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BURNING OF WOOD IN ATMOSPHERES OF REDUCED OXYGEN CONCENTRATION

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SUMMARY

A series of experiments have been carried out on the burning of arrangements of wooden dowelling in atmospheres of reduced oxygen concentration. Using nitrogen and carbon dioxide as diluents a reduction of rate of flame spread with reduction in oxygen concentration was noted for both upward and horizontal propagation; the relative effect, however, was much larger with horizontal propagation. Extinction was obtained when the oxygen concentration was reduced to values between 13.2 per cent and 19 per cent depending on the direction of propagation and the arrangement of the dowelling. The effect of reducing the oxygen concentration is more marked when the process of flame spread depends on radiant heat transfer than when it depends on convective heat transfer.

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

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INTRODUCTION

One of the methods of extinguishing a fire is to reduce the concentration of oxygen of the supporting atmosphere by the addition of a diluent, such as nitrogen, water vapour or carbon dioxide. The reduction which is needed depends to some extent on the diluent, but for many flammable vapours it has been found that flame propagation in a premixed gas does not occur if sufficient diluent has been added to reduce the adiabatic flame temperature to below that at the lower flammability limit[1]. On this basis, for the three diluents mentioned above the oxygen concentration needs to be reduced to between about 11 and 15 per cent according to the diluent.

Experiments on fires with very high flow rates of gas of reduced oxygen concentration[2] have indicated that extinction may sometimes take place with substantially higher oxygen concentrations than would be expected according to the above approach. An illustration of this is shown in Figure 1, which shows the reduction in oxygen concentration required to extinguish diesel oil fires of different size. Moreover, in crib fires and fires in burning heaps of solid materials that were not extinguished, there was often a significant reduction in flame size or rate of flame spread.

If the use of high flow rates of inert gas are to be introduced as a method for controlling fire in large premises, it is of some importance to understand the quantitative background whereby a reduction of the oxygen concentration, insufficient to bring about extinction, could yet lead to a useful degree of fire control. This is of particular importance in cases where the prime object of attack with a gas stream is to flush out smoke either to help occupants to escape or to help firemen to obtain access to the seat of the fire. As a step towards achieving this understanding a series of tests have been carried out on the combustion of wood dowelling in atmospheres in which the oxygen concentration had been marginally reduced.

Experimental

The apparatus used to carry out the tests is shown diagrammatically in Figure 2. The main part of the apparatus was a combustion vessel 182 cm (6 ft) long x 30.4 cm (1 ft) square section provided with a glass front for observation purposes. The apparatus was disposed either vertically or horizontally according to whether upward or horizontal propagation of flame was being studied. Atmospheres for combustion were obtained by mixing nitrogen or carbon dioxide with air in the appropriate amounts and there was provision for conducting this atmosphere to the cabinet. The linear speed of the gas in the cabinet was 2.7 cm/sec.

Figure 3 shows diagrammatically the arrangements of fuel that were studied. For upward propagation of flame a single dowelling and a triple dowelling were used. The single dowelling was marked at 7.6 cm (3 in) intervals by fine wire markers and with the triple bundles cardboard spacers placed at 15.2 cm (6 in) intervals and were used as markers. The specimens were clamped in the centre of the top of the cabinet so that they hung downward in the upper half of the cabinet. For horizontal propagation of flame cribs 61 cm long and either 3 or 7 stick thicknesses deep were used. These were supported 4 centimetres from the floor of the cabinet and the spread of flame was measured between the 25 cm (10 in) and 56 cm (22 in) marks along the crib using a time lapse cine camera set to take a photograph every 30 seconds. From the film the rate of spread of flame, the flame height and the flame width at the base of the flame were measured. Nitrogen and carbon dioxide were used as diluents and the cribs were ignited using a 5 cm (2 in) gas flame. In the tests with the seven layer crib the temperature at the centre of the crib was measured by three, thirty wire gauge T1/T2 thermocouple junctions.

Results

The rates at which the flames progressed up the single dowelling specimen and the triple stick crib are shown in Figure 4 and Figure 5 respectively. The lowest concentration of oxygen at which flame propagation was maintained with the single sticks was 15.7 per cent and for the triple sticks 13.1 per cent. The results obtained for the three layer horizontal sticks are summarized in Table 1. This table shows clearly the difference in rates burning between the 0.32 centimetre and 0.48 centimetre dowelling and the reduction in flame size and burning rate caused by reducing the oxygen concentration of the air to 19.5 per cent. The results for the seven layer crib are shown in Figures 6 to 9. Figure 6 shows the reduction in burning rate caused by diluting the air with nitrogen and carbon dioxide. The minimum oxygen concentration in which the crib could burn when nitrogen was the diluent was 18 per cent, and with carbon dioxide was 19 per cent. At the lowest oxygen concentration for flame spread the rate of flame travel was 1.1 cm s^{-1}, for dilution with both nitrogen and carbon dioxide, as compared with a rate of flame spread of 2.5 cm s^{-1} in air. Figures 7 and 8 show respectively the effect of decrease of oxygen concentration on the flame height and the width of the flame at its base. Both these curves show a reduction in the dimensions of the flame with the oxygen concentration, the relation for the flame width being linear.

From the length of the flame zone and the rate of flame spread it was possible to estimate the time for which the fuel was surrounded by flame, i.e. the time taken for the fuel to burn. It was found that there was no consistent variation of this time with the oxygen concentration. For the upward propagation of flame on the triple bundle the time varied between 23 and 30 seconds with a mean of 25.5 seconds, and for the horizontal propagation of flame along the seven layer crib the time varied between 41 and 48 seconds with a mean of 44.5 seconds. After the passage of flame the crib continued to remain integral for a distance of about 5–10 cm; over this portion the fuel smouldered until it was completely consumed leaving only ash.

The mean of the three maximum temperatures recorded by the thermocouples inserted in the seven layer horizontal crib is plotted against the oxygen concentration in the atmosphere in Figure 9. The maximum figure recorded appears to increase as the oxygen concentration is reduced below 21 per cent and then decreases below 19 per cent oxygen. However, as indicated by Figure 9 the scatter of results was wide.

Discussion

Rate of spread of flame. Nitrogen and carbon dioxide exercise their influence on fire mainly by imposing an extra thermal load on the combustion process. As a result the flame temperature and rates of heat transfer associated with the flame are reduced. The relevant property of the diluent in this respect is its thermal capacity. In Fig.10 the relative reduction in the rates of flame spread of the different fires tested have been plotted against the relative increase in the thermal load caused by adding the diluent to the atmosphere. For both ordinates in Fig.10 the flame spread and thermal load relating to atmospheric conditions have been taken as unity; the thermal load may be defined as the thermal capacity of the total diluent gases associated with a unit quantity of oxygen. Fig.10 shows that the points obtained in the tests are grouped about two curves for upward and horizontal propagation of flame respectively. The effect of increasing the thermal load by adding a diluent is very marked for horizontal propagation, the reduction being approximately inversely proportional to the fourth power of the increase in thermal load. The effect is not so great for upward propagation; for this the reduction in rate of flame spread is inversely proportional to the first power of the increase in thermal load. This difference may be ascribed in part to a difference in mechanism of heat transfer to the unburned fuel. For upward burning the heat transfer was by convection from the flame; for horizontal burning by radiation from the fuel bed.

