Fire Research Note
No 874

THERMAL MEASUREMENTS ON UNPROTECTED STEEL COLUMNS EXPOSED TO WOOD AND PETROL FIRES

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May 1971

FIRE
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F.R. Note No. 874
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SUMMARY

This note describes measurements of temperatures attained by an unprotected steel column heated by wood and petrol fires. From the rate of temperature rise of the column and its dimensions and thermal capacity, rates of heat transfer from the flame to the column were obtained.

The petrol fires gave higher column temperatures and higher rates of heat transfer.

KEY WORDS: Columns, Fire, Heat transfer, Temperature.

DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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Introduction

Considerable economies could be made if the structural steel work of multi-storey car parks did not have to be protected against fire. The fire load density in such buildings is fairly low (though no reliable data seem to be at present available) but in part is made up of petrol and may well on average be less than 10 kg/m^2 (2 lb/ft^2) of floor area.

Experimental fires sponsored by the British Iron and Steel Federation(1) showed that with one arrangement of wood cribs on the floor formed from thick sticks a fire load density of 7.5 kg/m^2 ($1\frac{1}{2}$ lb/ft^2) produced temperatures of not more than 360°C in unprotected steel columns in a compartment. These fires lasted some 30–35 min and the cribs gave flames not more than $1\frac{1}{2}$ m high. To supplement these experiments and to compare the heat transfer from petrol and wood flames, this report describes measurements of temperatures of an unprotected steel column exposed to the flame from a wood crib and from a tray of petrol of comparable size.

Apparatus and experimental method

The tests were carried out in a large building 12 m high, which was reasonably free from draughts. A single I-section mild steel British Standard Beam measuring 20 cm x 15 cm (8 in x 6 in), 2.1 m (7 ft) long and weighing 53 kg/m (35 lb/ft) was set up vertically and thermocouples were attached at 30 cm intervals. The thermocouple junctions were peened into holes, the leads then being attached to the surface for about 5 cm by means of "Autostic" high temperature cement. The lay-out and position of thermocouples, which were attached to both flanges and web, are shown in Fig.1. The outputs of the thermocouples were recorded automatically at 12 s intervals.

A 1 m square wood crib was built either symmetrically round the column or butted against one side of the column (see Fig.1), the latter position corresponding to that in the compartment used for the B.I.S.F. experiments. Cribs were built from sticks either 4 cm or 2 cm thick with an air space between sticks of 4 cm in each case. The weight of a crib of either stick thickness was 29.2 kg, the same as that of a crib in the B.I.S.F. experiments at 7.5 kg/m^2 fire load density. The cribs were ignited with kerosene-soaked strips of fibre insulation board placed between the sticks in the lowest layer.

The petrol fires were carried out with the petrol floated on water contained in a number of steel trays arranged round the column to form approximately a square of the same size as the wood cribs. Three depths of petrol were burned.

The quantities of petrol were chosen to give:-

a. the same fuel weight as a wood crib

b. the same total heat generated as a wood crib, approximately

c. a fire of very short duration.

The experiments are listed in Table 1. Flame height and duration of burning were noted for both wood and petrol fires. The steel temperature was recorded throughout the whole of the flaming period and for some time after, to obtain cooling curves, wood embers being raked away as soon as flaming ceased.

Results - column temperature

The results are given in Table 2 and in Figs 2-8, which show the variation with time of flame height and mean steel temperature at different heights in the column. The mean steel temperatures are averages of the temperatures indicated by all thermocouples at each level (Fig.1). In general, the web thermocouple indicated a higher temperature than the flange thermocouples at the same height; this was probably due to the flames "funnelling" up the column and to more cooling from the flanges. When the column was in the centre of the fire, the greatest temperature difference between the web and flanges at any height was generally less than 25 per cent of the mean temperature rise at that height. When the column was heated asymmetrically, i.e. the column was at one side of the fire, there were larger temperature differences between web and flanges.

Results - heat transfer to column

The column receives heat from the flame by radiation and convection transfer. When the column is relatively cool this heat produces a corresponding rate of temperature rise in the column. Some heat, however, is re-radiated by the column and the amount of re-radiation increases as the column temperature increases. In addition the column temperature is modified by heat conduction up and down the column along temperature gradients.

The contribution to the rate of temperature rise in any thin section of the column, arising from the non-linear temperature gradient along the column and the consequent difference between the rate of conduction of heat into and out of the section, was estimated from the temperature distribution along the column. It was found to be not more than 5 per cent of the actual rate of temperature rise in a section and was therefore neglected.

The nett heat transfer rate from the flame to the column was found directly from the rate of temperature rise of the column, its thermal capacity and surface area. For the tests with the column in the centre of the crib or petrol tray the perimeter of the column was taken as that of a rectangle 20 cm x 15 cm enclosing the column since it was assumed that radiation transfer was the predominant mode of heat transfer and that because the channels in the I-section column would tend to act effectively as cavities* this would give a more meaningful value for an intensity of radiation from the flame. Convection transfer would occur on all faces but was thought to be relatively unimportant for the large flames, though possibly the predominant mode for very small flames. For the tests with the column at the side of the crib it was assumed that heat transfer took place only to one

*It was thought that relatively little radiation transfer occurred from the flame inside the cavity since a flame from wood fuel several feet thick is required to give a substantial emissivity.

side of the column, i.e. to an area 20 cm wide.

The calculated nett heat transfer rates, calculated for these assumptions at a height of 60 cm above the base of the column, are given in Table 3 for the period of the fire when the flame height was a maximum and the heat transfer rate therefore relatively constant.

An estimate of the gross heat transfer to the column was derived (Table 3) from the heating and cooling curves, details of the calculation being given in the Appendix. This is a measure of the "thermal driving force" of the flame and is required before estimates can be made of the heat transfer rate to a column of different dimensions or mass. Actually since at these temperatures the rate of re-radiation from the column was generally less than 10 per cent of the rate of storage of heat in it, the gross heat transfer rate was only slightly larger than the nett.

Discussion

The cribs of 4 cm thick wood burned slowly and gave small flames which produced large percentage differences between the temperature rises at the top and bottom of the column. The cribs of 2 cm thick wood and the two larger petrol fires burned more rapidly, producing much larger flames and a more even heating of the column.

