_2	37.2	
H_2 B_2 C_2	30.6	6.6*

* significant at 5 per cent level.

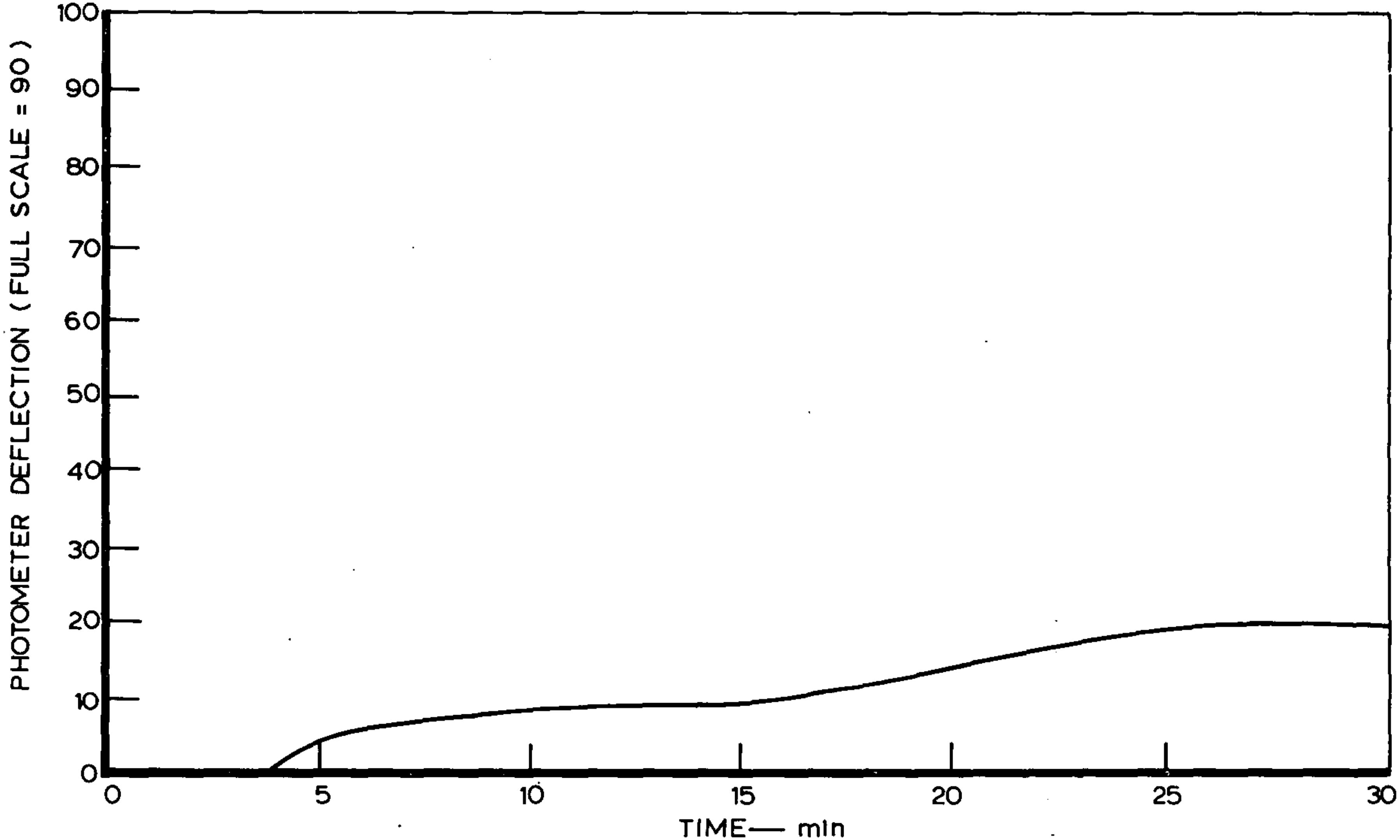

FIG. 1. SMOKE GENERATION BY WOOD FIBRE INSULATING BOARD (RELATIVE HUMIDITY 28 PER CENT)