THE BEHAVIOUR OF STRUCTURAL STEELWORK IN NATURAL FIRES

British Steel
Swinden Technology Centre

FRS
Building Research Establishment Ltd
Fire Research Station

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FOREWORD

Between 1983 and 1986 British Steel, Swinden Technology Centre, carried out two fire test programmes using a purpose built compartment constructed within the BRE/FRS large building test facility at Cardington in Bedfordshire.

The aim of the first programme was to obtain fundamental information concerning the heating rates and temperatures attained by various unprotected and partially exposed structural beams and columns, including a water filled hollow section, in natural fires of different but known severities. A total of 21 tests were conducted in a compartment having a floor area of 50 m^2 in which the size, nature and distribution of the fire loading, the ventilation characteristics and the thermal properties of the wall and ceiling linings were all altered.

In the second programme, two tests were carried out on simple structural frames constructed within the same compartment as described above using unprotected beams and blockwork infilled columns. These frames were loaded to normal design levels. The objective of the tests was to determine the extent of structural interaction under fire conditions when members are evaluated as part of an assembly rather than as single elements.

Both these research programmes were co-sponsored by British Steel, (Sections, Plates and Commercial Steels), and the UK Department of the Environment. Since the fundamental nature of the experimental data obtained could well be of benefit to other researchers in the field of fire engineering both organisations have kindly agreed to make the results of the work more widely available.

The information contained within the present document are reproductions of the original contract reports prepared for the sponsors at the time the work was carried out. In the light of more recent research some of the statements made may no longer be valid.

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THE TEMPERATURES ATTAINED BY UNPROTECTED STRUCTURAL STEELWORK IN NATURAL FIRES

FINAL REPORT

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THE TEMPERATURES ATTAINED BY UNPROTECTED STRUCTURAL STEELWORK IN NATURAL FIRES

FINAL REPORT

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SYNOPSIS

A collaborative test programme was initiated jointly by Swinden Laboratories of the British Steel Corporation and the Fire Research Station of the Building Research Establishment (DoE) to determine the heating rates of a wide range of unloaded and unprotected steel beams and columns in fires of different but known severities. For the purposes of this work a large fire compartment measuring 8.6 x 5.5 x 3.9 m high was built within the FRS hangar at RAF Cardington so that tests were independent of weather conditions.

A total of 21 fire tests were carried out between 15th August 1983 and 15th February 1985. Eight fire tests compared data generated by the combustion of 10, 15 and 20 kg/m^2 of soft wood using the $^1/2$, $^1/4$ and $^1/8$ ventilation of one wall of the compartment. An additional four wood fires examined alterations in the ventilation for a given opening factor, the effect of an uneven fire load, different methods of ignition and a change in the compartment lining. The remaining fire tests monitored the behaviour of the air and steel temperatures during the combustion of a mixed wood/polypropylene fuel.

An increase in the fire load density and a reduction in ventilation both raised the maximum average air/gas temperatures. The rate of combustion during the early stages of a fire using 15 kg of wood/m^2 of floor area and the $^1/4$ ventilation of one wall was similar to the BS476:Pt 8 standard furnace curve. The burning characteristics of mixed wood/polypropylene fuels resulted in a rapid rise in the air/gas temperature during the early stages of the test accompanied by a large volume of black smoke which influenced the combustion behaviour.

The rise in temperature of the steelwork was clearly influenced by the H_p/A value of the member and its location in the compartment. A reduction in the maximum air/gas temperature resulted in a fall in steel temperatures; hence the uneven distribution of fuel and the change from simultaneous ignition to a growing fire situation were beneficial. Also the change in compartment lining had a marked effect on steel temperature. The introduction of plastic to the fuel load had only a small effect on the maximum average steelwork temperatures recorded in these tests. Despite a degree of distortion the temperature profiles across the partially protected columns and the shelf angle floor were similar to those recorded across the same forms of construction in the standard furnace test. The water cooling of the rectangular hollow steel section was found to be most effective once recirculation problems had been overcome.

Fire tests inside the compartment lined with Gyproc 'Fireline' plasterboard had similarities with the records obtained in the early BISF/FRS work which utilised a smaller compartment with walls rendered in plaster. The results suggested that if the behaviour of a real fire is to be related to an equivalent heating time in the BS476:Pt 8 fire test an allowance must be made for the thermal capacity of the compartment and the height of the ventilation openings.

Sufficient confidence can be placed in the appropriate time equivalent relationship to assess the influence on steel temperature of more severe fires than examined at Cardington.

This investigation has provided valuable and hitherto unavailable experimental data on the behaviour of steel building elements in natural fires as compared to idealised furnace heating conditions. The provision of design tables related to the temperature sensitivity of structural steel beams and columns in a wide range of fire environments highlights those situations where individual steel members have adequate inherent fire resistance to remain unprotected. This information is particularly relevant in view of the current problems being experienced in the use of reinforced concrete as an alternative material for high rise buildings.

CONTENTS

THE TEMPERATURES ATTAINED BY UNPROTECTED STRUCTURAL STEELWORK IN NATURAL FIRES

FINAL REPORT

1. INTRODUCTION

The use of fire engineering principles permits a structural engineer to design a building to withstand a natural fire of a given severity without collapse. The method involves the determination of the temperature changes in any particular member and comparison with a limiting temperature based on its required load bearing capacity. Although much experimental data has been obtained through BS476:Pt 8 tests in standard fires, there is a need to gather additional information on the behaviour of unprotected steel members in well documented natural fires.

In recent years a number of research establishments have constructed compartments of various sizes and carried out natural fire tests using a variety of fire loads and ventilation conditions. The work carried out jointly by the Fire Research Station and the British Iron and Steel Federation in 1964 was of particular importance[1]. Two fire compartments measuring 7.7 x 3.7 x 2.9 m high formed part of a building, schematically illustrated in Fig. 1, which was erected on a greenfield site using materials of construction similar to those found in current buildings. The external walls of each fire compartment were of common brick, the internal subdivision being completed by a wall of lightweight concrete blocks. The whole of the inside wall surface of each compartment was rendered with a coating of vermiculite/gypsum plaster. The ceiling was lined with refractory concrete slabs and a concrete floor completed the design. Window openings having refractory concrete lintels were formed in each of the two opposite walls to give an initial ventilation area for each compartment equal to one half of the front wall; the area of the openings could be further reduced to one quarter and one eighth. A number of steel sections were positioned inside the building but with the exception of a 203 x 203 mm x 52 kg/m universal column they were all protected by insulation. There were also a number of unprotected steel members placed outside the building. Fire load densities spanning 7.5 to 60 kg/m^2 were considered to be representative of hospital, domestic, leisure and commercial occupancies.

