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RATES OF HEAT OUTPUT AND HEAT TRANSFER
IN THE FIRE PROPAGATION TEST

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SUMMARY

The Fire Propagation test is not an instrument for measuring basic properties of a combustible material such as its calorific value, its thermal properties or its rate of decomposition under constant heating conditions. Instead, it is intended for classifying materials according to their contribution to the growth of fire, which depends in a complex manner on the material itself and on other conditions in the fire as well.

Nevertheless it should be possible to interpret certain measurements that are or might have been made in the Fire Propagation test in terms of rather more basic properties, e.g. its rate of heat release in the test, and so to similar quantities measured in more general studies on fire growth in compartments.

This paper describes some recent progress in developing such interpretations.

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

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1. INTRODUCTION

The value of the Fire Propagation test[1] in assessing the hazard of a material used as a ceiling lining is discussed elsewhere[2]. That discussion makes use of measurements of the rates of heat transfer and burning during the test; the relevant experimental measurements and calculations are described in this paper which deals only with some special aspects of the test. Measurements have also been made of the oxygen content of the flue gases from the test and it is shown here how the rate of burning of cellulosic building boards can be calculated from the measured oxygen content of the flue gases and their calculated rate of flow.

2. EXPERIMENTAL METHODS

2.1. Oxygen content of flue gases

The flue gases were sampled through a 6 mm diameter stainless steel tube at a rate of about 1 litre/min. Solid particles were removed by a filter of glass wool and moisture by silica gel. The oxygen content was measured by a Beckman oxygen analyser. The time taken for a given sample of flue gases to pass through the filters and reach the analyser was of the order of one minute.

2.2. Heat transfer

The heat transfer to an asbestos wood specimen in the Fire Propagation test was measured by a method based on that developed by Christensen et al[3]. A diagram of the apparatus is shown in Fig.1. Chromel-alumel 36 s.w.g. thermocouples were attached to the front and rear surfaces of the asbestos wood and embedded at depths of 3, 6 and 9 mm behind the front surface. This was done by cutting a 4 cm square and 1.2 cm thick asbestos wood block into two equal halves, 2 cm wide, and fixing the thermocouples in grooves made in the cut surface. The two halves were then cemented together and secured in a 4 cm square hole in a larger sheet of asbestos wood.

This heat flow measuring device was inserted in the apparatus in place of the specimen and backing sheet. The rate of heat flow into the

specimen was calculated from the temperature gradient at the surface and the thermal constants of the asbestos wood[3]. The temperature gradient at the surface was obtained from the thermocouple readings by a difference method.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Rate of flow of flue gases

The mass flow of hot gases (a mixture of air with the volatile products of decomposition and combustion) was calculated from the equation[4] for the flow through the flue by natural convection.

$$M_f = 0.6\ A_f\ \rho_o\ (2\ gh\ \theta_f\ T_o)^{\frac{1}{2}}\ (T_o + \theta_f)^{-1}$$

where A_f is the cross sectional area of the flue

θ_f is the true flue gas temperature (this is <u>not</u> the temperature attained by the thermocouple in the flue).

T_o is the absolute ambient temperature.

ρ_o is the density of the ambient air.

h is the height over which the pressure difference due to the heated gases operates.

The factor 0.6 is to allow for entry and exit losses and friction. Since temperature gradients were present in both the chamber where the gases were being heated and in the flue where they were being cooled it was difficult to assign values to h and θ_f. The maximum possible value of h (the distance between the lower ventilation opening and the flue outlet) was taken.

The mass flow of hot gases M_f is plotted against flue gas temperature θ_f in Fig.2. M_f increases with θ_f up to a maximum of just over 1.1 g/s when θ_f is 290 degC above ambient (17°C) after which M_f decreases slowly as θ_f increases. The flue gas temperature has relatively little effect on the mass flow rate when more than about 80 degC above ambient and the mass flow rate is then about 1.0 g/s.

The heat lost by convection in the flue gases expressed in watts was approximately numerically equal to their temperature in degC.

3.2. Oxygen content of the flue gases

The variation in oxygen content of the flue gases during tests with the materials given in Table 1 are shown in Figs 3-8 and the minimum oxygen content of the flue gases is given in Table 1.

It is unlikely that the burning of the less hazardous materials during the test would be affected by oxygen deficiency although this may happen with the most hazardous materials such as untreated fibre insulating board, only for this material, of those tested, did the oxygen content drop to zero.

Table 1

Fire propagation indices and minimum oxygen contents

Material	Fire propagation index	Minimum oxygen content of flue gases per cent by volume
Untreated fibre insulating board	75.3	0
Fibre insulating board with chlorinated rubber paint	53.5	2
Fibre insulating board with emulsion paint	42.0	2
Impregnated medium hardboard	29.7	5
Impregnated fibre insulating board	18.7	12
Hardboard with intumescent paint	16.5	4

The excess temperatures measured by the flue thermocouples (defined as $\theta_m - \theta_c$ where θ_m was the temperature at time t in the test and θ_c was the temperature at time t in the calibration experiment with asbestos wood) are also shown in Figs 3-8. Generally a high excess temperature corresponded to a low oxygen content although the temperature variations were much slower than variations in oxygen content and showed no short term fluctuations as did the oxygen content. Because of this difference in time constants, excess temperature and oxygen content can only be compared when both have remained nearly constant for a relatively long period. Two minutes was arbitrarily adopted and Table 2 gives corresponding values of excess temperature and oxygen content under those conditions.

Table 2

Comparison between oxygen content of flue gases and excess temperature

Material	Time after commencement of test min.	Excess temperature (above calibration temperature) degC	Oxygen fraction by volume
Untreated fibre insulating board	8 17	230 120	0 0.11
Fibre insulating board with chlorinated rubber paint	3 7½ 17	90 220 110	0.14 0.03 0.11
Fibre insulating board with emulsion paint	3 16	60 130	0.165 0.115
Impregnated medium hardboard	3 16	40 90	0.16 0.13
Impregnated fibre insulating board	3 12	30 90	0.165 0.14
Hardboard with intumescent paint	4 11½	20 170	0.17 0.08

The excess temperature ($\theta_m - \theta_c$) was approximately a linear function of oxygen content (Fig.9) and this relationship did not appear to depend on the time after the commencement of the test (i.e. it did not depend on θ_c).

3.3. Heat output and rate of burning

Since the rate of flow of flue gases was approximately constant for much of the period of the test the heat output of the burning material could be directly related to the oxygen meter readings.

Generally heat was produced by the burning of the volatile content of the specimens and it is shown in the Appendix that, allowing for the water produced by the burning of the volatiles from cellulosic materials but assuming

the specimen to be dry, to a fair approximation

$$M_c/M_f = 0.95\ (0.21 - Y)$$

where M_c was the mass rate of consumption of oxygen

Y was the oxygen meter reading (fraction by volume of dry gases)

The town gas jets required about 0.04 g/s of oxygen for their combustion. Assuming the heat output from the burning volatiles to be $1.21 \times 10^4\ M_c$ watts and $M_f = 1.0$ g/s.

$$Q = 1.21 \times 10^4\ (0.17 - Y) \text{ watts}$$

where Q was the rate of heat output from the burning specimen.

When the volatiles had been exhausted so that heat was produced only by the burning of the charcoal residue, the heat output per unit mass of oxygen was little different (about 8 per cent greater) from that when the volatiles were being burnt.

The maximum rate of heat output was limited by the air flow to about 2 kW, i.e. the same as the total heat supplied electrically and by the gas jets.