The petrol fires gave very large flames enveloping the column and comparable heat transfer rates in their early stages. The rate of temperature rise of the steel was similar in these fires in the first 4 min., but the highest steel temperatures were eventually obtained in the fire which lasted longest. The 2 cm thick wood fires gave much larger flames than the 4 cm thick wood fires and a fire lasting only about half as long, yet they gave higher steel temperatures. The flame height of the 4 cm thick wood fires rapidly diminished after a maximum at 3 min. (This may in part have been because the ignition strips burned out then and no longer augmented the burning wood) so that the heat transfer rates quoted in Table 3 were not maintained for very long.

The heat transfer rate at a height of 60 cm in the petrol fires was 2-3 times that in the 2-cm wood fuel fires and this difference is probably a reflection of a higher flame temperature or emissivity since at this low height there was not much difference in flame thickness.

Even though the total release of heat was nearly the same in tests 1, 3, 4 and 7 the maximum column temperatures were different, being higher for the tests of shorter duration.

Conclusions

1. In general the maximum temperature attained in the column depended on

(a) the quantity of fuel
(b) the duration of the fire
(c) the type of fuel

2. Near the base of the column the petrol fires gave higher heat transfer rates producing higher column temperatures than the 2-cm thick wood cribs, even though the flames appeared to be similar in thickness. This suggests that the higher heat transfer of the petrol flames was due to higher emissivity or flame temperatures.

3. The petrol fires also gave larger temperatures than the wood higher up the column and this may in part be due to the taller flames produced by the petrol fires which would tend to give a thicker flame higher up the column.

4. The arrangement of fuel makes substantial differences to the flame height and the extent of the heating and there is sufficient variation of heating rates at various heights and of conduction up the column to produce temperatures at the column base which for some fuel arrangements, albeit corresponding to a low fire load, exceed the value of 500°C usually taken as safe for a loaded column. The column temperatures that would be reached had the fire been in an enclosure could be higher as a result of re-radiation from the walls.

References

(1) BUTCHER, E. G. and CHITTY, T. B. Department of Scientific and Industrial Research and Fire Offices' Committee Joint Fire Research Organization. Internal Note No.218. The behaviour of structural steel in fire conditions representative of low fuel loads. March, 1965.

(2) Technical Data on Fuel. Ed. by H. M. Spiers. 6th edition, 1961.

APPENDIX

DETAILS OF HEAT TRANSFER CALCULATIONS

A heat balance on a section of the column of height H bounded by two horizontal planes can be written

$$I\,L\,H + C = m\,H\,\sigma\left(\frac{d\theta}{dt}\right)_1 + R\,L\,H \qquad \text{........ (1)}$$

where I = the gross rate of heat transfer to unit area of the column by convection and radiation transfer from the flame

L = the effective perimeter of the column

C = the net accumulation of heat in section by conduction along the column

m = the weight per unit length of column

σ = specific heat of mild steel* at the mean temperature of section (θ)

$\left(\frac{d\theta}{dt}\right)_1$ = rate of temperature rise of the section

R = rate of radiation loss per unit area from section

R could be estimated with sufficient accuracy from the rate of cooling of the column, i.e. from

$$R\,L\,H\,(1 + f) - C^1 = m\,H\,\left(\frac{d\theta}{dt}\right)_2 \qquad \text{........ (2)}$$

where f = the ratio of rates of heat loss by natural convection from vertical surfaces and by radiation obtained from published charts(2). f was generally about one-third.**

C^1 = the net accumulation of heat in the section by conduction along the column and $\left(\frac{d\theta}{dt}\right)_2$ is the rate of fall of temperature of the section.

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*The specific heat of steel varies markedly with temperature(2).

**Assuming an emissivity for rough oxidised steel of unity(2).

Table 1

Type and position of fires

Test No.	Weight of fuel : kg	Type of fire	Position of column relative to crib or petrol tray	Comments
1	29	Wood crib : 28 sticks 4 cm x 4 cm x 1 m 1 : 1 spacing.	Centre	Long duration of burning, crib similar to that used in B.I.S.F. compartment tests.
2, 5	29	"	Side	"
3, 4	29	Wood crib : 112 sticks 2 cm x 2 cm x 1 m 1 : 2 spacing.	Centre	Higher burning rate shorter duration than cribs used in tests 1, 2 and 5.
6	29	Petrol (9 gal)	Centre	Weight of petrol same as weight of wood cribs in tests 1-5.
7	12	Petrol (3.5 gal)	Centre	Approximately same calorific output as wood cribs.
8	3.5	Petrol (1 gal)	Centre	Petrol fire of short duration.

Table 2

Combustion and temperature results

Test No.	Fuel	Column position	Maximum flame height m	Duration of substantial burning* min	Mean rate of burning kg/min	Mean rate of heat release** k cal/min	Maximum temperature of column °C	Time to reach maximum column temperature min
1	Wood, (4 cm sticks)	Centre	2.1	24	1.21	4,000	420	20
2	"	Side	2.2	22	1.32	4,350	137	24
5	"	Side	1.8	22.5	1.29	4,250	137	28
3	Wood (2 cm sticks)	Centre	3.3	13	2.23	7,350	505	8
4	Wood (2 cm sticks)	Centre	3.6	12	2.42	8,000	505	8
6	Petrol (29 kg)	Centre	4.5	12	2.42	25,000	730	8
7	Petrol (12 kg)	Centre	4.5	5.5	2.2	23,000	620	4
8	Petrol (3.5 kg)	Centre	3.0	1.5	2.3	24,000	232	2

*Time for which flames were more than 30 cm high

**Assuming volatile calorific value of 3,300 cal/gm

Table 3

Estimated gross and nett heat transfer rates to column at 60 cm above base of column

Test No.	Fuel	Position of column	Gross heat transfer rate cal $cm^{-2}s^{-1}$	Nett heat transfer rate cal $cm^{-2}s^{-1}$
1	Wood crib (4 cm sticks)	Centre	1.00	0.97
2 5	"	Side	0.73 0.57	0.68 0.57
3 4	Wood crib (2 cm sticks)	Centre	0.93 1.38	0.84 1.17
6	Petrol (29 kg)	Centre	2.73	2.64
7	Petrol (12 kg)	Centre	2.42	2.26
8	Petrol (3.5 kg)	Centre	2.69	2.67