A similar programme of fire testing was carried out by CTICM in which data on the behaviour of unprotected steelwork was based on a column with a section factor close to that used in the BISF/FRS work[2]. However, in this case the compartment size was much smaller than that used in the BISF/FRS tests. In view of the limited available information, a collaborative test programme was initiated jointly by Swinden Laboratories of the British Steel Corporation and the Fire Research Station of the Building Research Establishment, DoE, to determine the heating rates of a wide range of unloaded and unprotected steel beams and columns in fires of different but known severities. The principal objectives were as follows:-

(1) To highlight situations where steelwork may have sufficient inherent fire resistance to be left unprotected.

(2) To study the burning characteristics of modern materials in relation to the specification of fire protection requirements.

(3) To provide sufficient information to enable the heating rates of steel members to be calculated for different fire exposure conditions.

(4) To provide confidence in the adoption of an analytical approach which would avoid the costs of expensive fire tests.

For the purposes of this work a large fire compartment measuring 8.6 x 5.5 x 3.9 m high was built inside the FRS hangar at RAF Cardington so that tests were independent of weather conditions. As the hangar, measuring 200 x 80 x 60 m high was so much larger than the test rig there was little possibility of it influencing the combustion characteristics. Individual reports have been prepared on the construction of the compartment and on each of 21 fire tests carried out since August 1983[3-22].

A number of factors were considered in the design of the compartment[3], the front elevation of which is shown in Fig. 2.

(a) The size was to be representative of multistorey building compartments such as a large office or a 6-bed hospital ward. In the final tests the compartment volume was reduced by 45%.

(b) The size of windows had to be sufficiently large to study the effect of changes in ventilation on fire development. The precise dimensions were chosen to be directly comparable with those used in theoretical studies.

(c) A number of steel section sizes typical of present day construction were incorporated in the form of columns and beams, Figs. 3 and 4 and Table 1. Where appropriate, a specific section size, or form of construction, that had been evaluated in an earlier BS476:Pt 8 fire test was selected. The steelwork was evenly distributed throughout the compartment to minimise its effect as a localised heat sink.

(d) The constructional materials were selected on the basis that they would withstand repeated exposure to high temperatures without collapsing or changing their thermal characteristics. Certain of the materials used would not, therefore, normally be found in modern buildings. In particular, the inner walls comprised spall resistant MPK 125 insulating refractory bricks and the precast concrete roof planks were lined with 38 mm thick ceramic fibre tiles. It was recognised that the highly insulating properties of these materials would influence the maximum combustion gas temperature within the compartment and therefore in later tests the inner walls were lined with a fire resistant plasterboard and the fibre tiles were removed from the ceiling. The thermal properties are given in Table 2.

The fire load ranged from 10 to 20 kg/m^2 using up to 12 equally spaced cribs comprised either of 50 x 50 mm x 1 m Western Hemlock sticks spaced 1:1 with alternate rows at right angles to each other, or of a mixture of similar soft wood with 25 x 25 mm x 1 m polypropylene sticks. Apart from one test all the cribs were ignited simultaneously. For the majority of the tests the ventilation area of the front wall was changed from $^1/2$ to $^1/4$ and $^1/8$ total area using replaceable shutters. The temperature distribution of the combustion gas throughout the compartment, the steel temperature gradients and the inner brick lining were monitored every 30 s using 3 mm dia. chromel/alumel mineral insulated thermocouples placed at heights of 0.5 and 2.0 m below the ceiling[3,4]. Steel and water temperatures from the water filled RHS were also recorded as were the rates of burning of selected cribs. The outputs from the thermocouples were fed back to a BSC Compulog 4 computer controlled data acquisition system.

An earlier report summarised the test data from 16 natural fire tests carried out under the RSC 2921 contract[23]. This work was extended under a further joint BSC/BRE contract RSC 7281 to study the effects of a change in the wall material, compartment size and alternate fuels on the heating rates of unloaded steel sections. The purpose of the present report is to summarise all the test data from both contracts and to comment on their significance in relation to the principal objectives set out above. It is assumed that reference will be made to the individual test reports for specific aspects of experimental detail. As the ambient conditions changed with the time of the year at which the tests were carried out the experimental data have been corrected to a 20°C ambient temperature to aid comparison. This approach was not followed in previous reports where actual temperature measurements were given and explains why certain apparent differences exist in the presentation of data.

The measurements taken by FRS personnel, relating to the deflection of columns in walls, air flow into the compartment and radiation during each fire will be the subject of separate DoE reports.

2. EXPERIMENTAL PROGRAMME

A total of 21 fire tests have been carried out on unloaded steel sections inside the Cardington compartment between 15th August, 1983 and 15th February, 1985 and the parameters examined may be conveniently categorised by the types of fuel used.

2.1 Wood Fires

Earlier studies by FRS established the importance of the size of the fuel load and the ventilation conditions on the heating rate of the atmosphere inside the compartment. Eight fire tests (numbers 1-6, 8, 9) compared the data generated from the combustion of fire load densities of 10, 15 and 20 kg/m^2 using the ventilation of $^1/2$, $^1/4$ and $^1/8$ of one wall. Based on the limiting steel temperatures considered in design, the combustion of a fire load density of 20 kg/m^2 at $^1/8$ ventilation in the insulated compartment was considered to be severe enough to initiate structural collapse. Ventilation from one wall of the compartment mirrored the BISF/FRS approach. However, Test No. 7 examined the effect on fire development of an alteration in the ventilation for a given opening factor by providing a $^1/4$ ventilation from both long walls of the compartment at a fire load density of 15 kg/m^2, for comparison with the $^1/2$ ventilation results of Test No. 3.

The programme standardised on the uniform distribution of the fire load between 12 equispaced cribs. As this arrangement may not be typical of many real fire situations Test No. 11 concentrated on the combustion of an uneven fire load across the compartment with an overall average density of 15 kg/m^2 and the $^1/4$ ventilation of one wall. The wooden cribs were stacked to provide a progressive increase in fuel, such that the 4 sets of 3 cribs corresponded to localised fire load density of 5, 10, 20 and 25 kg/m^2 respectively.

The temperature history of a natural fire is divided into three stages, a 'growth period' where the temperatures are comparatively low, a 'burning period' initiated by flashover where the temperature rises sharply, followed eventually by a 'decay period'. As all the cribs were ignited simultaneously the growth period was virtually non-existent. In contrast to ignition in the vicinity of an unprotected steel section, concern was expressed that the maximum temperature attained by the steelwork might be increased as a result of convection and radiation from a distant spreading fire. Such a condition was simulated in Test No. 13 for a fire load density of 15 kg/m^2 and the $^1/4$ ventilation of one wall. The four front cribs in close proximity to the south wall were lit simultaneously and the flames allowed to spread to the remaining fuel.