The excess temperatures are shown also as a function of heat output in Fig.9. When the heat output was zero there was an excess temperature of about 35 degC. This was probably due to the difference between the thermal properties of the asbestos wood used in the calibration experiment and those of the relatively good insulators used in the tests[5].

After the heat output of the specimen had remained nearly constant for at least two minutes

$$(\theta - \theta_c) = (0.12\ Q + 35) \text{ degC} \quad \text{to a first approximation}$$

where θ was the temperature measured by the flue thermocouple with the test specimen.

θ_c was the corresponding temperature with the asbestos wood calibration specimen.

Because of the complexity of the heat balance within the chamber it would be difficult to obtain the above equation from theoretical considerations.

The rate of burning of the specimen/unit area (M''_b) was given by

$$M''_b = 2.2 \times 10^{-3} (0.17 - Y) \text{ g cm}^{-2}\text{s}^{-1}$$

When $Y = 0$ $M''_b = 3.7 \times 10^{-4}$ g cm^{-2}s^{-1}; if the burning rate increases above this the flue gas temperature will decrease because the presence of unburnt volatiles in the constant flow in the flue results in a corresponding decrease in air flow and heat output. This apparently occurred with untreated fibre insulating board.

3.4. Heat transfer to asbestos wood

The rates of heat flow into the asbestos wood block measured as described earlier in this paper are not directly comparable with most measurements of heat transfer rates made in experimental fires.

Comparable rates of heat transfer to the asbestos wood block in the Fire Propagation test are gross rates defined by

$$G = Q_i + Q_r + Q_c$$

where G is the gross rate of heat transfer
Q_i is the rate of heat transfer into the asbestos wood*
Q_r is the heat loss by radiation
and Q_c is the heat loss by convection.

$$Q_r = \epsilon \sigma T_s^4$$

where T_s is the absolute surface temperature of the asbestos wood
ϵ is its emissivity (0.95)
and σ is Stefan's constant.

Q_c is difficult to assess but a rough estimate was made by assuming that the temperature was uniform over the surfaces within the chamber and that the exit gases were at the same temperature as the walls.

Then

$$Q_c = M C_p \theta_w / A_w$$

where M is the mass rate of flow of hot gases (calculated as described later)
A_w is the area of the internal surfaces of the chamber
and θ_w is their temperature.

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*This is the heat transfer to the surface as evaluated by Christensen et al[3]

The mean convective heat loss was calculated to be about 0.5 W/cm^2 when the temperature was 600°C and 0.25 W/cm^2 at 300°C. Since this was only about 10 per cent of the total the uncertainty in its calculation is not important.

The rate of conduction of heat into the mid-point of the inner face of a single sheet of asbestos wood and the "gross" heat transfer rate are shown in Fig.10. The difference between these two rates represents the heat lost from the surface, mainly by radiation. As the asbestos wood became hot the temperature gradient near the surface and therefore the heat conducted into the asbestos decreased although the gross heat transfer rate increased. The decrease in heat conducted into the asbestos wood at the measuring point was compensated by an increase in heat lost by convection in the flue gases and by conduction into other areas of the inner surface of the chamber where heating by radiation direct from the electrical elements was relatively small.

The gross heat flow to the centre of an asbestos wood specimen in the fire propagation test due to the gas jet alone was about 0.5 W/cm^2. However, the flames impinged on a line below the centre of the specimen and the rate of heating locally may have been much higher. When the power was turned on the rate of heat transfer rose to about 2.8 W/cm^2 but when the power input was reduced to 1500 watts the rate of heat transfer fell slightly; subsequently it continued to rise more slowly to about 5.0 W/cm^2 at 20 minutes; the rate of heat transfer at this time was still rising. A maximum heating rate of about 5.0 W/cm^2 is also obtained in the B.S. 476 Spread of Flame test.

These rates of heat transfer are strictly not applicable to any other type of material or to different thicknesses of asbestos wood. The heat balance within the chamber is complex and will be considerably affected by the thermal characteristics of the specimen itself. If the chamber were at a uniform equilibrium temperature equal to the temperature of the gases within it, this temperature may easily be calculated to be about 610°C for an asbestos wood specimen and 670°C for a perfectly insulating specimen. The measured temperature of the centre of an asbestos wood specimen was over 600°C after 50 minutes although even at this time equilibrium had not been attained.

The combustion of the specimen would itself be expected to increase the heat transfer, since the heat to be dissipated through the walls of the chamber may be nearly doubled by a rapidly burning specimen. Thus the temperature of the interior surfaces of the chamber may be nearly doubled and the "gross" heat transfer rate greatly increased since this is mainly controlled by radiation transfer (proportional to T^4 where T is the absolute temperature of a surface).

4. CONCLUSIONS

(1) The "gross" rate of heat transfer to an asbestos wood specimen was found to rise to a maximum of about 5 W/cm^2 by the end of the test.

Similar rates of heat transfer to those measured with an asbestos specimen should be found with non-combustible materials and with combustible materials up to the time when they ignite. After ignition it is likely that heat transfer rates will be higher depending on the rate of burning.

(2) The mass rate of flow of flue gases is about 1.0 g/s when their temperature exceeds about 80 degC above ambient.

(3) There is sufficient oxygen for the complete combustion of the gases emitted by most specimens although there is not sufficient for rapidly burning ones such as fibre insulating board.

(4) The oxygen content of the flue gases responds more rapidly to changes in burning rate than does their temperature and could be used to indicate the instantaneous rate of heat output. Only after the burning rate has remained nearly constant for at least two minutes can the excess temperature above the corresponding temperature in the calibration experiment be related to the heat output. There is also some dependence on the insulation value but for good insulators

$$(\theta - \theta_c) = 0.12\ Q + 35 \text{ watts}$$

There is as yet no complete theoretical justification for this relationship.

The excess temperature indicated by the flue thermocouples underestimates the heat output of those materials which burn so rapidly that the atmosphere in the test apparatus becomes starved of oxygen and also those materials which burn transiently. For other materials having a heat output per unit mass of oxygen burnt similar to that of cellulosics, the excess flue thermocouple temperature is an adequate measure of the burning rate of the material in the test apparatus.

5. REFERENCES

(1) Fire propagation test for materials. British Standard 476 : Part 6 : 1968.

(2) HINKLEY, P. L., WRAIGHT, H. G. H. and WADLEY, Ann. The fire propagation test as a measure of the fire hazard of a ceiling lining. Joint Fire Research Organization F.R. Note No.710, 1968.

(3) CHRISTENSEN, G., LOHSE, U. and MALMSTEDT, K. Full scale fire tests. Danish National Institute of Building Research S.B.I. Report No.59, 1967.

(4) THOMAS, P. H. et al. Investigation into the flow of hot gases in roof venting. Fire Research Technical Paper No.7. London, 1963, H.M.S.O.

(5) HIRD, D. and THOMAS, P. H. The growth of fires in rooms and a test for internal linings. Joint Fire Research Organization F.R. Note No.207, 1955.

(6) SPIERS, H. M. (ed) Technical Data on Fuel, 5th Edition, 1950. British National Committee, World Power Conference.

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APPENDIX

Heat output from oxygen meter readings

(a) Burning wood volatiles

It was assumed that the volatiles from the heated cellulosic materials had approximately the same composition as those from wood.

Consider 1 g of flue gases, derived from the combustion of wood volatiles and air. If the mass of oxygen burnt is y g the mass of wood volatiles before combustion was y/1.15 g*. The oxygen analyser gave the oxygen content as the volumetric fraction of the dry flue gases. Neglecting the moisture content of the fuel, most of the water was derived from the combustion of the hydrogen content, which was about 7 per cent of the fuel**. Since 1/9 of the mass of water is hydrogen the mass of water in 1 gram of combustion products was 0.63 y/1.15 g and its volume at N.T.P. was 0.68 y litre.