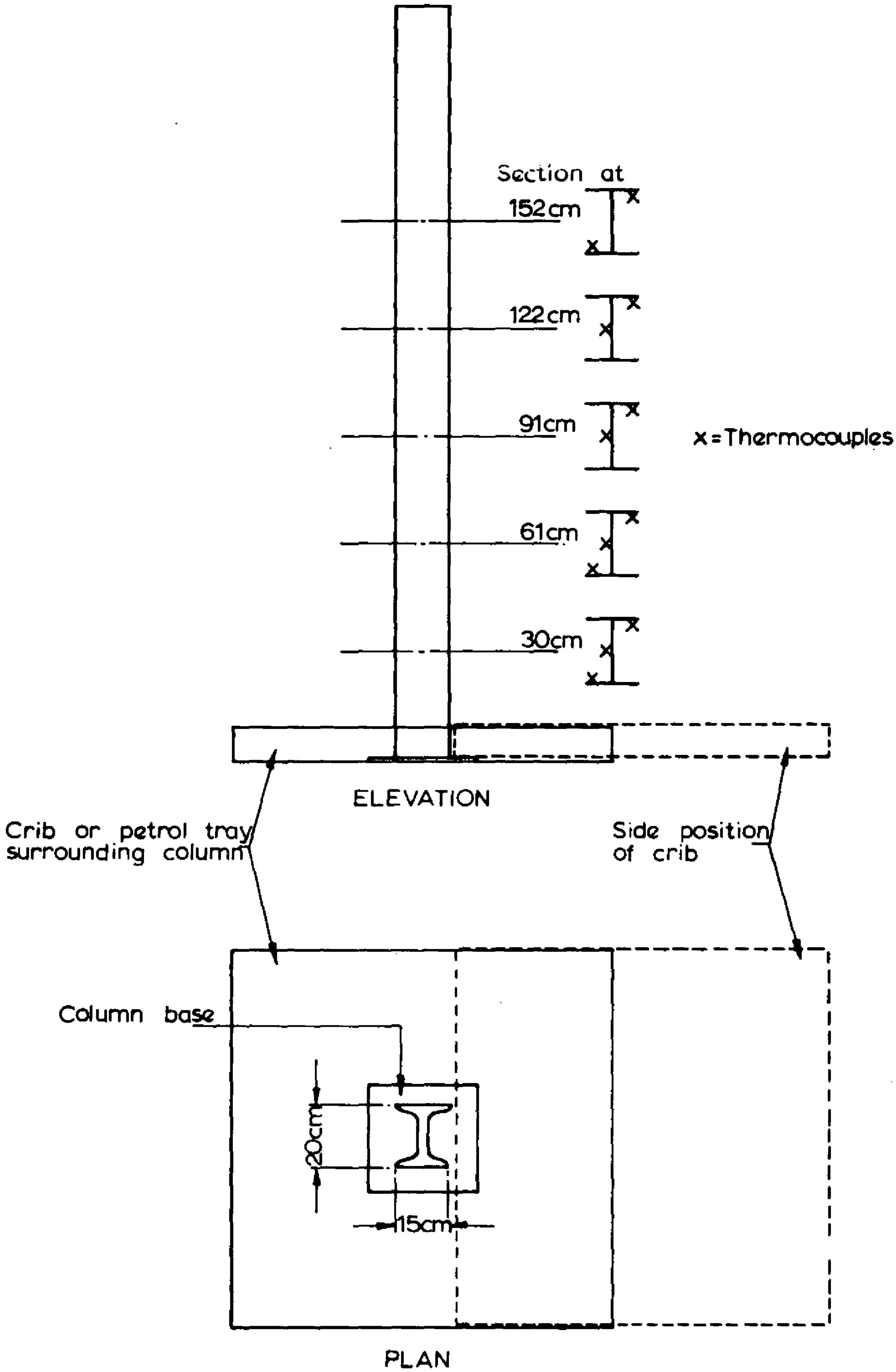
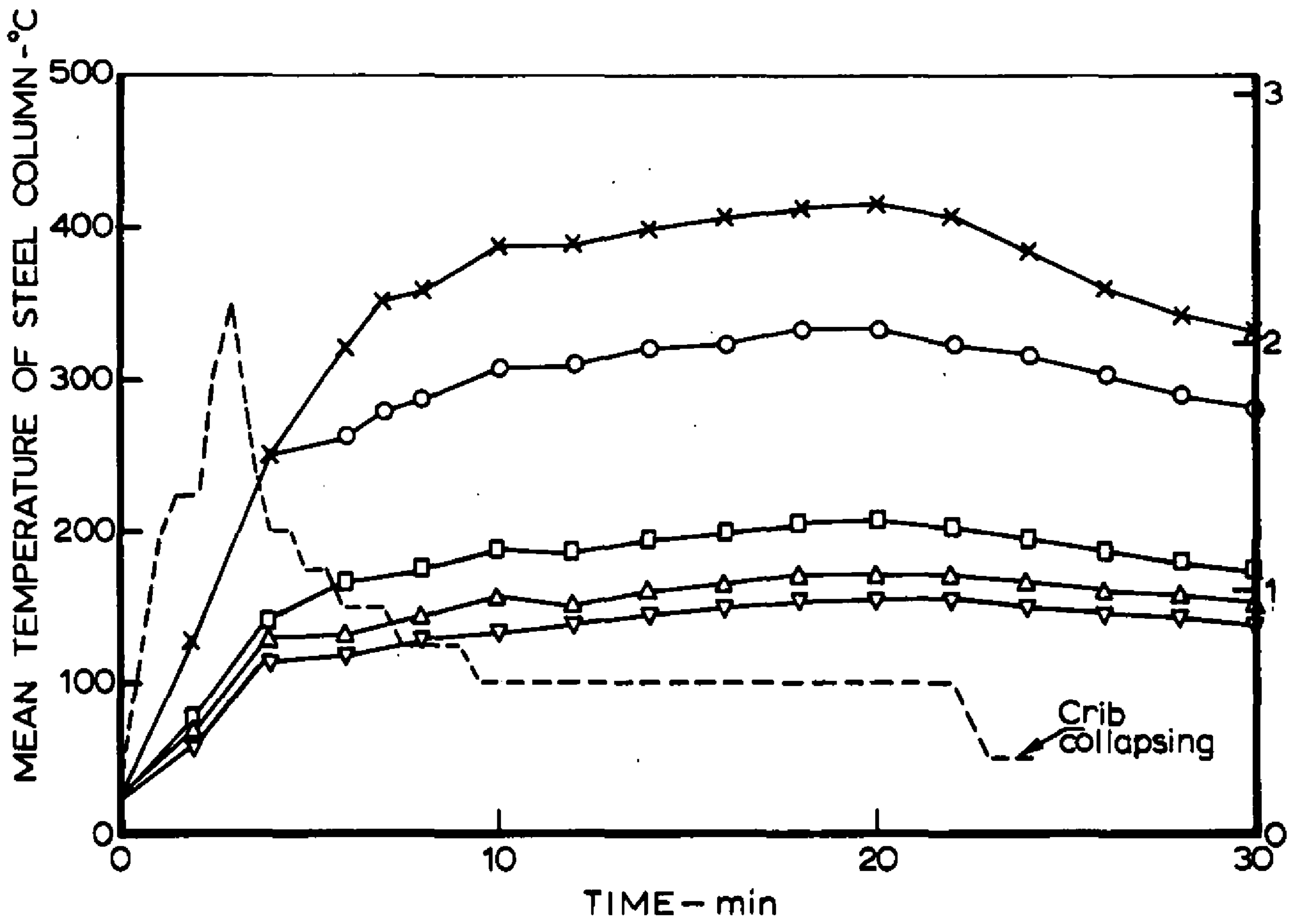