Thomas et al[3] have put forward equation 1 to cover horizontal flame spread in cribs.

$$R \rho_b \Delta H = I - aQ \qquad \text{........ (1)}$$

where R = the rate of fire spread

ρ_b = the bulk density of the crib

ΔH = the enthalpy rise of uniformly heated wood at the temperature of ignition of a pilot flame (taken as 750 J/g for a moisture content of 10 per cent)

a = a coefficient for non-uniform direction of heat

Q = rate of heat loss at ignition temperature

I = $\varepsilon \sigma T^4$ = the forward flux of heat

where

$$\varepsilon = 1 - e^{-bD} \qquad \text{........ (2)}$$

$$b = \frac{\rho_b}{2D \rho_f} \qquad \text{........ (3)}$$

T = absolute temperature of fuel in the burning crib

b = an attenuation coefficient

D = the thickness of the flame

d = the diameter of the sticks

ρ_f = the density of the sticks

Sufficient information was available to apply equation 1 and 2 to the seven layer crib with horizontal propagation of flame and to obtain an estimate of the temperature of the burning crib. Taking D the depth of the burning zone to be the flame widths shown in Fig.8 crib temperatures of 1,220°C and 1,080°C of the crib for 18 per cent oxygen and 20.9 per cent oxygen respectively were calculated. These are clearly wrong, since they are both much higher than would be expected and because they show a higher burning temperature for the weaker atmosphere. It is clear then that radiation from the burning zone is not sufficient to account for the measured flame spread. It may be shown that the radiation from the flame itself and conduction along the crib is insignificant. The discrepancy is almost certainly due to radiation from that part of the crib that continues to smoulder after the passage of the flame. If it is assumed that the emissivity of the crib is unity then the estimated crib temperatures for 18 per cent oxygen and atmospheric conditions are 730°C and 850°C respectively. Although these values are much nearer the actual measured value of crib temperature shown in Fig.9, they are still substantially different from the measured values. However, there is reason to believe that in this instance the measured values may be in error. The crib was freely suspended in air, and under atmospheric conditions when a long flame was present air was entrained into the crib from underneath, which tended to reduce the measured temperature. On the other hand with a short flame the crib was filled with flame; this would increase the measured temperature since the temperature of the flame was higher than the temperature of the fuel in the crib.

Rate of burning

From the width of the flame zone and the rate of flame spread it was possible to estimate the time for which the fuel was surrounded with flame. For horizontal flame spread this time may be taken directly as the time taken for the fuel to burn, although for upward flame spread this time would include part of the time required for the fuel to be heated to the ignition temperature.

For horizontal flame spread the burning time was 21 seconds for the 0.32 cm sticks and 45 seconds for the 0.48 cm sticks; there was no consistent difference between the different cribs or between the different atmospheres. For upward flame spread in the triple bundle (0.32 cm sticks) the burning time varied between 23 and 30 seconds with a mean of 25.5 seconds. Here again there was no consistent variation with oxygen concentration. In view of the fact that the burning time for upward flamespread was bound to be a slight over-estimate, the evidence indicates that there was no difference either between vertical and horizontal propagation.

The mechanism of heat transfer governing the rate of burning is predominantly convective heat transfer to each stick from the shell of flame that surrounds it and it would have been expected that this heat transfer rate would decrease with flame temperature to give a reduced burning rate. The experiments do not provide clear evidence for this. The amount of heat transfer required to produce the volatiles from the wood is not known. Under various fire conditions heat transfer associated with the production of these volatiles has been estimated as varying from 400 - 800 cal/g of volatiles[4,5]. However, much of this heat transfer undoubtedly is taken up by reradiation from the hot surface of the wood. Thus it is possible that as the temperature of the flame is reduced and the resulting temperatures of the wood sticks are reduced the heat transfer from the flames, required to produce the volatiles may also be reduced because of the reduction in the amount of heat lost by radiation. On the other hand, the dependence of the burning time on the stick diameter checks with the expected change of heat transfer occurring by convection. With mixed natural and forced convection the transfer coefficient to thin sticks should be inversely proportional to 0.5 - 1.0 power of diameter; for a given transfer coefficient the burning time should be inversely proportional to the diameter. The combined effect of these two factors suggests a dependence of burning time on stick diameter as the inverse 1.5 - 2.0 power. The observed value was 1.9.

<u>Extinction of fire</u>

Assuming that the volatiles have the empirical formula $C\,H_2O$ and a heat of combustion of 4000 cal/g it may be estimated that dilution with nitrogen would cause extinction when the oxygen concentration was reduced to 11.3 per cent. The range of concentration at which the flame was actually extinguished varied from 13.2 per cent oxygen up to 18 per cent oxygen. It is also quite clear that horizontal propagation in some instances e.g. along a single stick was not stable even under atmospheric conditions.

It is of interest to note in Fig. 8 that for horizontal propagation the width of the flames near the extinction point were on the average only approximately 1 cm thick and that the scatter of measurements was such that occasionally flame widths only as low as 1 - 2 mm were measured. This suggests that for horizontal flame propagation the limits occur because the flame was not spreading at a sufficiently fast rate to cover fluctuations in volatile

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production due to variations in the wood. However, with upward propagation of flame the flame was extinguished while it was of quite substantial size, indicating that the flame itself was extinguished rather than the rate of spread of flame was insufficient. For premixed flames it may be assumed that the extinction of the flame takes place when the temperature of the reaction zone is reduced to 1,300°C. Presumably at this temperature the rate of combustion which is determined by chemical factors, is insufficient to compensate for the heat losses. With practical diffusion flames, however, there are forms of heat loss which are not present with homogeneous premixed flames. For example, with the flames tested here, the flame has a higher emissivity because of the presence of soot particles which would not be present in premixed flames. Moreover, heat transfer to the fuel surfaces and subsequent loss of this heat by conduction and radiation is also a form of heat loss which is not present in premixed flames.

Generally speaking, therefore, diffusion flames should be extinguished at higher concentrations of oxygen than premixed flames, but the difference will depend on the intrinsic heat loss from the system. It is difficult to carry out precise calculations on this matter but it would be expected that as the size of a fire increases the heat loss from the combustion zone in flame per unit mass burned in the zone would decrease because

(a) the radiant emissivity will be less than proportional to the dimension of the flame - in fact the relationship would be similar to that given in equation 2;

(b) the more items of solid fuel there are present the less will be the radiation losses from each item.

In a qualitative way this accounts for the difference between the single stick fire and the triple stick fire tested in this report and for the scaling effect noted in Fig. 1. It also suggests that emissive flames of a given dimension should be more easily extinguished than non-emissive flames and also that the presence of a large number of small radiating bodies in the flame would help extinction. It would be interesting to check these observations, since they may be factors contributing to the extinguishing efficiency of certain dry powders and vaporizing liquids.