The density of the wet combustion products at N.T.P.[6] was 1.3 g/l, i.e. the volume occupied by 1 g was 0.77 litre.

The volume of y g oxygen at N.T.P. was 0.7 y litres.

If Y was the oxygen meter reading, the volumetric fraction of oxygen burnt was

$$0.21 - Y = \frac{0.7\,y}{0.77 - 0.68\,y}$$

As a fair approximation

$$y = 0.95\,(0.21 - Y) \qquad \ldots\ldots\ (1)$$

Since the mass rate of flow of volatiles was 1 g/s equation (1) becomes

$$M_c = 0.95\,(0.21 - Y)\ \text{g/s} \qquad \ldots\ldots\ (2)$$

where M_c was the mass rate of consumption of oxygen.

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*1 g wood having a moisture content of 15 per cent requires 5.1 g air for complete combustion[6], i.e. 1g dry wood requires 6 g. Approximately, wood consists of 83 per cent volatiles and 17 per cent "fixed" carbon[7] (which requires 11 times its mass of air) so that 1 g volatiles require 5 g air or 1.15 g oxygen for complete combustion.

**About 6 per cent of the total mass of fuel was hydrogen[6] and this was all contained in the volatiles so that the hydrogen content of the volatiles was 7 per cent.

The town gas jets required about 0.04 g/s of oxygen for their combustion and the mass rate of flow of oxygen consumed by the burning volatiles from the material under test (M_o) was given by

$$M_o = 0.95\ (0.17 - Y)\ g/s$$

The gross calorific value of wood volatiles[7] is about 1.65×10^4 J/g, i.e. 1.43×10^4 J per gram of oxygen; this is equivalent to a net calorific value (after deduction of the latent heat contained in the water vapour) of 1.27×10^4 J per gram of oxygen.

Then

$$Q = 1.21 \times 10^4\ (0.17 - Y)\ \text{watts}$$

Where Q was the net heat output from the burning material.

(b) Burning charcoal

After some time the volatile content of the burning material becomes exhausted and heat is then produced only from the burning of the charcoal residue.

Consider 1 g air before combustion. If y" gram of oxygen are burnt

$$y'' = 1.095\ (0.21 - Y)\ g$$

The ratio (density of carbon dioxide)/(density of oxygen) is 1.37 so that the mass of combustion products is given by $(1.0 + 0.37\ y')$g.