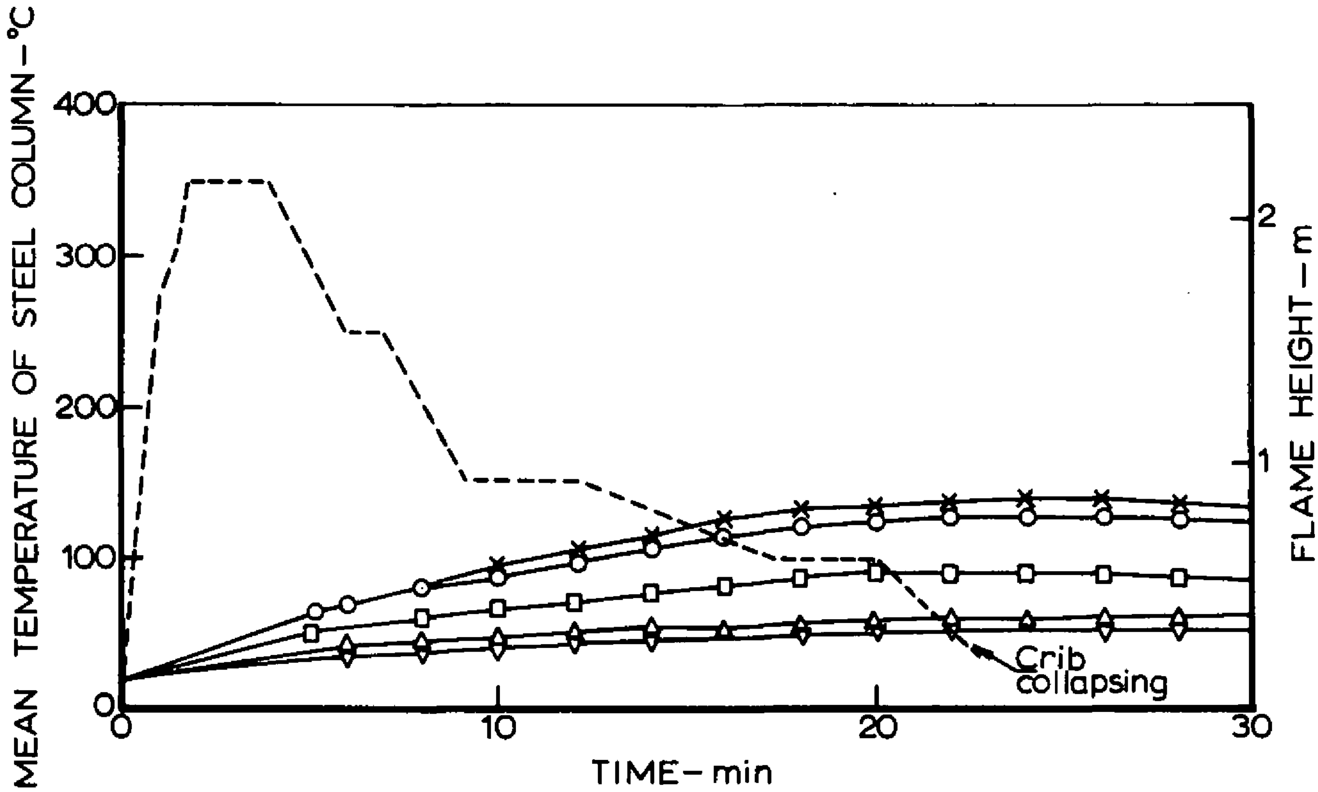