Application to practical conditions

The experiments described in this report have been carried out only on a very small scale, but used in conjunction with information gained in previous full-scale tests the results suggest the effects that a moderate reduction in the oxygen concentration in the atmosphere would have in practice. It would appear that where a rate of burning or a rate of flame spread relies primarily on radiation from a flame, then a fairly substantial reduction in the rate concerned might be expected with reduction of oxygen concentrations insufficient to bring about extinction. Such processes include horizontal flame spread due to radiation from either the burning fuel, the vertical column of flame or the flames under a ceiling. Where convective heat transfer controls the process the effect would be much less marked; such phenomena would include upward spread of flame on surfaces. There is also a range of conditions where extinction of the flame may be obtained with substantially smaller dilution of the atmosphere than would be expected theoretically. However, such effect is likely to be important only to the extent to which the fraction of heat lost from the flames by either conduction or radiation is substantial, since such heat loss reduces the thermal load required in the supporting atmosphere to bring about extinction. The effect is not likely to be very marked for fires with a dimension greater than about 5 ft.

References

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(3) THOMAS, P. H., SIMMS, D. L. and WRAIGHT, H. G. H. F.R. Note 599.

(4) RASBASH, D. J. Extinction of fires by water sprays. Research Abstracts and Reviews. Vol. 4 Nos. 1 and 2. January and May, 1962. Nat. Acad. of Sciences, Nat. Research Council.

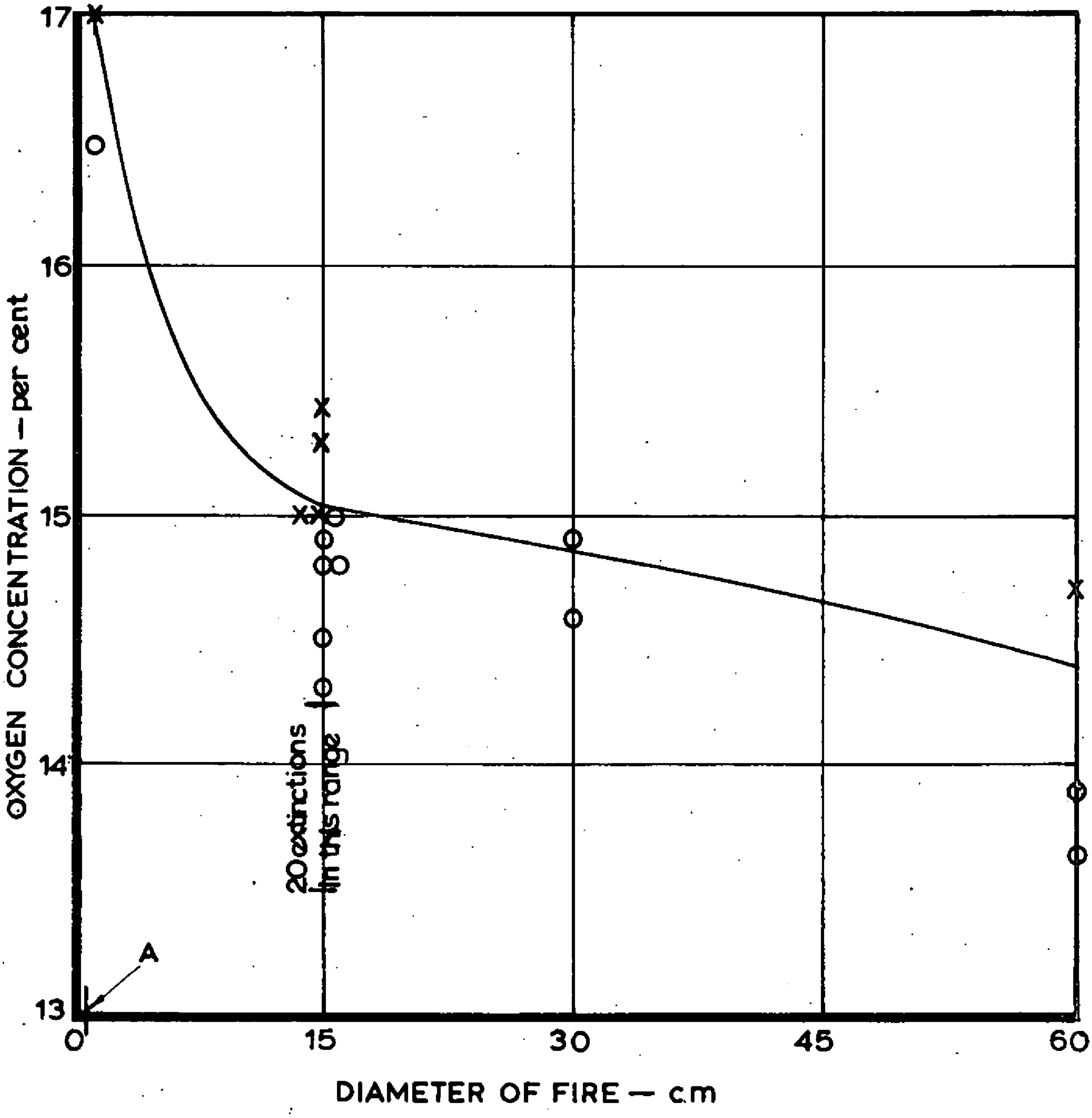
(5) THOMAS, P. H., HESELDEN, A. J. M. and LAW Margaret. Fully developed fires - to be published.

Table 1

Horizontal propagation of fire along cribs in air and in atmosphere containing 19.5 per cent O_2

Crib containing three layers of dowelling
Diluent - nitrogen

Oxygen concentration of supporting gas	Diameter of dowelling	Rate of spread of flame cm/sec	Mean height of flame cm	Mean width of flame base cm	Burning time sec.
20.9% (Air)	3.2 mm (1/8 in.)	0.126	17.4	2.64	20.8
	4.8 mm (3/16 in.)	0.064	20.8	2.95	46
19.5%	3.2 mm (1/8 in.)	0.104	12.4	2.2	21.2
	4.8 mm (3/16 in.)	0.045	14.5	2.05	45.5



X No extinction after exposure to atmosphere for at least 5 minutes

O Extinction within 5 minutes

A Wick lamp points based on many tests over wide concentration range

Diluent—Inert gas based on water vapour and nitrogen produced by jet engine generator