Then

$$y' = \frac{1.095\ (0.21 - Y)}{1.0 + 0.405\ (0.21 - Y)}$$

Where y' was the mass fraction of oxygen burnt

As a fair approximation

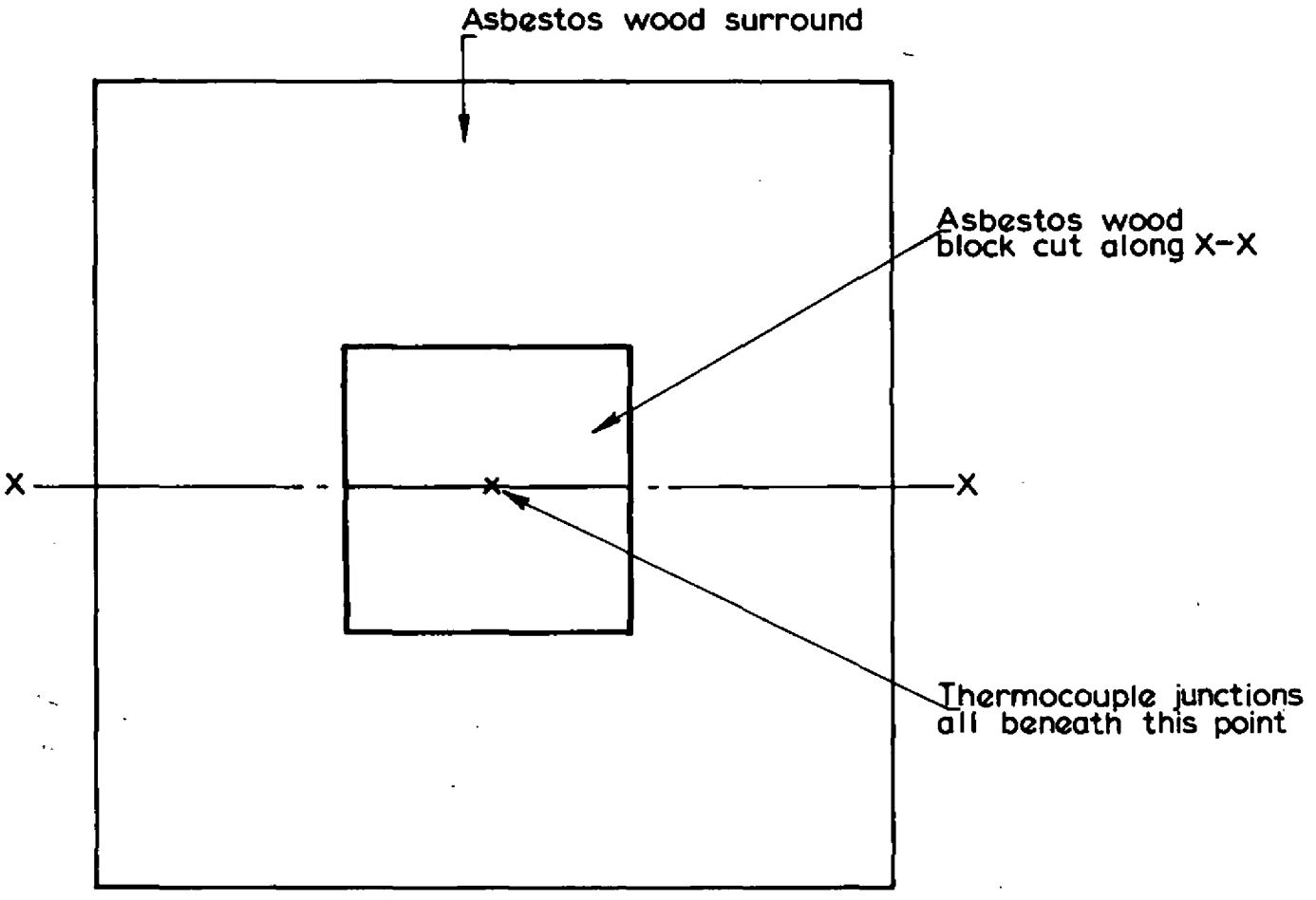
$$y' = (0.21 - Y)$$

With a flow rate of 1 g/s

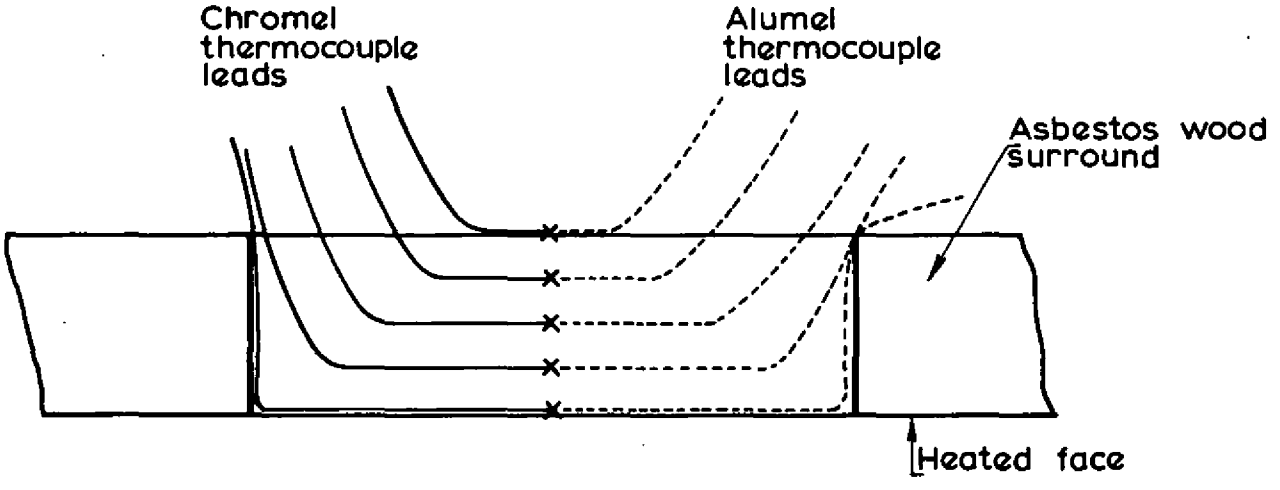
$M_c' = (0.21 - Y)$ where M_c' was mass rate of consumption of oxygen.

$M_o' = (0.17 - Y)$ where M_o' was mass rate of flow of oxygen consumed by burning charcoal

and $Q' = 1.3 \times 10^4\ (0.17 - Y)$ watts, where Q' was heat output due to burning charcoal. This was less than 10 per cent higher than the heat output from burning volatiles.



(a) Plan (actual size)



(b) Section X-X through thermocouples (twice actual size)

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FIG. 1. DIAGRAM OF HEAT FLOW APPARATUS