FIG. 1. LAYOUT OF CRIBS OR PETROL TRAY AND POSITIONS OF THERMOCOUPLES



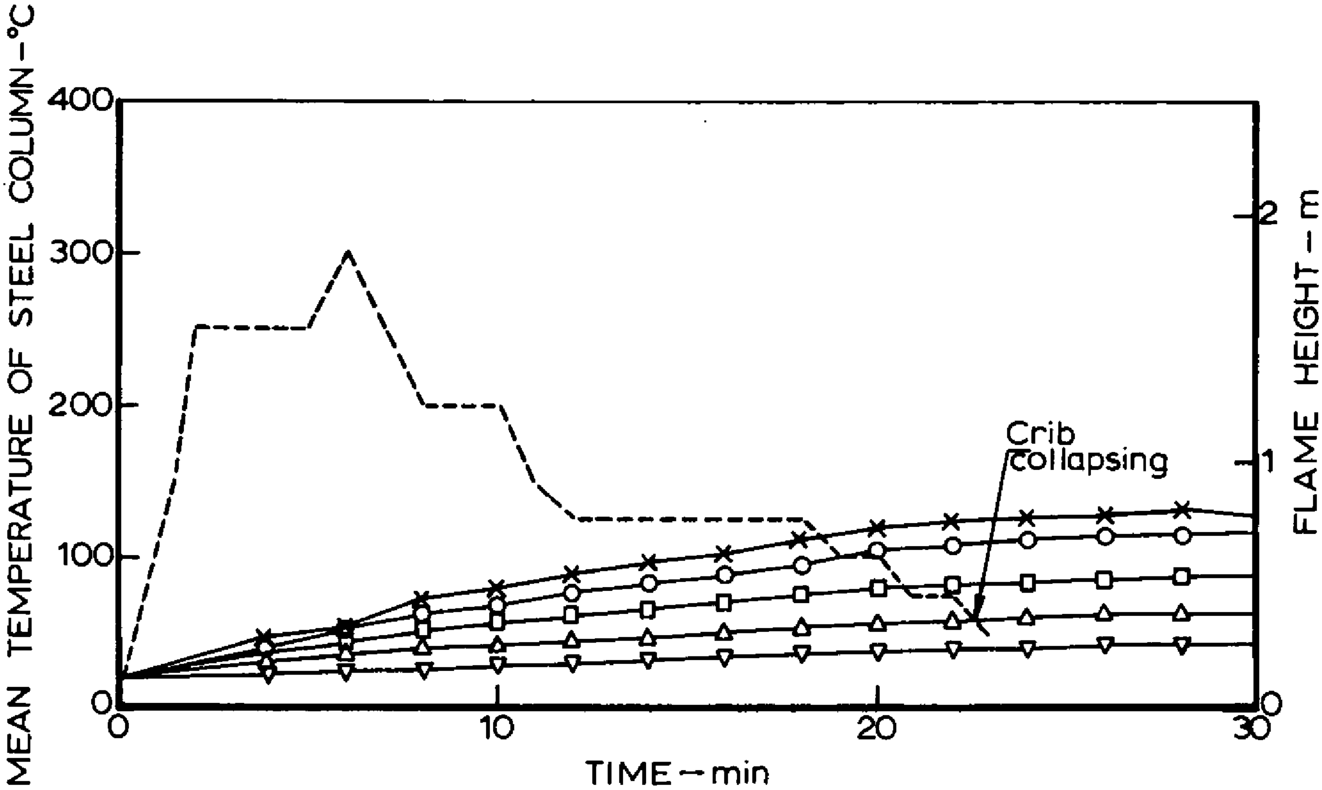
Mean temperatures of steel column	
Symbol	Height above ground
×——×	30 cm
○——○	61 cm
□——□	91 cm
△——△	122 cm
▽——▽	152 cm
-------	Flame height

FIG. 2. TEST No. 1: MEAN CROSS-SECTION TEMPERATURES OF COLUMN AND FLAME HEIGHT
COLUMN IN CENTRE OF WOOD CRIB: 4 cm STICKS



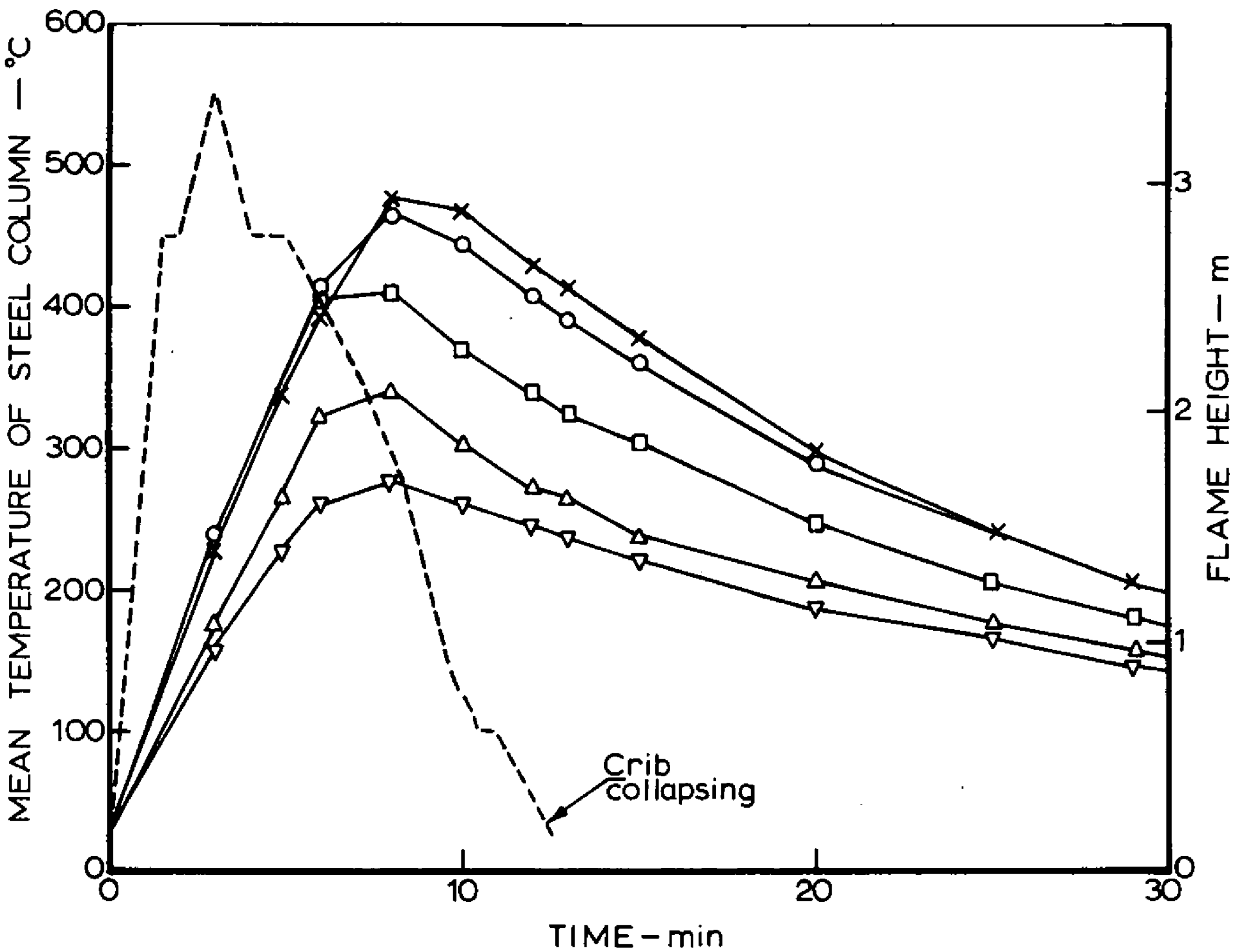
Mean temperatures of steel column	
Symbol	Height above ground
×——×	30 cm
o——o	61 cm
□——□	91 cm
△——△	122 cm
▽——▽	152 cm
--------	Flame height