As mentioned earlier in the report, the life of the compartment was prolonged by using insulating fire bricks on the inner wall. It was recognised that such materials would influence the maximum combustion gas temperature. Therefore, for Test Nos. 16-19 the thermal characteristics of the compartment walls were altered by lining them with two layers of 12.7 mm thick Gyproc 'Fireline' plasterboard mounted on 50 x 25 mm wooden battens, and the ceramic fibre tiles were removed from the ceiling. The fire load density used in Test Nos. 16 and 17 was 15 kg/m^2 and the corresponding ventilation conditions were $^1/4$ and $^1/8$ of one wall. A fix load density of 20 kg/m^2 was used for Test Nos. 18 and 19 with, respectively the $^1/2$ and $^1/4$ ventilation of one wall.

For the majority of modern steel framed buildings experience suggests that in the event of a fire an excess supply of air is present. Under these conditions the severity is controlled by the quantity and type of fuel and a change in compartment size would not be expected to have a marked effect on its behaviour. In order to confirm this point the effective length of the compartment was reduced prior to Test No. 20 by erecting a block work partition across its width and the walls lined with 'Fireline' plasterboard. The total floor area was reduced to 27 m^2. A fire load density of 15 kg/m^2 with a 23% ventilation of one wall was selected for the test.

2.2 Wood/Plastic Fires

Modern building materials and contents include a wide variety of plastic products. The temperatures attained in a plastic fire and the production of smoke and other decomposition products, depend upon the chemical constitution of the material and the combustion conditions. Some plastics have been found to burn more rapidly than wood reaching localised higher temperatures. It was considered important to include mixed wood/plastic fire loads in the Cardington tests to determine their influence on the temperature of the steelwork.

Polypropylene was selected as the plastic fire load in view of its extensive use in the form of plastic moulded chairs; building partitions, walls and ceilings; water pipes; fabrics and carpets.

In the light of FRS experience with plastics the Cardington Users Committee stipulated that a trial burn involving a fire load not exceeding 100 kg polypropylene be carried out in the compartment. The effective calorific value of polypropylene being 10.5 Mcal/kg and that of wood 4.4 Mcal/kg meant that for the limit imposed on the plastic load, a 1:1 balance of these physical properties would represent the equivalent wooden fire load density of 10 kg/m^2. Test No. 10 was carried out under these conditions with the $^1/8$ ventilation of one wall.

A consideration of the maximum combustion temperatures recorded in Test No. 10, the limitation on smoke emission and the need to study the influence of higher fire loads resulted in a redistribution of the mixed fuel to the equivalent of 75% wood and 25% plastic for the remaining tests. The equivalent fire load density of 10 kg/m^2 at $^1/4$ ventilation comprised Test No. 12, whereas 15 kg/m^2 at $^1/2$ and $^1/4$ ventilation were examined, respectivey, in Test Nos. 15 and 14.

A similar mixed fuel with an equivalent fire load density of 15 kg/m^2 was ignited in the plasterboard lined compartment of reduced volume with the 23% ventilation of one wall in Test No. 21.

3. RESULTS

The temperature measurements recorded during each fire test have been reported in detail. Consequently, the discussion of the results is based on averaged data for the full size compartment with combustion gas temperatures in Table 3 and steelwork temperatures in Table 4. The rates at which the fuels burnt in 14 fire tests are given in Table 5. The influence of compartment size on the maximum average atmosphere and steelwork temperatures is shown in Table 6.

3.1 Compartment Temperatures and Fire Severity

3.1.1 Wooden Fires

Fires of eight different severities were used involving three different wooden fire load densities with up to three conditions of window opening. A photographic record of each test was obtained to indicate the state of combustion. In general the wooden cribs burnt uniformly producing little smoke, the height of the flames and the extent to which they emerged from the compartment depending upon the fire severity. One example of the state of combustion after 8 min for a wooden fire load density of 15 kg/m^2 and $^1/4$ ventilation of one wall is shown in Fig. 5. The flames projected from the compartment during the $^1/4$ and $^1/8$ ventilation tests with the exception of a fire load of 10 kg/m^2 ($^1/4$ ventilation).

The time-temperature curves for the eight different conditions are presented in Figs. 6, 7 and 8. As anticipated an increase in the fire load density raised the maximum average combustion gas temperature, from for example, 691^{o}C (10 kg/m^2, $^1/4$ ventilation) to 966^{o}C (20 kg/m^2, $^1/4$ ventilation). Also, for each value of fire load density the smaller degree of window opening produced a fire which was hotter and of longer duration, for example, 605^{o}C (15 kg/m^2, $^1/2$ ventilation) to 872^{o}C (15 kg/m^2, $^1/8$ ventilation). The severity of the fire produced by the fire load density of 10 kg/m^2 at $^1/4$ ventilation is slightly greater than that produced by the fire load density of 20 kg/m^2 at $^1/2$ ventilation.

The work of FRS has shown that two types of burning rate exist inside compartments which depend on the processes by which air is drawn into the fire[24]. When the window area is large in relation to the fire load the burning rate depends on the characteristics of the fuel itself (i.e. its size, shape and porosity) and is virtually independent of air supply through the window. For small window openings the burning rate relies on the air supply through the window and the expulsion of hot gases. The transition from one regime to the other can be related to the ratio of fuel load (L): window area (A_v) and occurs when L/A_v exceeds approximately 150 kg/m^2. On this basis, the fire developed during the combustion of a fire load density of 15 kg/m^2 at $^1/8$ ventilation was the only test in the series under ventilation controlled conditions, since L/A_v = 169 kg/m^2.

The BS476:Pt 8 standard time-temperature curve is plotted in Fig. 7 for purposes of comparison suggesting that the rate of combustion during the early stages of a wooden fire load of 15 kg/m^2 and ventilation conditions between $^1/2$ and $^1/4$ of one wall is similar to the standard fire curve.

The maximum average combustion gas temperatures are plotted against fire load/unit floor area in Fig. 9(a) showing three distinct curves. There is also a general relationship with fire load/unit window area, Fig. 9(b).

The effect on fire development due to an alteration in the ventilation for a given opening factor by providing ventilation from two walls (Test No. 7) in comparison with one wall (Test No. 3) was comparatively small. As shown in Table 3, openings in two opposite walls raised the maximum average temperature of the combustion gases by 89^{o}C at a similar time interval to that observed in Test No. 3.