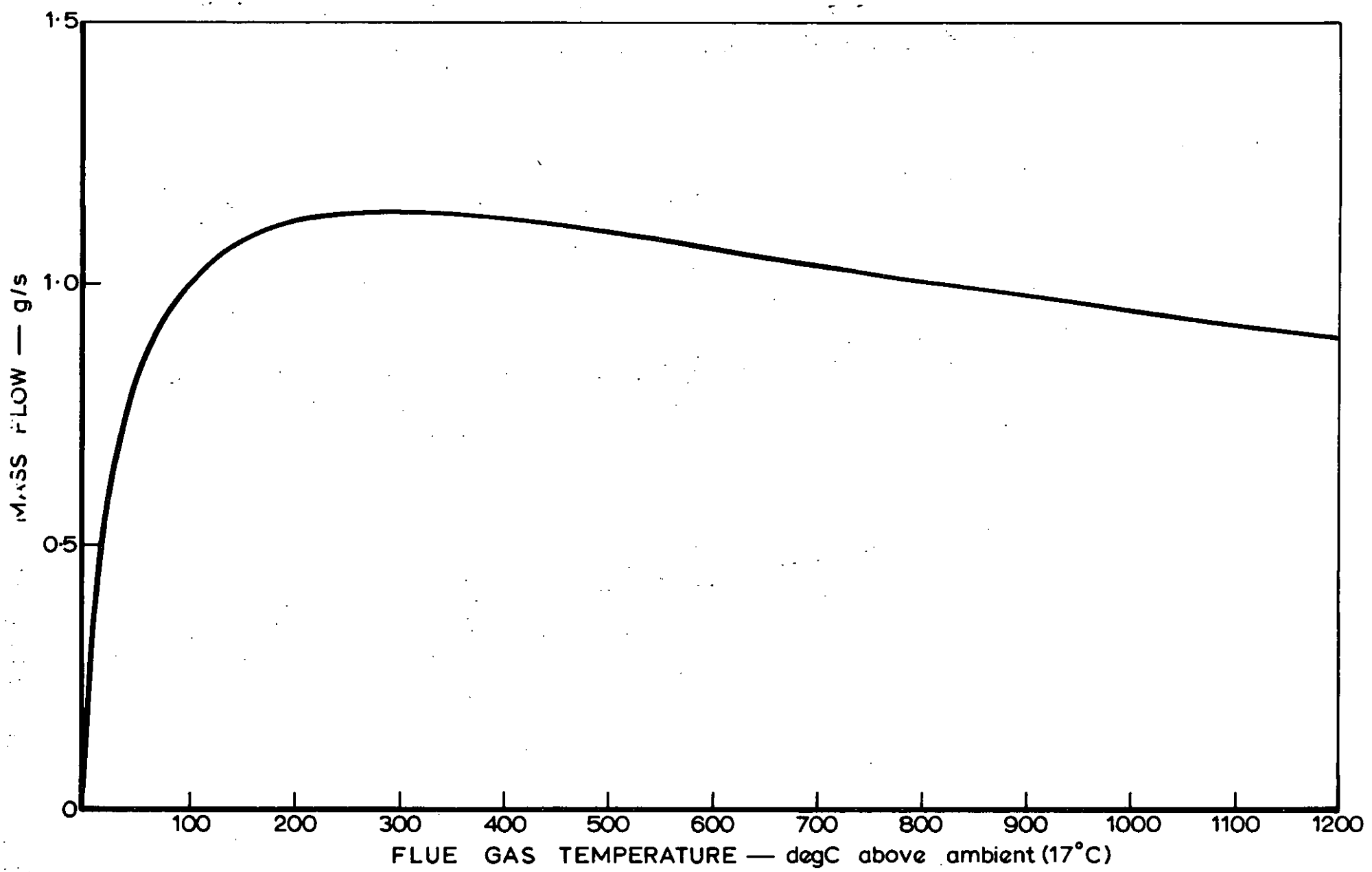


FIG. 2. CALCULATED MASS FLOW RATE OF FLUE GASES

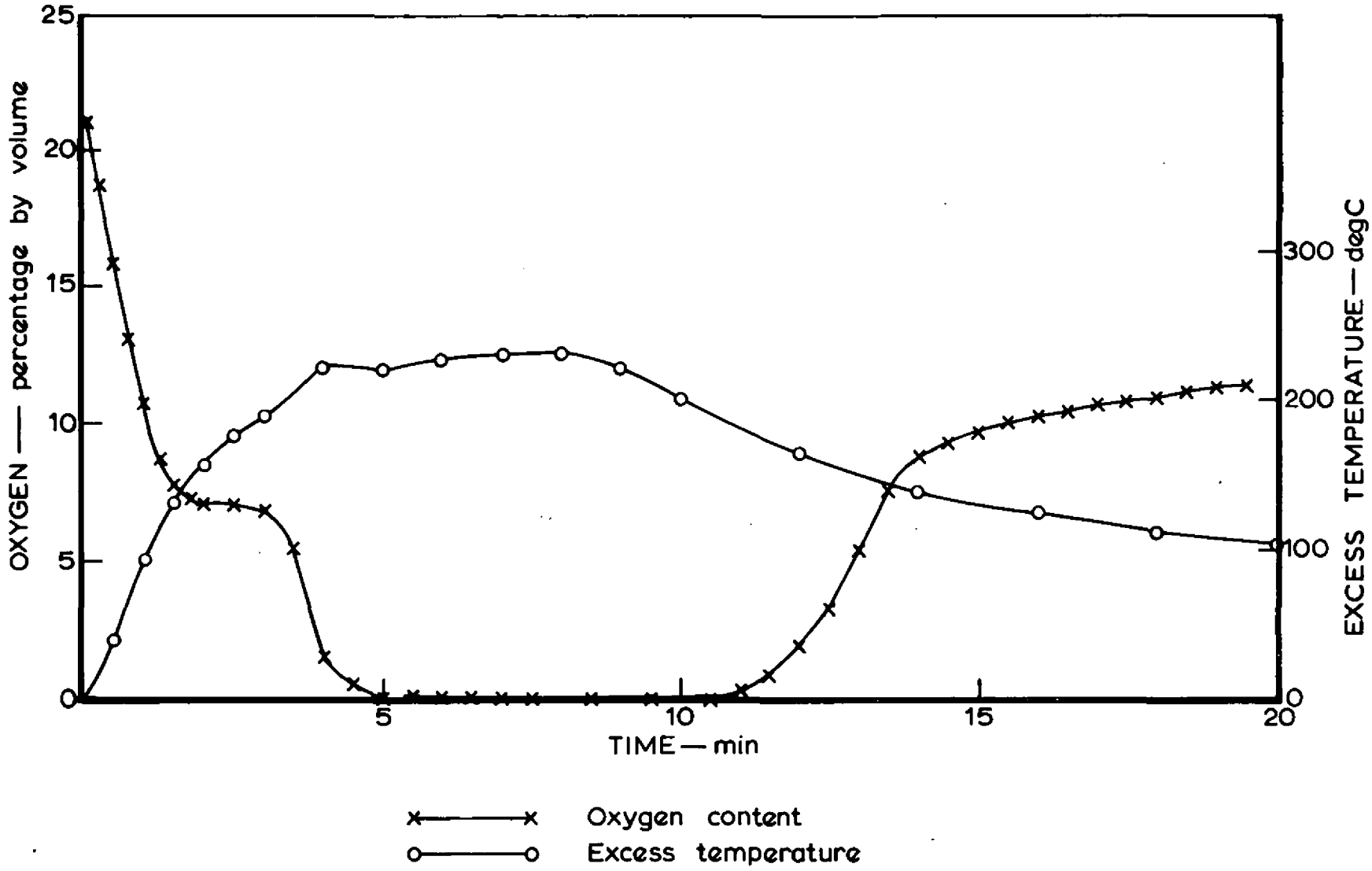


FIG. 3. OXYGEN CONTENT AND EXCESS TEMPERATURE OF FLUE GASES (FIBRE INSULATING BOARD)

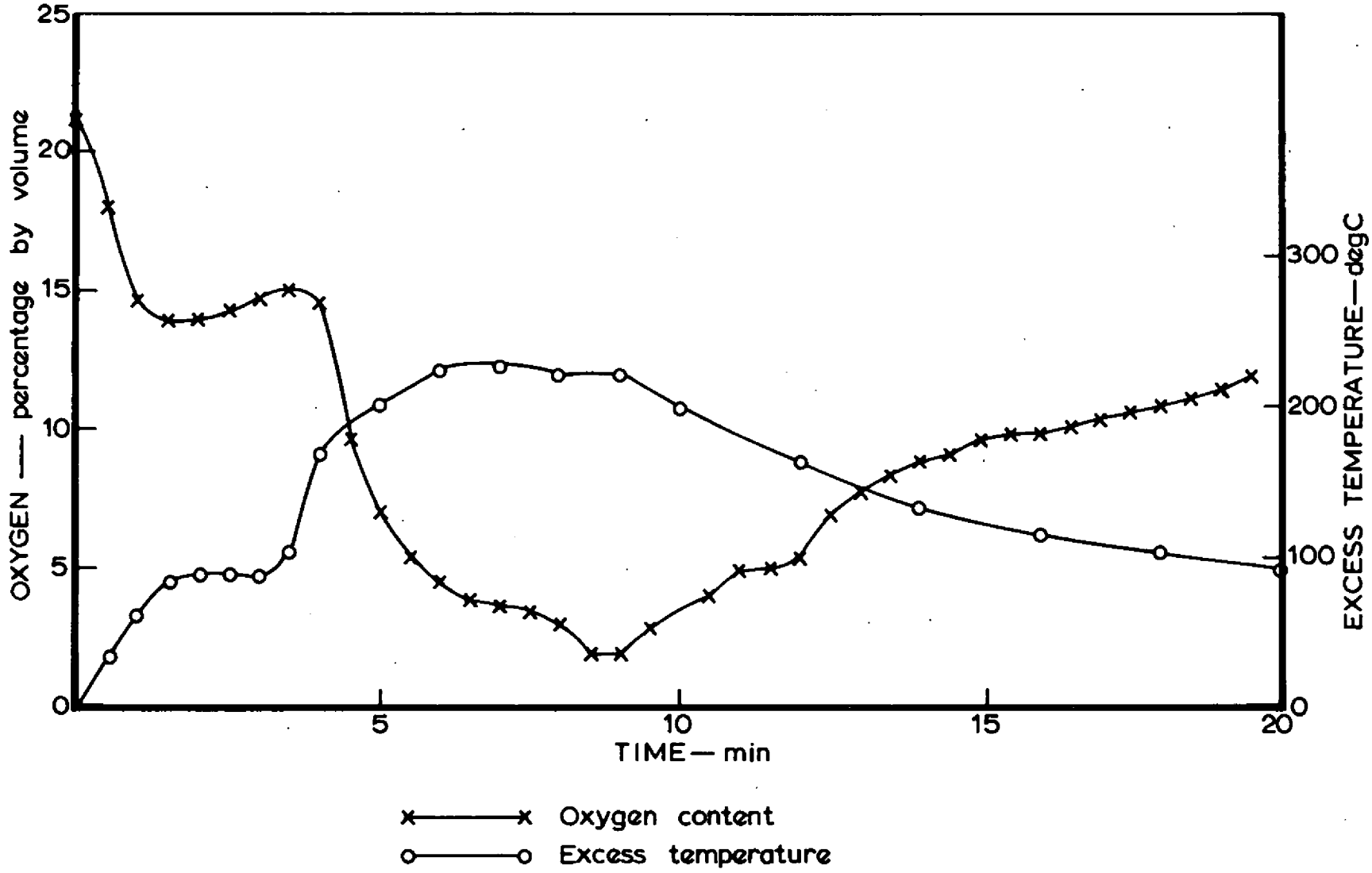


FIG. 4. OXYGEN CONTENT AND EXCESS TEMPERATURE OF FLUE GASES (FIBRE INSULATING BOARD WITH CHLORINATED RUBBER PAINT)