FIG. 3. TEST No. 2: MEAN CROSS-SECTION TEMPERATURES OF COLUMN AND FLAME HEIGHT
COLUMN AT SIDE OF WOOD CRIB: 4 cm STICKS



Mean temperatures of steel column	
Symbol	Height above ground
×———×	30 cm
o———o	61 cm
□———□	91 cm
△———△	122 cm
▽———▽	152 cm
- - - - - -	Flame height

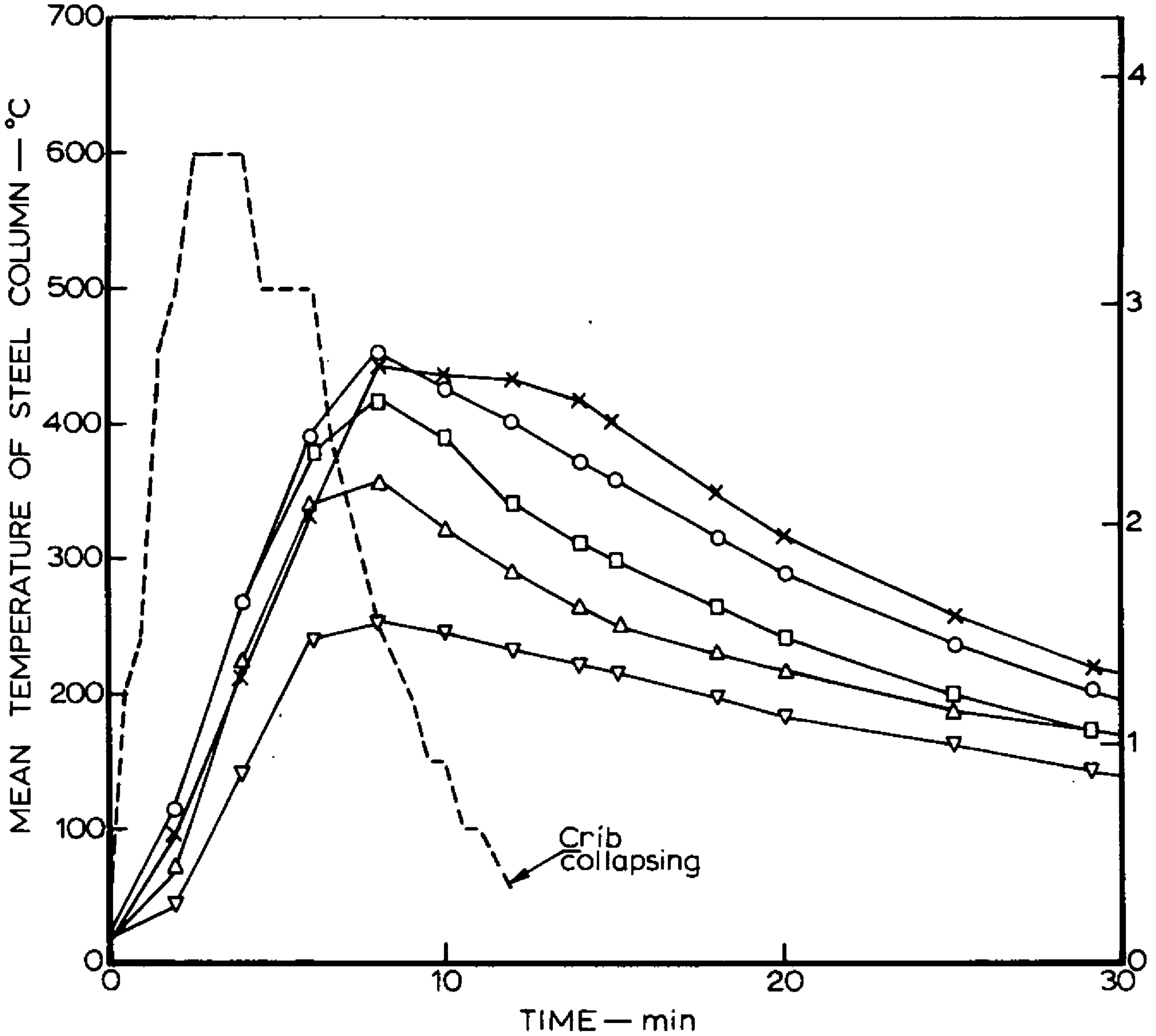
FIG. 4. TEST No. 5: MEAN CROSS-SECTION TEMPERATURES OF COLUMN AND FLAME HEIGHT
COLUMN AT SIDE OF WOOD CRIB: 4cm STICKS



Mean temperatures of steel column	
Symbol	Height above ground
×———×	30 cm
o———o	61 cm
□———□	91 cm
△———△	122 cm
▽———▽	152 cm
- - - - - -	Flame height