FIG.1. EFFECT OF OXYGEN CONCENTRATION ON THE EXTINCTION OF DIESEL OIL FIRES

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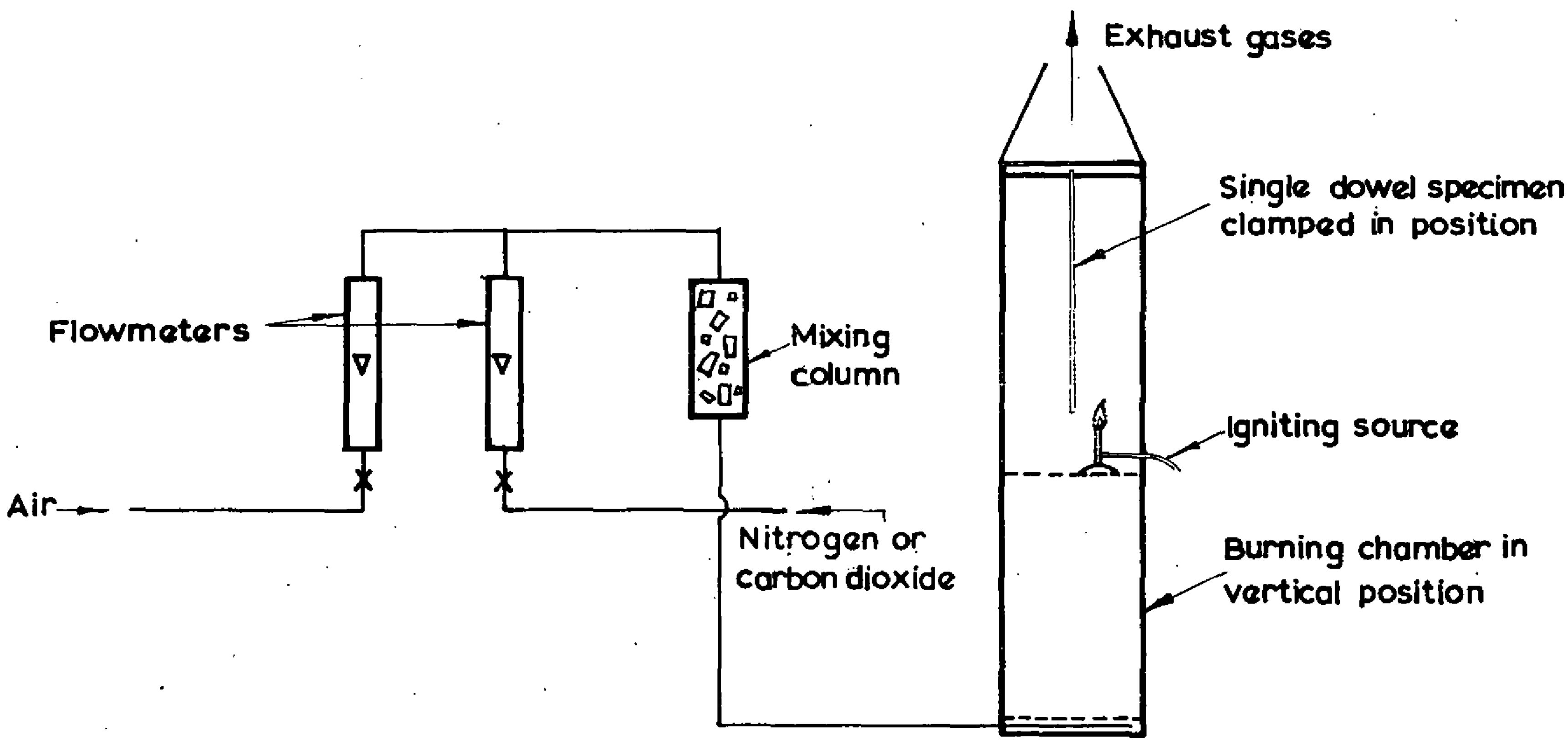