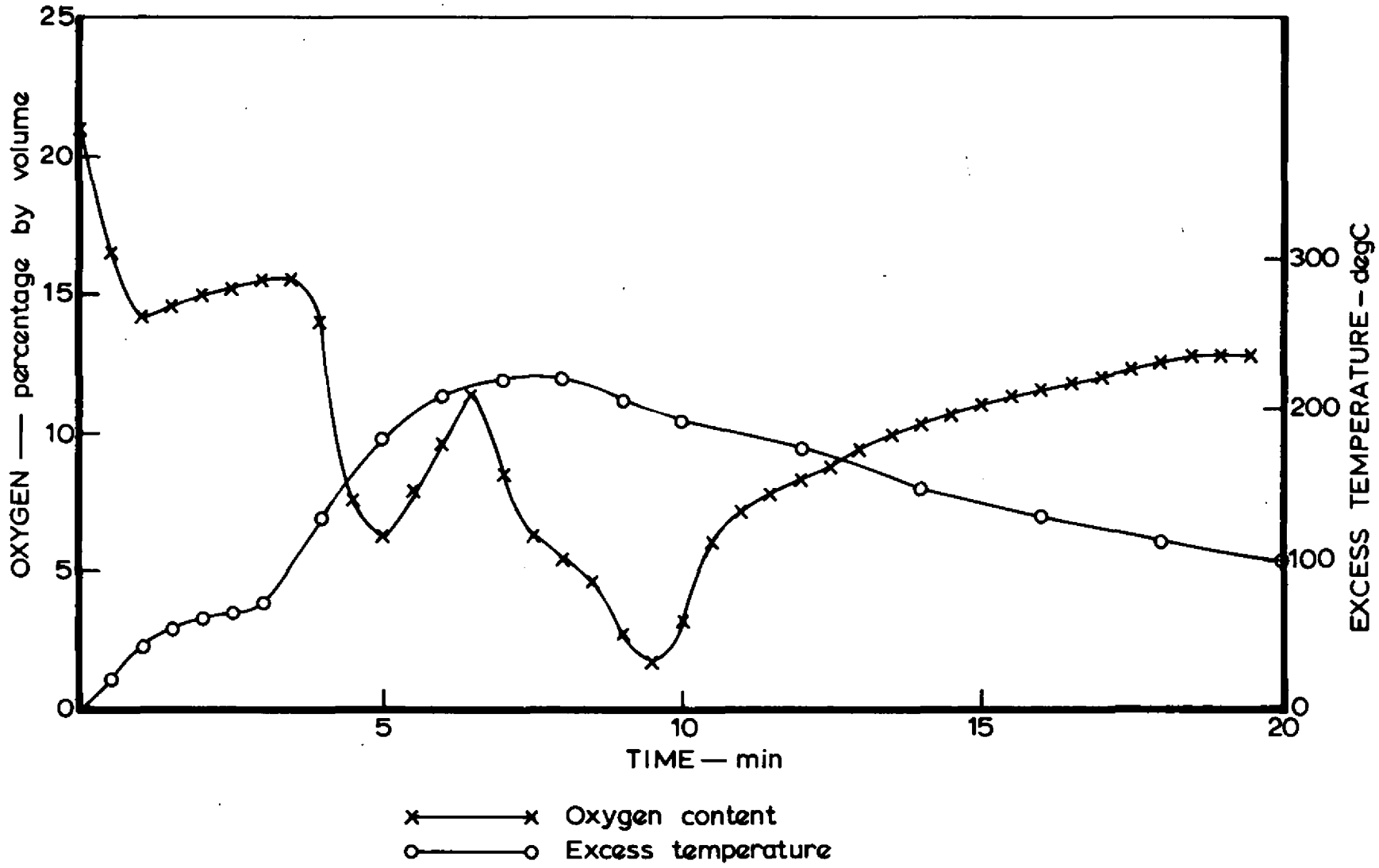


FIG. 5. OXYGEN CONTENT AND EXCESS TEMPERATURE OF FLUE GASES (FIBRE INSULATING BOARD WITH EMULSION PAINT)

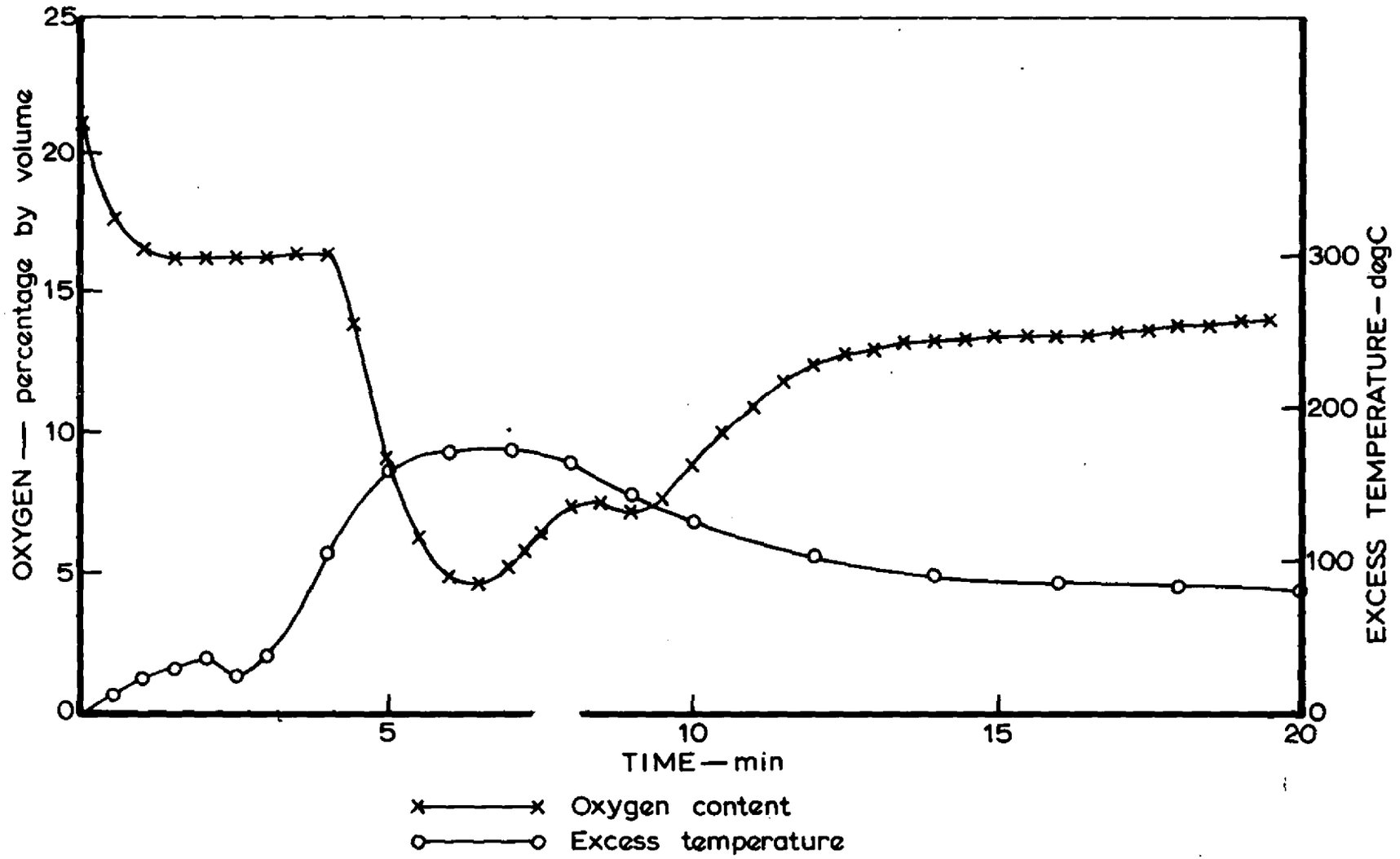


FIG. 6. OXYGEN CONTENT AND EXCESS TEMPERATURE OF FLUE GASES (IMPREGNATED HARDBOARD)