The effect of a redistribution of the fire load and a change in the type of ignition on combustion gas temperature is shown in Fig. 10. The total heat content retained by the compartment was significantly reduced by igniting the uneven compared with the uniform fire load; the overall maximum average combustion gas temperatures and times were respectively 724^{o}C (16.5 min) and 850^{o}C (13.0 min). The simultaneous ignition of only four cribs reduced the burning rate in the early stages of the test followed by a 'growth period' and 'flashover' to the remaining cribs. In consequence the duration of the fire was prolonged but the maximum average compartment temperature was reduced to 627^{o}C (31.0 min).

3.1.2 Wood/Plastic Fires

The burning characteristics of polypropylene had been found by FRS to produce 40 times the volume of smoke in comparison with beech plywood[25]. As a result a considerable quantity of black smoke emerged from the compartment (Fig. 11) in the early stages of the wood/plastic fire tests. Once the polypropylene had been destroyed, the quantity of smoke was reduced and the combustion of the wooden cribs could clearly be seen. The temperature measurements showed a degree of erratic behaviour at certain locations in the compartment associated with the changing conditions of combustion. Jetting flames were observed during the early stages of the tests.

A comparison between the combustion gas temperatures of a wood and wood/plastic fire is given in Fig. 12 for an equivalent fire load of 15 kg/m^2 and the $^1/4$ ventilation of one wall. All the mixed fuel fires were characterised by a rapid rise in temperature to values of 1000-1100^{o}C in 5.5 min (see Table 3) followed by a fall to more conventional temperatures once the polypropylene had been consumed.

3.1.3 Compartment Lining

The effect of changing the compartment lining on the thermal characteristics is shown in Fig. 13 for a wooden fire load of 15 kg/m^2 and the $^1/4$ ventilation of one wall. The introduction of the Gyproc 'Fireline' plasterboard resulted in a marked reduction in the maximum average compartment temperature from 851 to 732^{o}C. Similar changes were observed for the same fire load density at $^1/8$ ventilation and for 20 kg/m^2 at $^1/4$ ventilation but less marked at $^1/2$ ventilation. An instantaneous drop in temperature of approximately 200^{o}C was thought to be due to the removal of free and chemically combined water from the plasterboard. In view of the results from this test it was considered that the data from the other Cardington tests represented the most severe conditions likely to be experienced by unprotected steelwork in a fire.

3.1.4 Rate of Burning

Insulated platforms designed to weigh a crib during combustion were placed at two locations (D and J) across the compartment. The change in weight of each crib during combustion was registered by a load cell placed centrally under each platform which was raised 75 mm above the floor. Temperature sensors applied to the body of the load cells suggested that under the most adverse conditions these components did not exceed their operating temperature specification.

The weight loss is recorded in Table 5; the instrumentation was installed for Test No. 2 and used in subsequent tests although measurements were not obtained in Test No. 8 due to a damaged cable. The rate of burning in the wood fires in some cases showed a slight reduction as the test progressed. For the $^1/4$ ventilation condition the average weight loss increased with fire load density from 0.54 kg/s (10 kg/m^2) to 0.73 kg/s (15 kg/m^2) and 0.85 kg/s (20 kg/m^2). A slight reduction in the rate of burning occurred when plasterboard lined the compartment, suggesting less feedback radiation to the fuel due to the lower maximum combustion gas temperature. During the growing fire test combustion of Crib D was delayed by 30 min whilst the fire spread to this location. The uneven fire load showed a variation in weight loss from 0.41 kg/s (5 kg/m^2) to 0.92 kg/s (25 kg/m^2). In some cases, the mixed fuel fires also showed a variation in burning rate across the compartment due to mixed combustion conditions.

3.1.5 Compartment Size

The size and shape of the compartment can influence the burning rate in ventilation controlled fires. As the combustion was fuel load controlled a reduction by 45% in the compartment volume was relatively insignificant, as shown by Table 6(a).

A comparison between Test No. 16[(18)] with Test No. 20[(22)] showed a slight fall in the maximum combustion gas temperature within the smaller compartment. The difference was considered to have arisen from the unusual pattern of air currents observed in Test No. 20 which resulted in a considerable delay to the ignition of one crib[(22)].

A change in fuel from wood to a mixture of wood plus polypropylene influenced the combustion behaviour in a similar manner to that observed in earlier tests.

3.2 Temperatures of Internal Unprotected Structural Steel

The internal steel members studied in these tests were positioned in the compartment as shown in Fig. 3. These included free standing columns (FSC1, 2, 3), columns located close to the walls (CAW1, 2), columns partially built into walls (CIW1, 2), a rectangular hollow section filled with water (WFC), three beams (B1, 2, 3) and a shelf angle floor beam (SAFB). In addition an external column was placed outside the compartment (EC). The section factors ranged from 31 to 242 m^{-1}.

The exact location of the thermocouples in each steel member has been described previously[4], but Fig. 14 shows the thermocouple numbering system adopted in the programme.

The maximum average steelwork temperatures and times recorded during the 21 fire tests are presented in Tables 4 and 6(b). By reference to Fig. 14 the temperatures recorded in the Tables were derived as follows:-

FSC1, 2, 3	$T = \frac{1 + 3 + 5}{5}$
CAW1, 2; CIW1, 2	$T = \frac{1 + 3}{2}$
EC	$T = 5$
WFC	$T = \frac{2 + 4}{2}$

B1, 2, 3	T = 6
SAFB	T = 7

With regard to the data presented in this document the values differ from earlier records in two respects. The first is the use of 20°C as a standard for the ambient temperature from which changes in temperature were calculated; previously the actual temperatures measured at the start of each fire test ranged from 1 to 30°C depending on the time of year at which the work was carried out. The second is the emphasis placed on lower flange temperatures in beams which has been adopted by BS5950:Pt 8; in earlier work the recorded temperatures were averages between the lower flange and lower web positions. Analysis has shown the latter approach to give maximum average temperatures approximately 20°C lower than the revised procedure.