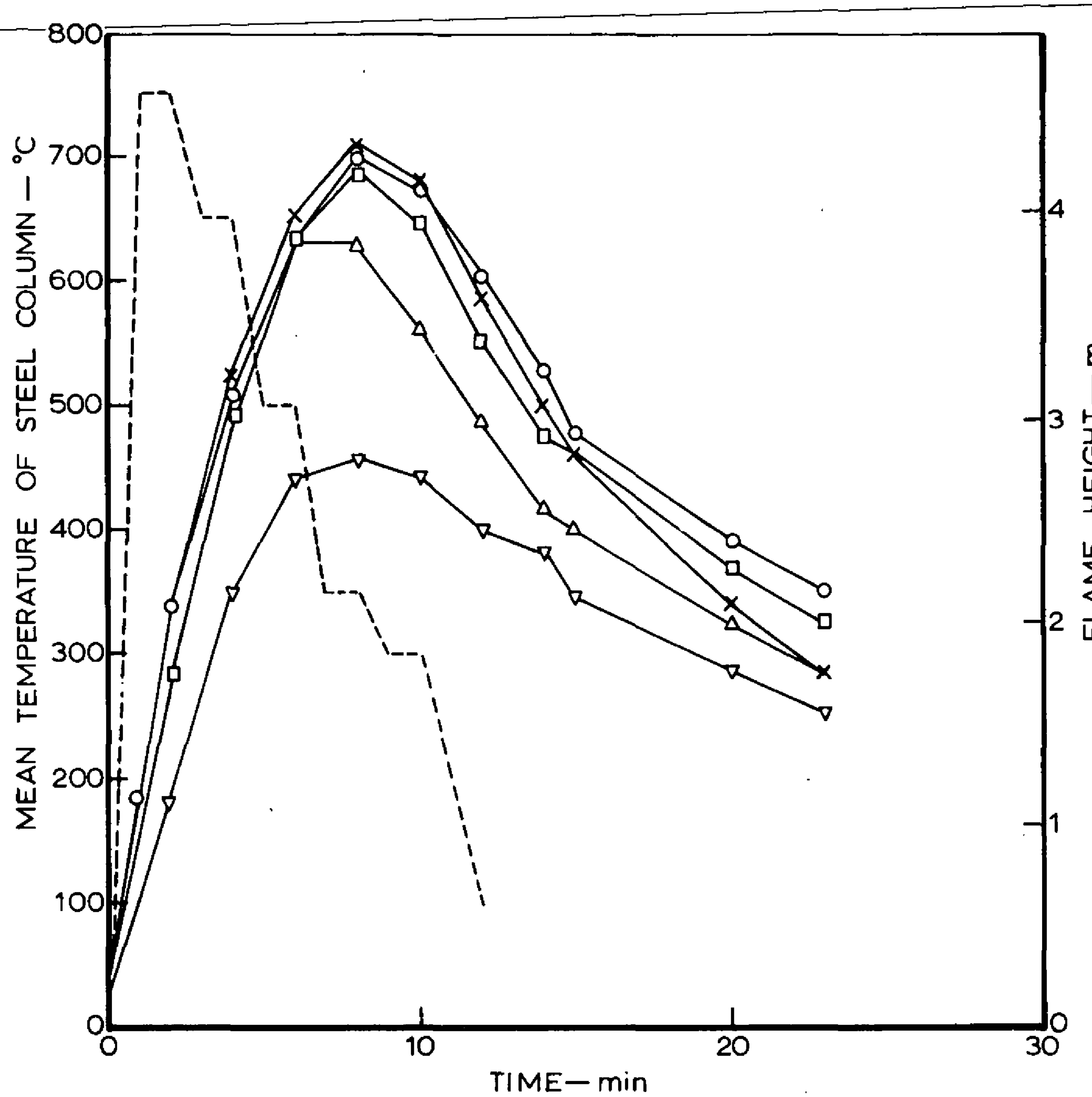
FIG. 5. TEST No. 3 : MEAN CROSS-SECTION TEMPERATURES OF COLUMN AND FLAME HEIGHT
COLUMN IN CENTRE OF WOOD CRIB : 2 cm STICKS

1/6619 Internal Note 246 + F.R. 874



Mean temperatures of steel column	
Symbol	Height above ground
×———×	30 cm
o———o	61 cm
□———□	91 cm
△———△	122 cm
▽———▽	152 cm
- - - - - - -	Flame height

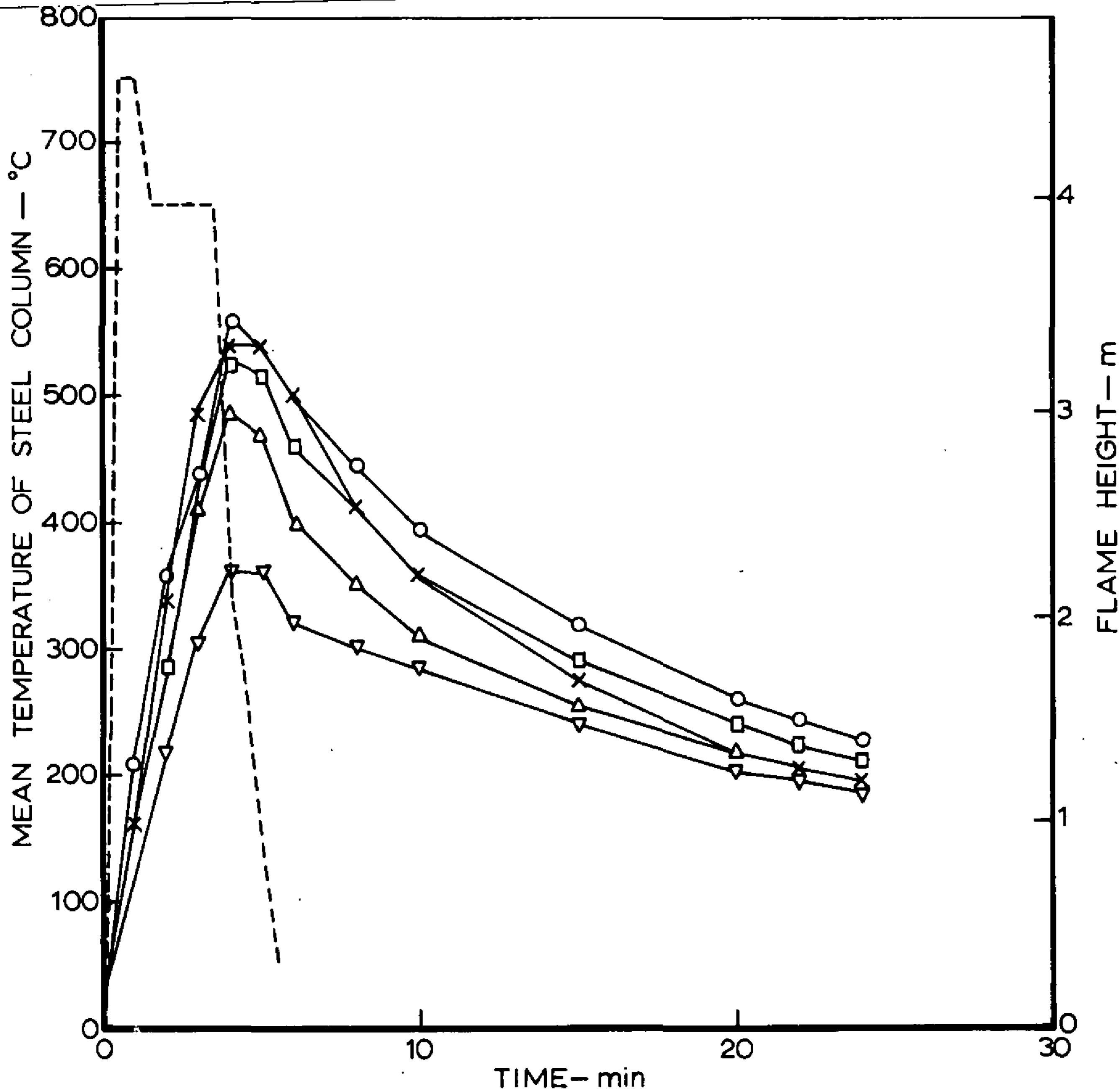
FIG. 6. TEST No. 4: MEAN CROSS-SECTION TEMPERATURES OF COLUMN AND FLAME HEIGHT
COLUMN IN CENTRE OF WOOD CRIB: 2cm STICKS