FIG. 2. ARRANGEMENT OF APPARATUS

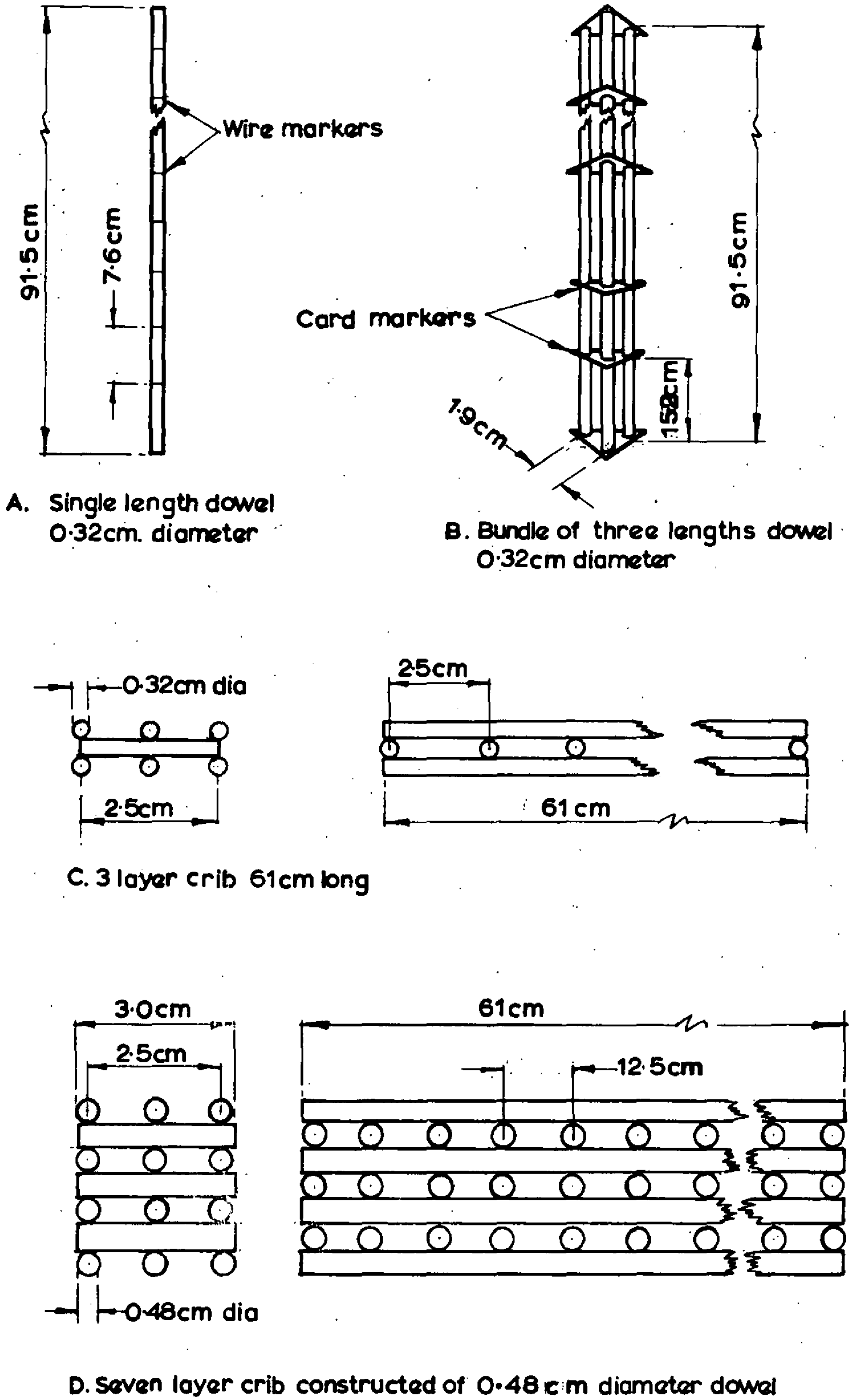

FIG.3. ARRANGEMENTS OF DOWELLING CRIBS USED

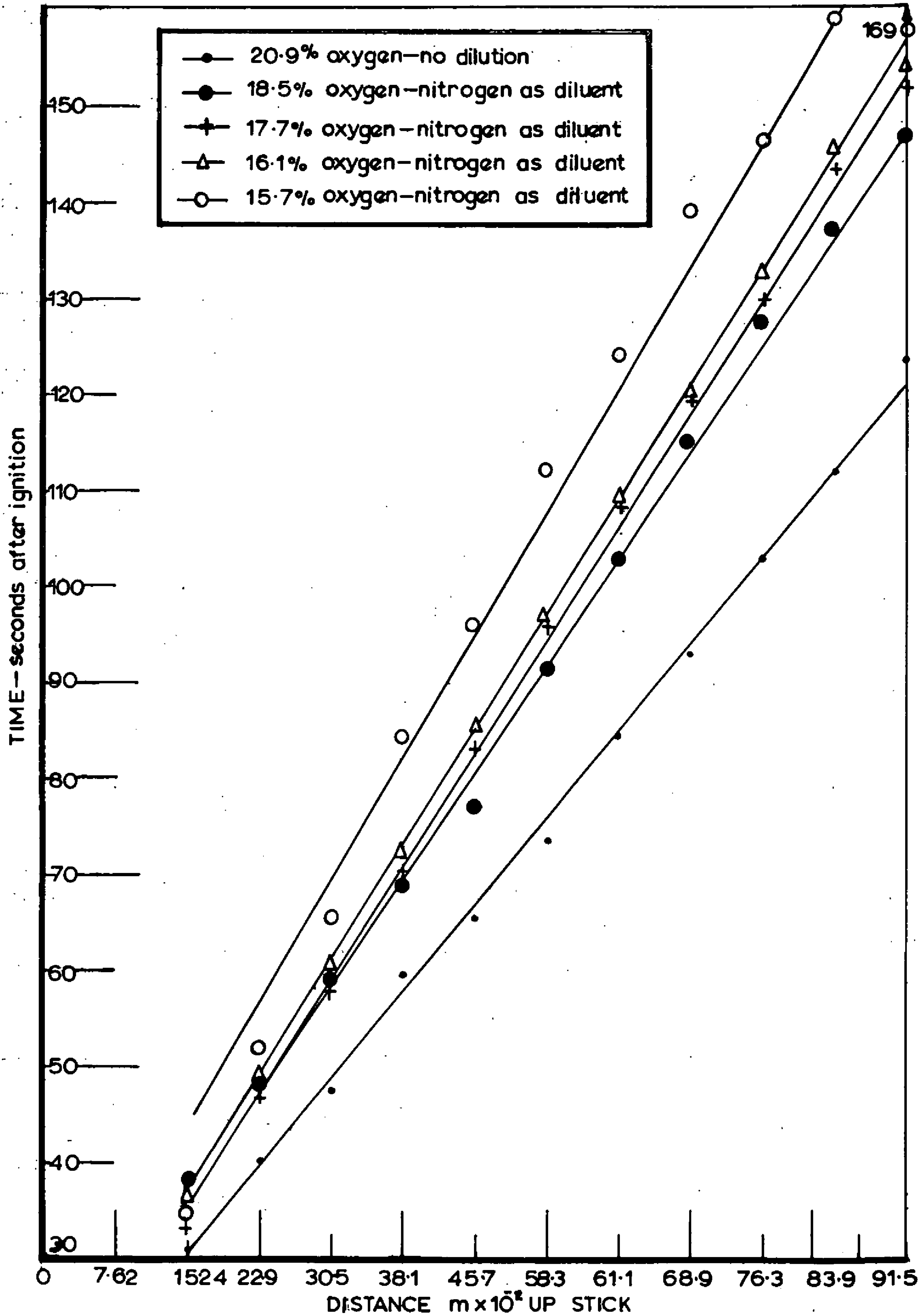

FIG.4. MEAN RATE OF UPWARD TRAVEL OF TRAILING EDGE OF FLAME ON SINGLE 0·915m.(36") LENGTHS OF DOWEL 0·0032m (1/8") DIAMETER

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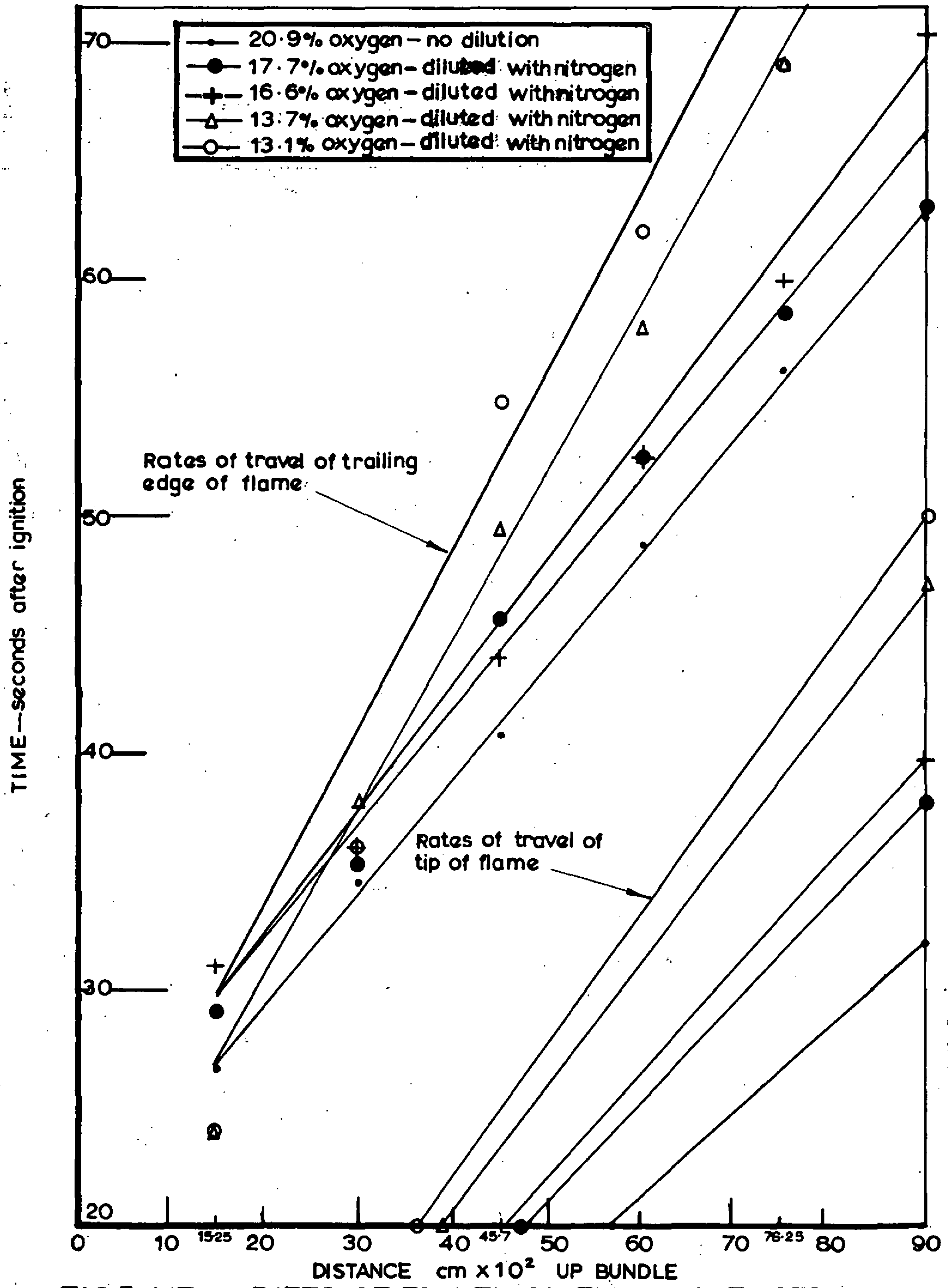