3.2.1 Wooden Fire Loads - Insulated Compartment

As a greater fire load density and a reduction in the degree of ventilation produced fires of increasing severity it was to be expected from the examples given in Figs. 15 and 16 that the behaviour of the unprotected steelwork would respond in a similar manner. This was also shown for the range of beams and free standing columns in Figs. 17 and 18 in which the maximum average temperature is plotted against the H_p/A value of the section. A degree of scatter in the results is to be expected as differences in resultant emissivity exist for the individual steel members. The CAW sections followed a similar trend, Fig. 19 but for a fire load density of 20 kg/m^2 at $^1/2$ ventilation the maximum average temperatures were significantly greater than those measured on the smaller free standing columns. A maximum average temperature of 550°C (once considered to be the maximum permissible value) was attained in beams in $^1/4$ ventilation fires having an H_p/A value of 150 m^{-1} (10 kg/m^2), 65 m^{-1} (15 kg/m^2) and 45 m^{-1} (20 kg/m^2); the corresponding values for free standing columns were 150, 68 and 30 m^{-1}. It must be emphasised, however, that these results represent an upper bound situation in view of the highly insulating nature of the MPK 125 brickwork. It is of interest to note that the change from fuel load to ventilation controlled fires, namely 15 kg/m^2 at $^1/4$ and $^1/8$ ventilation resulted in only a small increase in steel temperature.

The effect on steel temperature of an alteration in the ventilation for a given opening factor was comparatively small, as shown in Fig. 20. The $^1/4$ ventilation of two walls raised the steel temperature of FSC2 (H_p/A = 96 m^{-1}) by 30C° compared to the $^1/2$ ventilation of one wall.

The redistribution of the fire load across the compartment ranging from a density of 5 to 25 kg/m^2 with an average of 15 kg/m^2 reduced the total heat content retained by the compartment and established a marked temperature gradient during the earlier stages of the test. The effect on the steelwork temperature is shown in Fig. 21 based on the measurements obtained using a uniform fire load of 15 kg/m^2 and the $^1/4$ ventilation of one wall. The intensity of the fire was greatest on the east side of the compartment resulting in the small increases (+18 to +45°C) in the temperature of the beams and columns in this area; the maximum average temperature on the west side of the compartment was below 550°C.

The simultaneous ignition of only four cribs instead of the 12 cribs reduced the burning rate during the early stages of the test but prolonged the duration of the fire. The steel temperature was reduced as shown in Fig. 22 for a wooden fire load density of 15 kg/m^2 and the $^1/4$ ventilation of one wall. For example, the steel temperature of FSC2 (H_p/A = 96 m^{-1}) fell by 176°C in the growing fire situation.

3.2.2 Wood/Plastic Fires

A comparison between the combustion gas temperature for wood and a wood/plastic fire showed a rapid rise in the early stages of a plastics containing fire followed by more conventional temperatures once the plastic had been consumed. The effect on steel temperatures for an equivalent fire load density of 15 kg/m^2 and the $^1/4$ ventilation of one wall is shown in Fig. 23 for unprotected beams and Fig. 24 for columns. For the particular wood/polypropylene fuel used the maximum average temperature of steel sections with an H_p/A value of 100-180 m^{-1} was raised by only 50°C and the time taken to reach the maximum temperature was reduced.

3.2.3 Compartment Lining

One of the most important observations made in the current programme was the significance of compartment lining on the maximum temperatures measured in fires. A change from MPK 125 bricks to 'Fireline' plasterboard reduced the maximum temperatures recorded in the steelwork as shown for beams in Fig. 25 and for columns in Fig. 26. A maximum average temperature of 550°C was attained in beams in 1/4 ventilation fires having an H_p/A value of 145 m^{-1} (15 kg/m^2) and 65 m^{-1} (20 kg/m^2) while the corresponding values for free standing columns were 130 and 65 m^{-1}. The CAW sections followed a similar trend, Fig. 27, but again the maximum average temperature on the member with an H_p/A = 149 m^{-1} was greater than a similar free standing column.

3.2.4 Partially Protected Steelwork

Two types of building construction involving the partial protection of steelwork are perimeter columns built into walls and shelf angle floor beams. Standard BS476:Pt 8 fire tests have been carried out on both systems utilising 203 x 203 mm x 52 kg/m columns (CIW1) and 406 x 178 mm x 54 kg/m shelf angle beams (SAFB) respectively.

During the Cardington tests, the free standing columns in walls underwent significant deflection which damaged the walls on either side of the web. The roof concrete cover slabs that rested on the shelf angles of the beams also moved during the tests, dislodging the sand infill in the proximity of the web. As a result the hot gases of combustion penetrated to the protected area of each section. Figures 28 and 29 show temperature profiles across the CIW1 and SAFB at the respective times corresponding to the maximum steel temperatures for fires based on a wooden fuel load of 15 kg/m^2 and for both types of compartment lining.

3.2.5 Water Filled Column

The initial tests involved filling the 9 m high RHS water to a height of 7.8 m. This assembly was considered to be suitable for operation at low fire loads. However, water overflowed from the column during Test No. 4 (15 kg/m^2 and 1/4 ventilation). Modifications were then carried out to improve water circulation by placing a 219 mm dia. x 5250 mm long steel tube inside the column and by reducing the initial water level to a height of 5.75 m. Further adjustments were made to the quantity of water in subsequent tests to improve the recirculation and find the limits for effective cooling.

Steel and water temperatures before and after the modification are shown in Fig. 30. The internal thermocouple positions were altered with the modifications and certain unusual temperature values recorded at this time were due to alignment problems. A sudden rise in the water temperature at the 0.75 m level occurred during Test No. 16. This was thought to be due in part to a local restriction inside the column influencing the movement of steam pockets, but also to the water level being 0.75 m below the recirculating tube requiring an additional pressure head to initiate recirculation.

Maximum average steel temperatures are compared in Fig. 31 against the atmosphere temperature in the vicinity of the column (Fig. 31(a)) and also against the maximum average compartment temperature (Fig. 31(b)). The erratic behaviour of water cooling in Tests No. 4 and 6 is clearly shown. The variable combustion conditions developed in the mixed fuel fire of Test No. 15 showed an apparent low steel temperature based on average combustion gas temperatures (Fig. 31(b) which was rectified by plotting against localised combustion gas temperatures (Fig. 31(a)).

Water cooling was particularly effective under stable recirculation conditions. For example, in Test No. 9 with a fire load density of 15 kg/m^2 and the 1/8 ventilation of one wall FSC2 (H_p/A = 96 m^{-1}) recorded a maximum average temperature of 680°C; the similar section factor (102 m^{-1}) of the water filled column reached 215°C.

3.2.6 External Column

The original intention had been to move the external column to different locations relative to the window opening but the member was left for the duration of the work at the centre of the west ventilator and 630 mm from the outer wall of the compartment. Thus it received almost the full heating effect from the flames and in the case of plastic fires was completely engulfed by flames and smoke.

Maximum steel temperature values observed with a series of ventilation conditions and a fire load density of 15 kg/m^2 are shown in Fig. 32. In general, the temperatures increased with the average compartment temperature and following a reduction in the degree of ventilation. Maximum radiative temperatures monitored by FRS were approximately 70C° below those in the compartment for wood fires, a difference that was increased to 200C° with the mixed fuel fires[26].