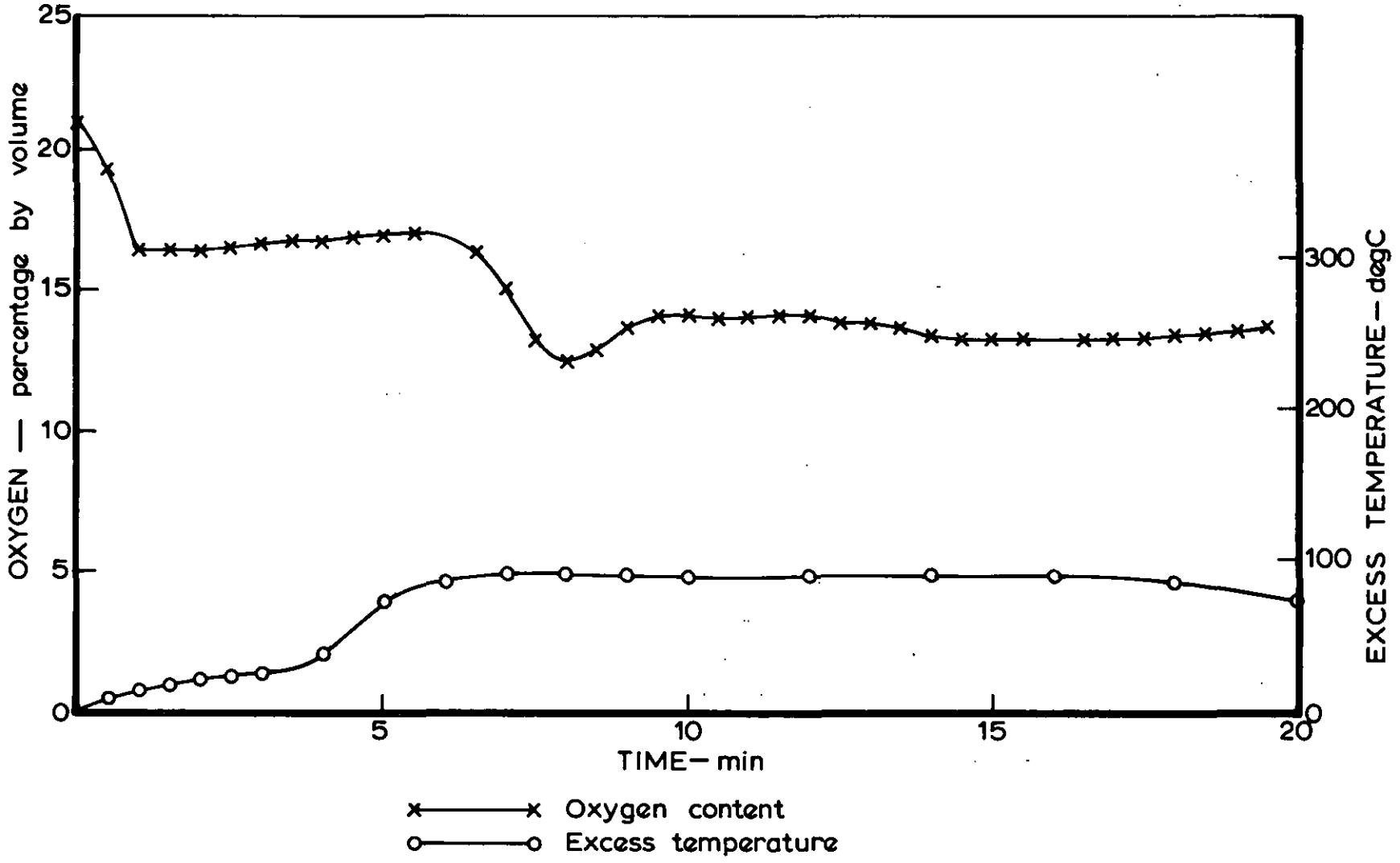


FIG. 7. OXYGEN CONTENT AND EXCESS TEMPERATURE OF FLUE GASES (IMPREGNATED FIBRE INSULATING BOARD)

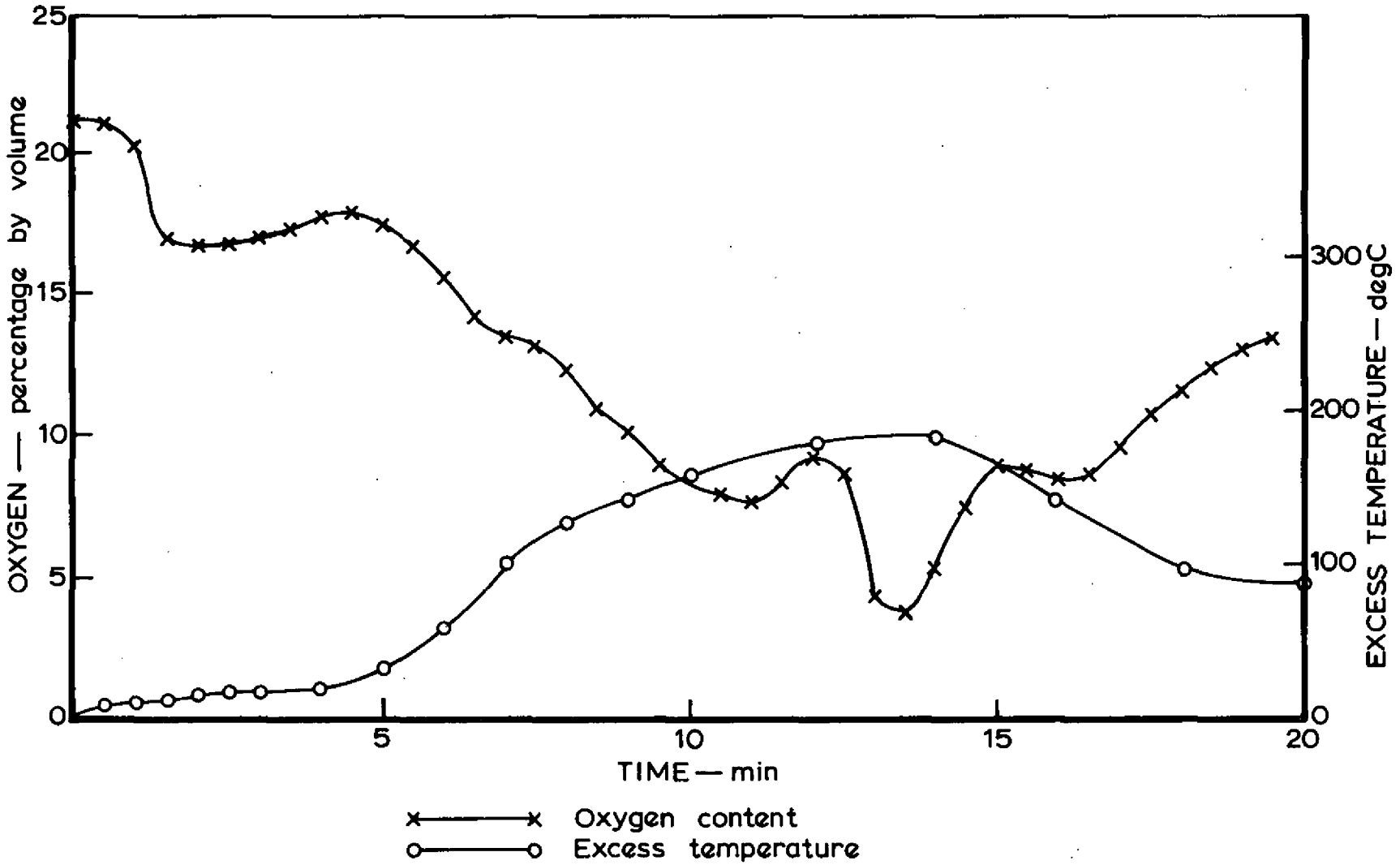
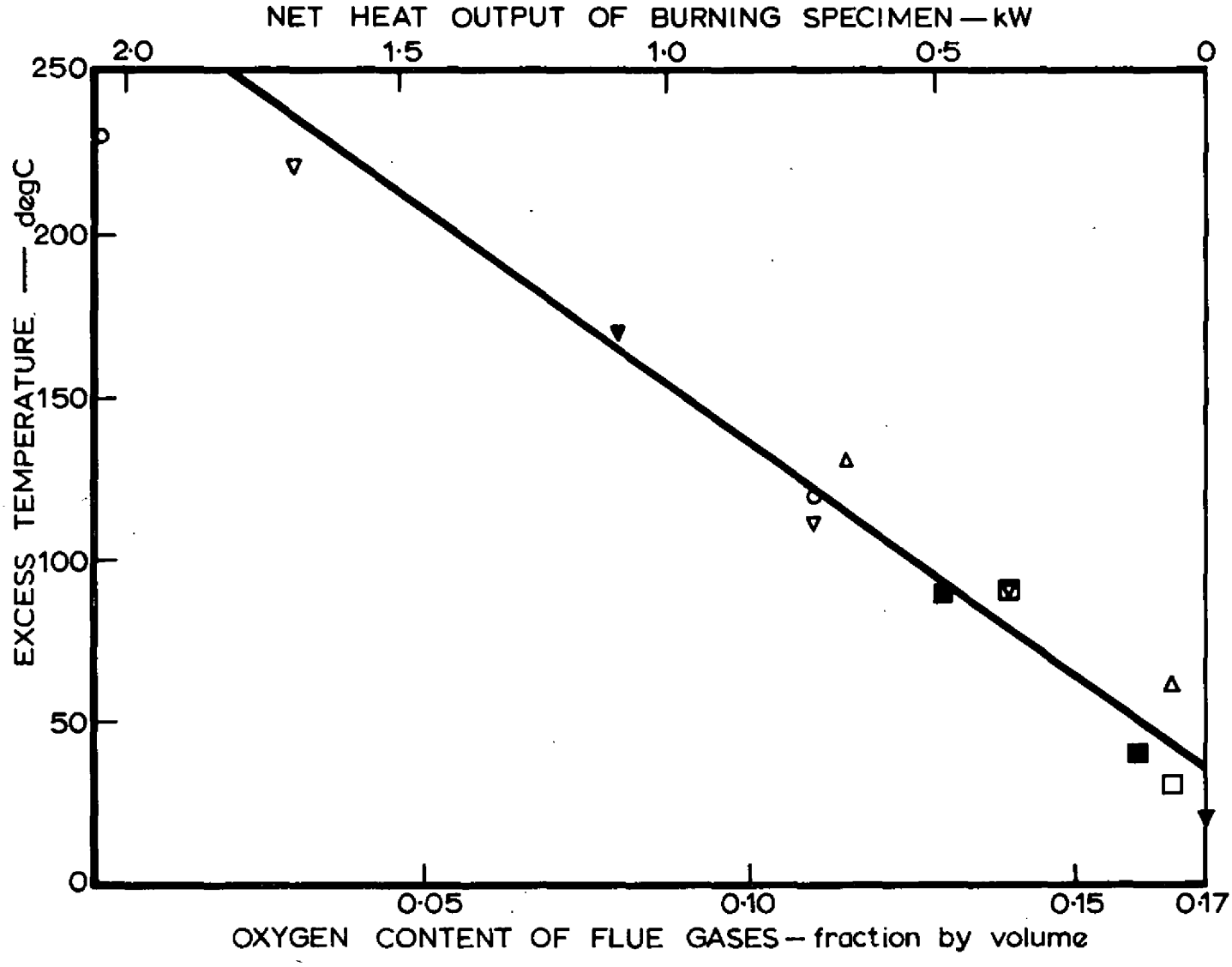