FIG.5. MEAN RATES OF TRAVEL OF TRAILING EDGES OF FLAMES UP TRIPLE STICK BUNDLES AND RATES OF TRAVEL OF FLAME TIPS

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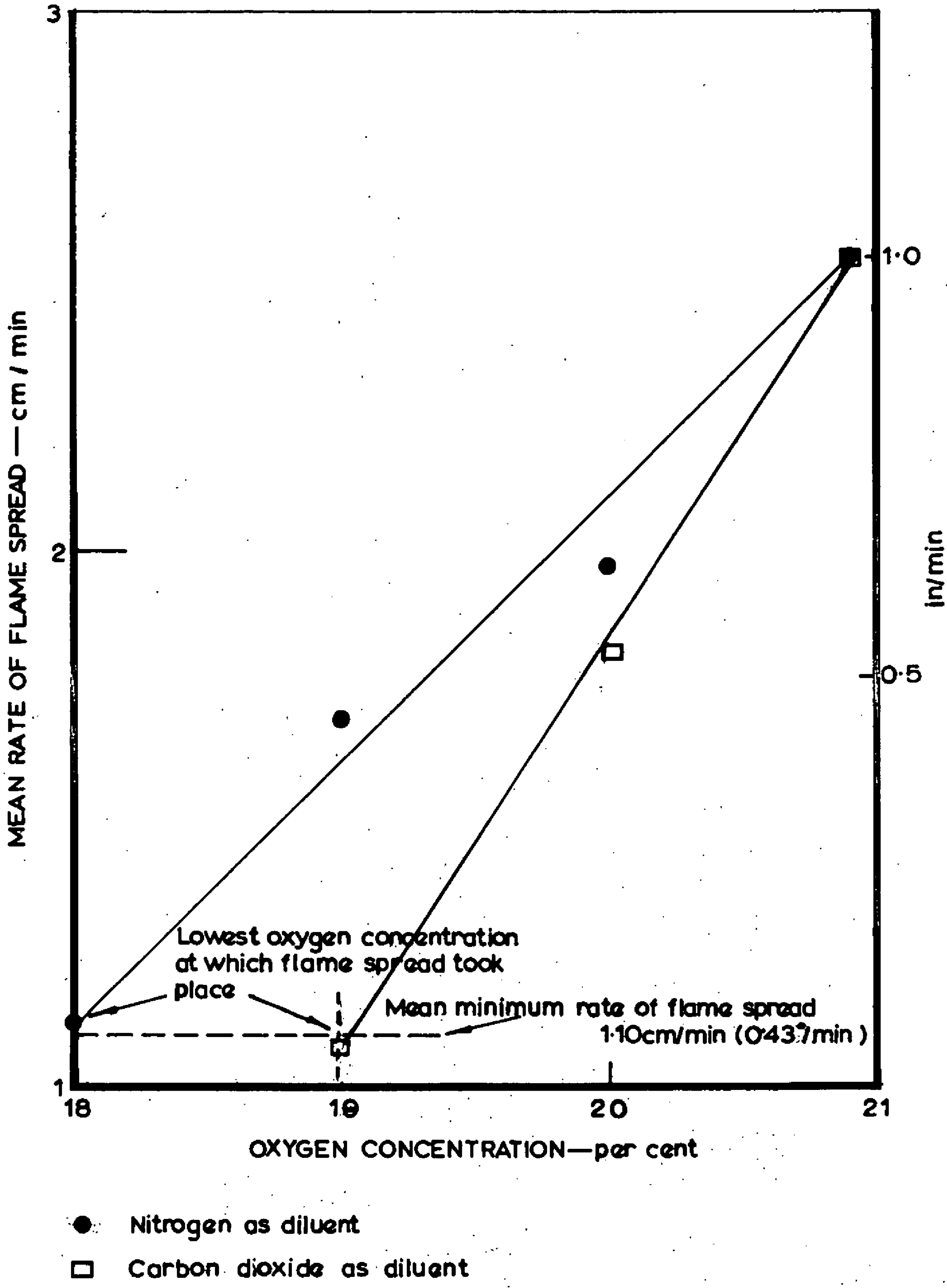

FIG.6. VARIATION OF MEAN RATE OF SPREAD OF FLAME WITH OXYGEN CONCENTRATION (HORIZONTAL 7 LAYER CRIB)