Mean temperatures of steel column	
Symbol	Height above ground
×——×	30cm
o——o	61cm
□——□	91cm
△——△	122cm
▽——▽	152cm
-------	Flame height

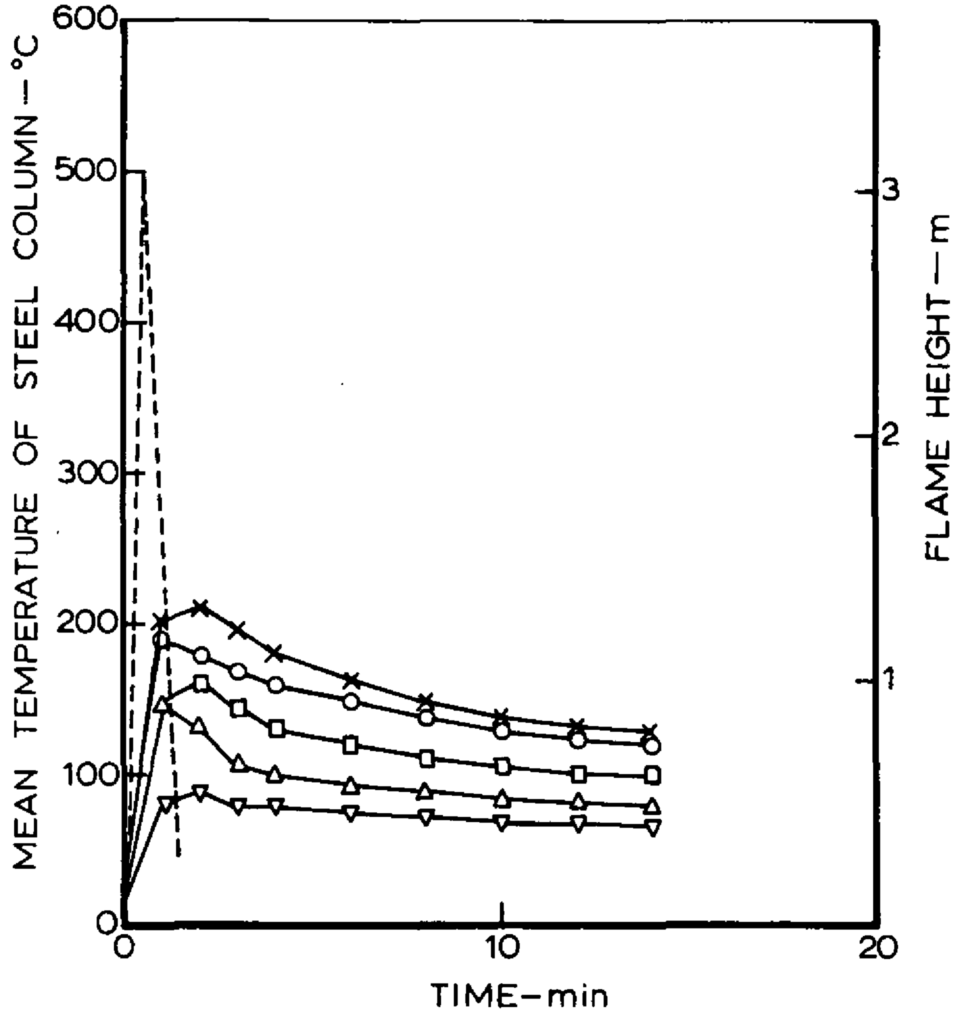
FIG. 7. TEST No. 6: MEAN CROSS-SECTION TEMPERATURES OF COLUMN AND FLAME HEIGHT
COLUMN IN CENTRE OF PETROL FIRE (29 kg)

1/6621 Internal Note 246 + F.R. 874



Mean temperatures of steel column	
Symbol	Height above ground
×——×	30cm
○——○	61cm
□——□	91cm
△——△	122cm
▽——▽	152cm
------	Flame height

FIG. 8. TEST No.7: MEAN CROSS-SECTION TEMPERATURES OF COLUMN AND FLAME HEIGHT COLUMN IN CENTRE OF PETROL FIRE (12kg)



Mean temperatures of steel column	
Symbol	Height above ground
×——×	30 cm
o——o	61 cm
□——□	91 cm
△——△	122 cm
▽——▽	152 cm
------	Flame height

FIG. 9. TEST No. 8: MEAN CROSS-SECTION TEMPERATURES OF COLUMN AND FLAME HEIGHT
COLUMN IN CENTRE OF PETROL FIRE (3·5 kg)