As a consequence of differential thermal expansion some distortion of the column occurred during the fire but this disappeared on cooling.

3.2.7 Compartment Size

The effects of a change in compartment volume on the maximum average steelwork temperatures are summarised in Table 6(b).

As a consequence of the delayed ignition of one wooden crib during the fire test in the small compartment the duration of the fire was prolonged. In comparison with a similar test in a full sized compartment the maximum average temperature in FSC1 (H_p/A = 180 m^{-1}) was reduced by 51C° and in B3 (H_p/A = 169 m^{-1}) by 31C°. In view of the differences in the fire behaviour between the two tests it was concluded that the change in compartment size had an insignificant effect on the maximum temperatures measured in steelwork.

3.3 Brick Temperatures

During the installation of the compartment the opportunity was taken to measure the temperature of the brick panels at the surface and at the depths of 25 mm and 50 mm into the brickwork. It soon became apparent that the surface measurements were unreliable due to their sensitivity to flame impingement. The maximum temperatures recorded at depth of 25 mm were greater in the MPK 185 material than either the MPK 125 or the fireclay bricks. For example, respective temperatures of 307, 262 and 262°C were recorded for a wood fire load density of 20 kg/m^2 in the insulated compartment and the $^1/4$ ventilation of one wall. These differences reflected the higher thermal diffusivity of the MPK 185 brick compared to the other materials.

During fires in the lined compartment the interface temperature between the two 12.7 mm layers of plasterboard was also measured. For example, for a maximum combustion gas temperature of 852°C reached after 14 min (Test No. 19) the interface temperature was 554°C which increased to a maximum value of 636°C after 18 min.

4. DISCUSSION

A structural fire engineering design approach can be subdivided into three main areas, namely:-

(a) prediction of the heating rates of the combustion gases and the maximum temperatures obtained inside the compartment.

(b) prediction of the maximum temperatures and heating rates achieved by the steel members.

(c) assessment of the stability of the structure.

The data generated in the Cardington fire tests have been particularly valuable in generating information in the first two areas.

4.1 Combustion Conditions Inside Compartment

The wooden fire load densities ranged from 10 to 20 kg/m^2 and the mixed fuel tests were based on 10 and 15 kg/m^2. These values are considered to be low fire loads when compared to statistical data prepared on specific purpose groups. The fire load of 15 kg/m^2 used as the standard in the current comparisons is typical for parts of hospital buildings such as waiting areas and modern wards, airport concourse lounges, cafeteria, reception areas, car parks, sparsely furnished offices, hotel bedrooms, gymnasia and some school classrooms.

The prediction of the combustion conditions depends upon the balance between the rate at which heat is produced in a fire and lost from the compartment. As shown in this work and in the BISF/FRS studies the potential fire severity increased with the fire load and with a decrease in ventilation openings. Maximum average combustion gas temperatures ranged from 405°C for a fire load of 10 kg/m^2 ($^1/2$ ventilation) to 966°C for a fire load of 20 kg/m^2 ($^1/4$ ventilation). Higher temperatures were recorded in the mixed fuel tests. With the exception of Test No. 16 the maximum temperatures recorded were well in excess of those observed in the BISF/FRS tests.

A theoretical analysis of the average temperatures developed in a series of experimental fires for low fire loads resulted in a relationship for no through draught fires[27]. The temperatures of a fire within a room is given by:-

$$T_f - T_a = \frac{6000\ (1 - e^{-0.1\eta})\ .\ (1 - e^{-0.05\psi})}{\eta^{\frac{1}{2}}}$$

where T_f = maximum temperature, °K

T_a = ambient air temperature, °K

$$\eta = \frac{A_t - A_v}{A_v\sqrt{h}} \quad \text{and} \quad \psi = \frac{L}{\sqrt{A_v(A_t - A_v)}}$$

The predicted (see Appendix) and maximum average gas temperatures measured in the wood fuel fires are compared in Table 7 for both the Cardington and BISF/FRS tests. The equation predicts reasonable behaviour for the BISF/FRS work and for the short duration Cardington tests.

The correlation makes no allowance, however, for the lining of the compartment and was based on model furnace tests in which the temperature distribution and flame behaviour were different from real fire situations.

A change in the characteristics of the boundary surfaces within the compartment has a significant effect on the maximum average temperatures obtained. Insulating fire bricks are comparatively stable chemically and exhibit specific heat and thermal conductivity values that increase slowly with temperature. Gypsum containing plasters provide a degree of fire protection in buildings due to a release of free water at 100°C and water of crystallisation from the gypsum ($CaSO_4 \times 2H_2O$) in the range 150 to 220°C. At 360°C soluble calcium sulphate is transformed into an insoluble modification. All these processes result in an irregular behaviour of specific heat and thermal conductivity with temperature.

A comparison between the combustion gas heating curves measured for the two boundary surface materials used at Cardington is shown in Fig. 32 together with data obtained in the BISF/FRS tests for a fire load density of 15 kg/m^2 of wood and the $^1/4$ ventilation of one wall. Replacing the insulating brick surface by the plasterboard resulted in a reduction in the maximum average gas temperature of 120C°. As all the cribs had been ignited simultaneously it was considered that the whole boundary surface area would rise in temperature at a rapid rate. The sudden drop in the gas temperature after 3.5 min was probably due to the release of combined and free water from the gypsum in the plasterboard, a process that would continue as heat was conducted through the lining. A thermocouple placed at the interface between the two boards indicated that at a depth of 12.5 mm, 100°C was reached after 3 min and 220°C after 7 min.

As the depth/width ratios of the compartments were similar a direct comparison with the BISF/FRS data is possible. The boundary surfaces of the original compartment were lined with gypsum/vermiculite plaster on the walls (Fig. 1) and it is understood that no replastering occurred before subsequent tests. It is possible, therefore, that despite being located outdoors the BISF/FRS compartment might have been comparatively dry before the 15 kg/m^2 ($^1/4$ ventilation) test, which could be the explanation for the absence of a temperature discontinuity and the slightly higher gas temperature profile compared with the Cardington test in the later stages of the fire.

Extensive theoretical studies have been carried out in Sweden to relate fire load density and opening factor with atmosphere heating curves under ventilation controlled conditions[25]. The decision to base calculations on ventilation rather than fuel load controlled conditions was to provide design guides for the most severe fire situations. The effect of the various types of construction materials is taken into account by determining an equivalent fire load density and opening factor applicable to a standard compartment, using a conversion value K_f. The factor K_f depends on the exact quantities of the different boundary surface materials used but for the Cardington compartment lined with Gyproc and concrete K_f = 1.18 for an opening factor of 0.03 m^{½} ($^1/8$ ventilation). The theoretical combustion gas heating curve is compared with the Cardington data in Fig. 33 for a fire load density of 15 kg/m^2 and the $^1/8$ ventilation of one wall which represented the only ventilation controlled fire in the series. The agreement between the two curves is excellent. The value of K_f derived for the highly insulated compartment was 2.5 for the same conditions.