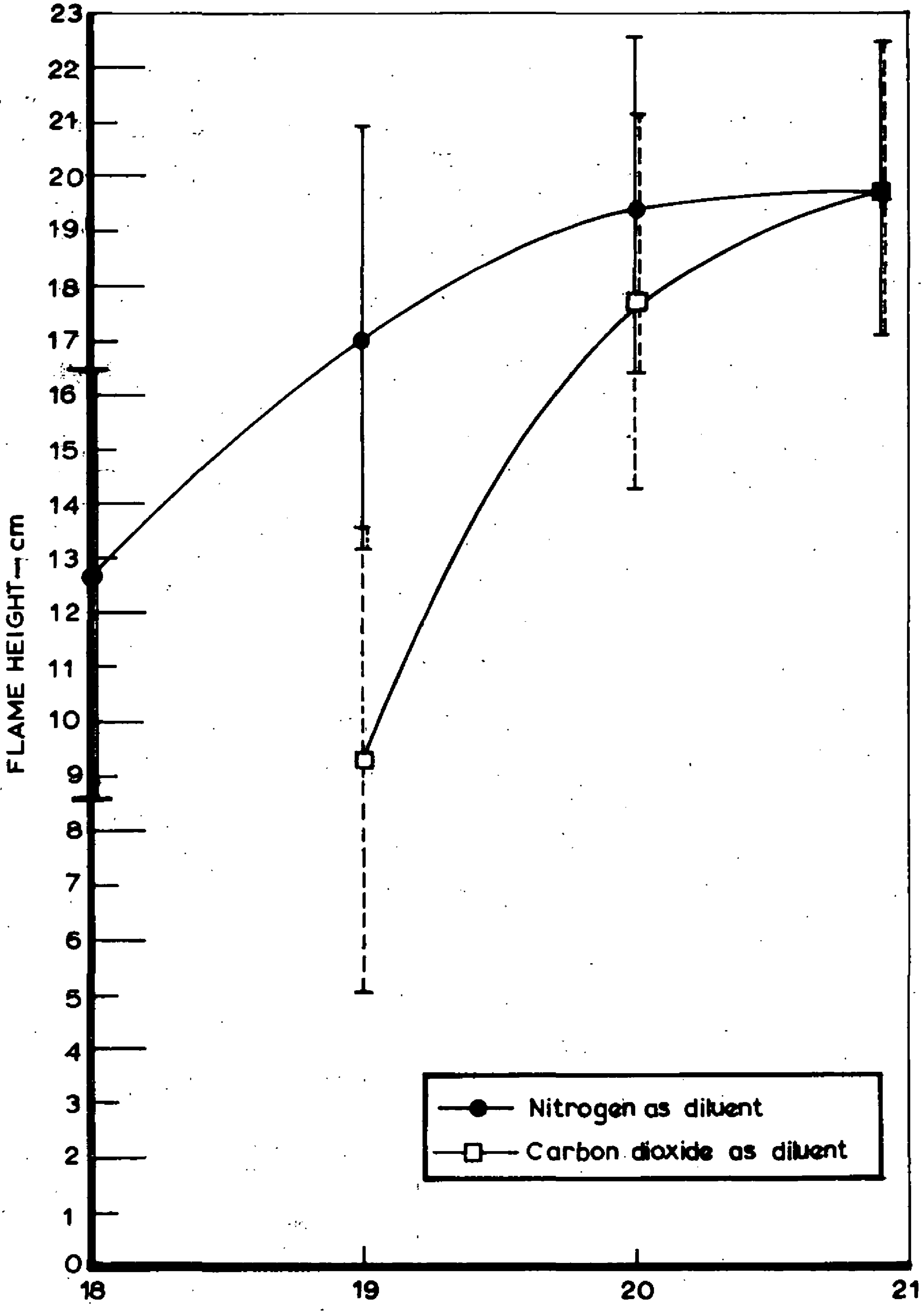

FIG.7 VARIATION OF FLAME HEIGHT WITH OXYGEN CONCENTRATION. MEAN VALUES PLOTTED AND ONE STANDARD VARIATION SHOWN

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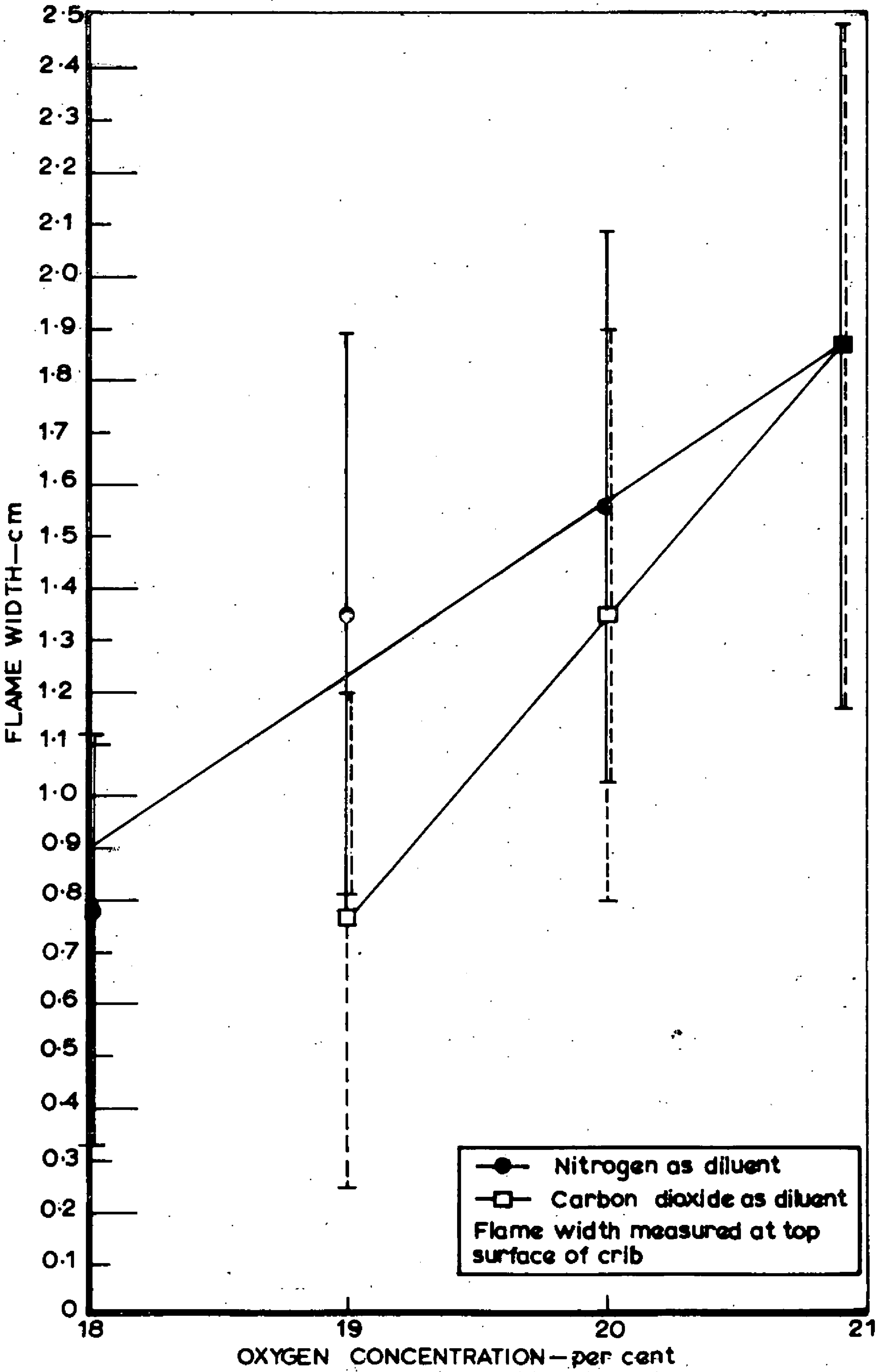
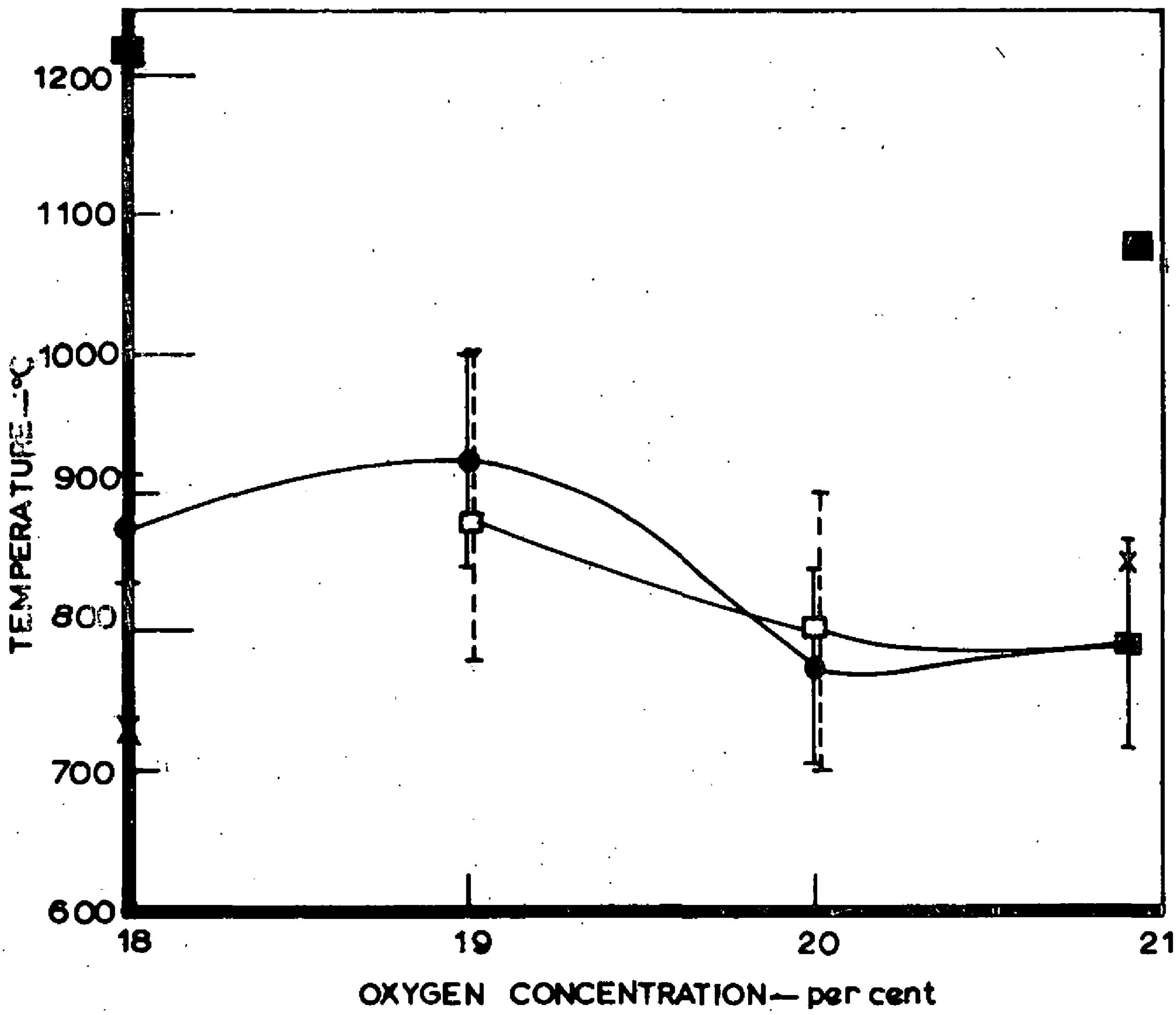