FIG. 8. OXYGEN CONTENT AND EXCESS TEMPERATURE OF FLUE GASES (HARDBOARD WITH INTUMESCENT PAINT)



○ — Untreated fibre insulating board
△ — Fibre insulating board with emulsion paint
▽ — Fibre insulating board with chlorinated rubber paint
□ — Impregnated fibre insulating board
▼ — Hardboard with intumescent paint
■ — Impregnated medium hardboard

FIG. 9. EXCESS TEMPERATURE AND HEAT OUTPUT OF BURNING SPECIMEN

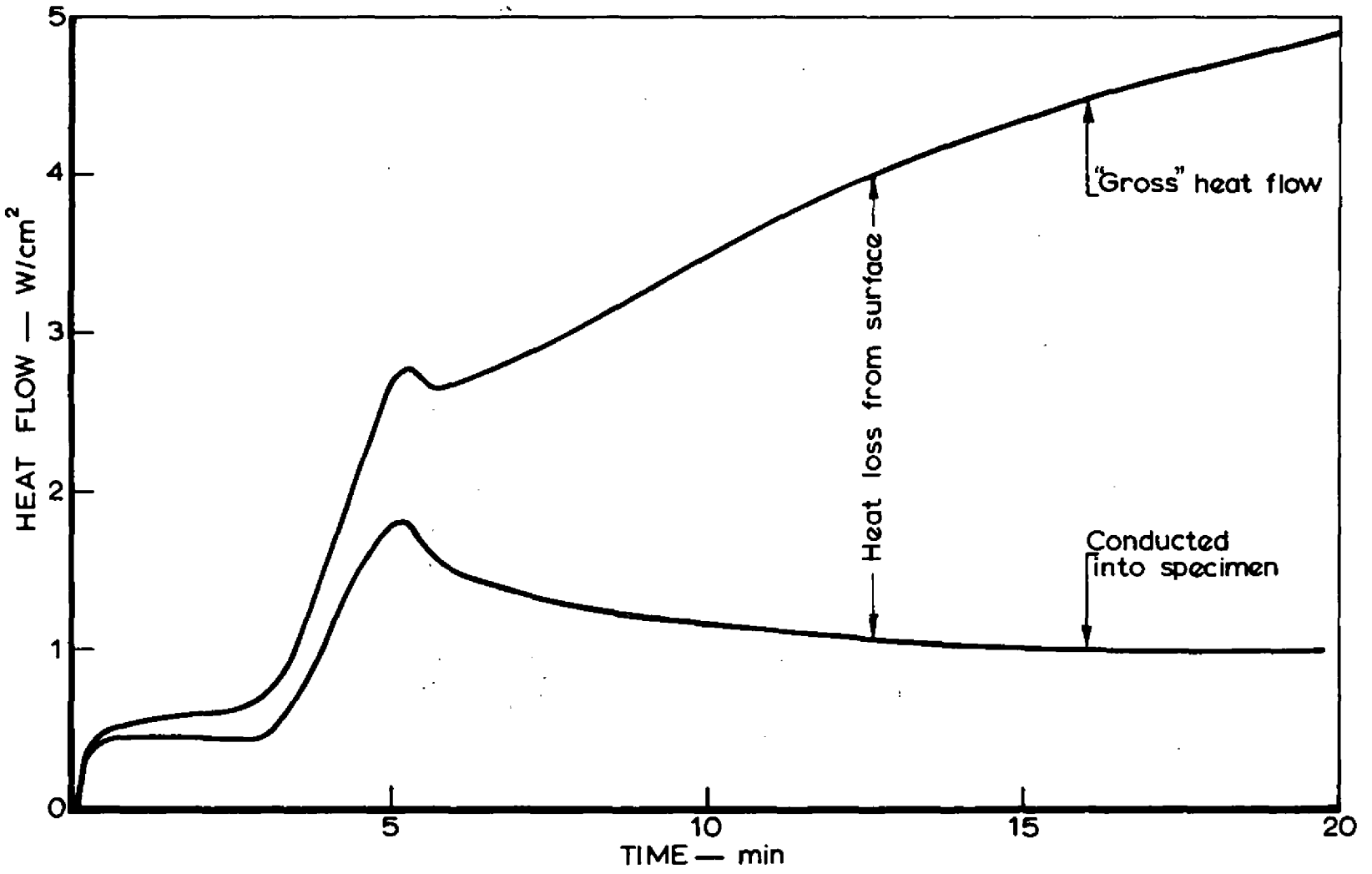


FIG. 10. HEAT FLOW TO SPECIMEN (ASBESTOS WOOD)