Another important observation related to the type of fuel burnt. By mixing polypropylene with wood very high combustion gas temperatures were recorded in a comparatively short time, for example 1092°C (5.6 min) in Test No. 14 compared with 850°C (13.0 min) in Test No. 4. Both tests were based on a wooden fire load density of 15 kg/m^2. The conversion of mixed fuels to an equivaent quantity of wood depends on an accurate knowledge of their respective calorific values. On this basis alone the high temperatures recorded for the mixed fuel would not be expected to arise and it is the burning characteristics of the fuel which predominates.

A number of fire tests have been carried out on plastics but unfortunately do not easily relate to one another. The FRS has reported fires on stacked polypropylene chairs, with a total moulded shell weight of 66 kg when a maximum atmosphere temperature of 795°C occurred after 9 min[25]. In comparison with beech plywood the plastic produced 40 times the volume of smoke. During burning the polypropylene ignited easily and molten droplets spread the fire. CTICM fire tests using a fuel of wood and expanded polystyrene with an equivalent fire load density of 27 kg/m^2 and spread over a restricted area of floor space were carried out inside a large warehouse. Localised gas temperatures as high as 1116°C were recorded after approximately 4 min[29] followed by a rapid fall. A wood/polyethylene fuel in a 2:1 ratio at an equivalent fire load density of 24 kg/m^2 was ignited under forced air conditions in a compartment with the $^1/4$ ventilation of one wall[30]. A maximum gas temperature of 1068°C was recorded after approximately 8 min but in this case the high temperature was maintained for a longer period. An unlimited variation in the utilisation of wood and plastic exists in building contents and it would be unrealistic to mount a large programme of testing. A statistical analysis of types of occupancy is needed to indicate the more likely wood/plastic combinations. In the context of the Cardington programme the examination of mixed fuels at fire load densities up to 20 kg/m^2 and different calorific values could be justified to the limits imposed by the maximum temperatures in the structural steelwork.

The duration of a fire depends on the rate of burning of the fuel. Materials that are well spaced out will burn at a faster rate than those which allow only restricted access for air. In the present work the rate of burning was nearly proportional to the fuel load density, although the range was limited. The single ventilation controlled fire showed no significant difference in behaviour. There was a tendency for the rate of burning to be faster in the early stages of the mixed fuel fires (particularly Test No. 10 which contained the greatest proportion of polypropylene) due to the melting and spreading of plastic. However, the change was erratic due to the irregular nature of combustion across the compartment.

4.2 Temperatures of Internal Unprotected Steelwork

As the increase in fire load density and a reduction in the degree of ventilation produced fires of increasing severity it was to be expected that the temperature of the unprotected steelwork would behave in a similar manner. Steel is a relatively good conductor of heat and a thin, light section will increase in temperature at a faster rate than a thick, heavy section. In order to accommodate this effect the H_p/A concept was introduced which can be applied to any shape and size of section[2]. Much of the data presented in this report related the maximum average steel temperature to the section factor H_p/A and it was found to be a reliable parameter.

Heat from a fire is transferred to the steelwork by radiation and convection. The rate of heat transfer is governed predominantly by radiation and described by the term resultant emissivity, ε_r, which depends on the interrelationship between the emissivities of the bare steelwork and the flames. The temperature rise of the steel member depends on its position in relation to the flames. For this reason a degree of scatter exists in comparing H_p/A and maximum average temperature which appears to become less marked at the higher fire loads. The general trend is for the maximum average steel temperature to be more dependent on low rather than high section factors, such that the lighter sections reach near equilibrium conditions. The most severe situation arose for a fire load density of 20 kg/m^2 and the $^1/_4$ ventilation of one wall in the insulated compartment. The limiting section factors taken from the respective graphs for maximum steel temperatures of 550 and 700^{o}C were 44 and 75 m^{-1} for beams and 31 and 69 m^{-1} for free standing columns.

Many of the tests were based on a fire load density of 15 kg/m^2 with the $^1/_4$ ventilation of one wall. Again, the most extreme conditions were produced in a highly insulated compartment with the simultaneous ignition of the 12 cribs. A redistribution of the fire load across the compartment and the test involving a growing fire, both fires being more typical of practical situations, reduced the burning rate and the total heat content retained in the compartment. In addition, the high compartment temperatures observed in the early stages of the plastic fire had only a small effect on the maximum average steel temperatures measured. A much more important observation related to changes in compartment lining when the steel section factor necessary to achieve a maximum average temperature of 550^{o}C was increased from 62 to 138 m^{-1} for unprotected beams and from 70 to 125 m^{-1} for columns.

One unusual feature that was particularly noticeable at a fire load density of 20 kg/m^2 and the $^1/_2$ ventilation of one wall was the tendency for the CAW sections to reach higher temperatures than their similar free standing counterparts. This was thought to be due to changing conditions in the combustion behaviour across the compartment. Gas temperatures recorded nearer to the walls tended to be higher than at locations further into the compartment. The steel columns close to the walls might also have been influenced by localised higher resultant emissivities.

4.3 Partially Protected Steelwork

203 x 203 mm x 52 kg/m columns built into a fire resistant wall have been subjected to a number of standard fire tests at FIRTO[31]. Also 406 x 178 mm x 54 kg/m beams have been evaluated as a shelf angle floor construction at the Warrington Research Centre[32]. Extracts from the temperature profiles obtained in Test No. 16 for each form of construction are presented in Table 8 with the corresponding data from standard tests. Test No. 16 (fire load density of 15 kg/m^2 and $^1/_4$ ventilation) was selected on the basis that it experienced a heating rate similar to that of the standard furnace curve in the early stages of the test. The duration has been extended just beyond the time required to reach maximum average temperatures in the real fire. It is of interest to note the similar gas temperature profiles in the proximity of the specimens up to the point at which the real fire started to decay. The unexposed flanges responded in a similar manner, but due to distortion the unexposed web of the SAFB increased in temperature much more rapidly in the real fire compared to the BS476:Pt 8 test. The exposed flanges of both sections were hotter in the

real fire compared with the furnace but the maximum difference in temperature after the first 15 min was only 22C°.