FIG.8. VARIATION OF FLAME WIDTH WITH OXYGEN CONCENTRATION. MEAN VALUES PLOTTED SHOWING ONE STANDARD DEVIATION



—— Measured values

● Nitrogen

□ Carbon Dioxide

■ Estimated values — crib emissivity and function of flame width (equation 2 and 3)

X Estimated values — crib emissivity equals unity

FIG.9. VARIATION OF MEAN PEAK BURNING ZONE TEMPERATURE WITH OXYGEN CONCENTRATION

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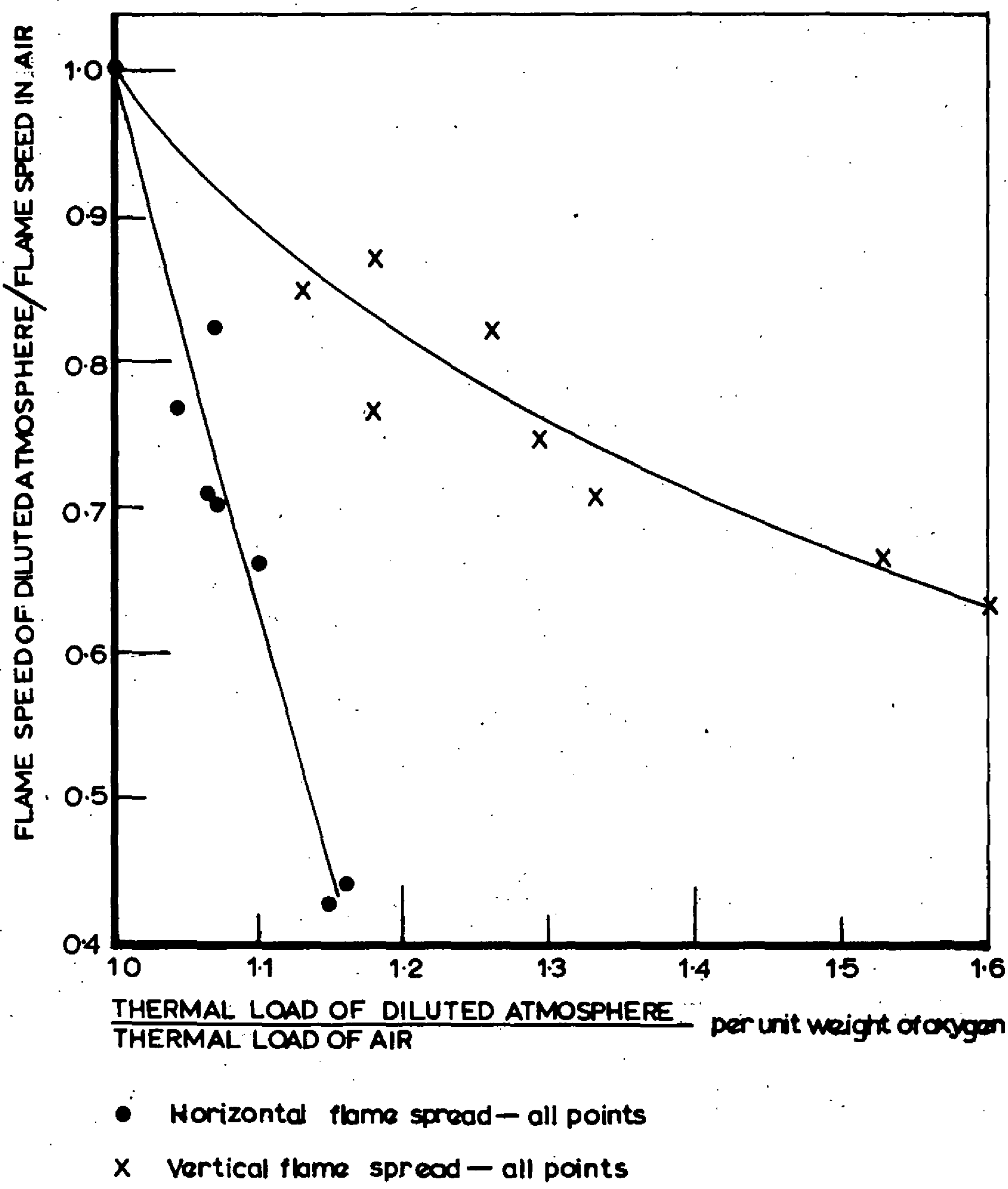

FIG. 10. FLAME SPEED AS FUNCTION OF THERMAL LOAD OF THE ATMOSPHERE

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