4.4 External Column

External steel elements are exposed to radiant heat from the windows and to radiation and convection from flames projecting from the windows, while they are free to lose heat to the surrounding air. The magnitude of the radiative temperature as measured by the thermopile was less than the combustion gas temperature. This effect was a consequence of the intensity of radiation falling off as the inverse square of the distance from the source.

The maximum temperature reached by EC during a natural fire in the relined compartment with a density of 15 kg/m^2 and 1/4 ventilation was 263°C which was 137C° lower than that recorded on a similar section size in the BISF/FRS tests. The amount of heat received by each column depended upon the combustion gas temperature and the relative distance of the section from the window.

The entry of air to the compartment during combustion occurs through the openings from which the flames are emerging. In this condition the flames tend to occupy the upper two thirds of the window with air being drawn in through the lower third. Preliminary information from FRS suggests that there is no increase in the rate of air flow into the compartment by changing from 1/4 to 1/8 ventilation. Therefore, the reason for the drop in the temperature of the external column at the lower thermocouple position at 1/8 ventilation is not clear.

The theoretical design guide for external unprotected columns indicated by using a simplified approach that for the column to remain below 550°C for 1/4 ventilation fires the safe distance from the compartment wall should be 2.0 m. In the current test programme the maximum temperature of the column placed at 630 mm from the opening never exceeded 440°C. The discrepancy is due to the analysis being based on much higher fire load densities (50 kg/m^2) than were used at Cardington. Where lower fire loads are encountered a more precise calculation procedure is followed. For example, in Test No. 14 the mixed fuel fire produced flames and smoke which engulfed the external column and raised the steel temperature to 440°C. By following the calculations[27], a temperature rise of 499°C is predicted; this shows the design approach for external unprotected steelwork to be realistic if slightly conservative.

4.5 Water Filled Columns

A number of systems exist for utilising water as a means of controlling the rate of temperature rise of hollow steel sections during a fire. The present work has demonstrated how effective this technique can be by restricting the rise in temperature of the hollow section ($H_p/A = 102\ m^{-1}$) to 220°C under the most arduous conditions. However, stable recirculation conditions relied on a degree of experimentation in the early stages of the programme. This emphasises the fact that designing such a system is complex involving consideration of the mechanics of water flow, heat transfer and convection and beyond the scope of the present contract.

4.6 Time Equivalent Approach

One concept employed by fire engineers is to relate the behaviour of a natural fire to an equivalent heating time in the BS476:Pt 8:1972 fire resistance test. In this way the ability of a steel member to withstand a real fire under load can be assessed. The equivalent fire resistance time, Te, can be obtained from:-

$$Te = K \frac{L}{\sqrt{A_v A_t}} \quad \text{min}$$

in which, A_t, is the total bounding surface excluding the openings and, K, is a constant usually taken as unity. The relationship was derived from an analysis of substantial quantity of international data based principally on fire compartments lined with 10 mm thick asbestos board[33]. A number of tests were carried out in brick plus concrete lined compartments when the value of K was taken to be 0.95. As shown in Fig. 34 this correlation was based on protected steel members in small scale tests. The comment was made that an allowance for the thermal capacity of compartments in real situations might be required. The present work has shown that this aspect must be considered in calculations.

One drawback of the above correlation is that no account is taken of the height of the ventilation which is known to have a marked effect on the behaviour of fires. An alternative relationship[28] derived for insulated structures has been generalised to:-

$$Te = 0.067 \frac{q}{\left(\frac{A_v\sqrt{h}}{A_t}\right)^{\frac{1}{2}}} \quad \text{min}$$

in which, q, is the fire load density in MJ/m^2 of the bounding surfaces of the compartment and:-

$$\frac{A_v\sqrt{h}}{A_t}$$

is the theoretical opening factor where, h, is the height of the ventilation. The advantage of this formula is that it enables the variables within a compartment to be altered to determine the equivalent time of fire duration.

From a series of BS476:Pt 8 fire tests steel heating curves were derived for the free standing columns, FSC1, FSC2 and FSC3 and the beams B1, B2, B3 and SAFB. Mathematical modelling of the temperature profiles developed in unprotected steel sections during standard fire tests was used to interpolate between and extrapolate beyond the available experimental data. The time taken for a range of steel section sizes to reach a predetermined temperature in the BS476:Pt 8 fire test is shown for beams in Fig. 35 and for columns in Fig. 36. A comparison between the maximum steel temperatures measured in the natural fires with the curves of Figs. 35 and 36 gave the time equivalent values of Table 9. An average value of Te from each fire test is shown together with the theoretical values derived from both formulae. The theoretical conversion factors to take account of the boundary wall materials as based on the Swedish work are also included.

Table 9 shows the importance of the boundary surfaces of the compartment on fire severity. For a wood fire load density of 15 kg/m^2 and the $^1/4$ ventilation of one wall the derived time equivalent was approximately 18 min. A similar value was obtained from fire tests in a compartment lined with plasterboard but this increased to 29.5 min for the highly insulated compartment. Thus for the fire load and ventilation conditions used in this example the change in boundary materials altered the fire severity by a factor of 1.6 compared to a theoretical conversion factor of 2.5. For a mixed fuel density of 15 kg/m^2 and the $^1/4$ ventilation of one wall the addition of the polypropylene extended the average measured time equivalent by 5.5 min.

The relationship between the time equivalent and opening factor for the various fires carried out in the compartment at Cardington is shown in Fig. 37. The form of the curves showing peak values for the time equivalent at opening factors of 0.02-0.03 m$^{\frac{1}{2}}$ is based on theory as the tests did not extend to small areas of ventilation. As shown by Table 9 both time equivalent formulae gave similar results. The shutters of the compartment were altered to provide two openings in one wall in which the height remained fixed at 2.3 m and the widths reduced from 3.67 to 1.81 and 0.9 m. If the width had remained fixed and the height altered to vary the ventilation the severity of fires at $^1/8$ ventilation would have been greater, as shown in Fig. 38. Fortunately, a high percentage of fire engineering enquiries received by BSC are typified by the ventilation geometries as studied at Cardington.

The only unprotected steel column placed inside the BISF/FRS compartment was similar to FSC1. The rise in temperature of the steelwork from both series of tests is compared in Fig. 39 for a wood fire load density of 15 kg/m^2 and the $^1/4$ ventilation of one wall. The rate of heating was much lower in the early work which might have been influenced at the time by climatic conditions since the stacking of the cribs was not significantly different from that used in the recent tests. The maximum average steel temperature reached in the BISF/FRS work for these particular fire conditions gave an experimental time equivalent that was 1.5 min less than the theoretical prediction. In the Cardington tests both methods of obtaining the time equivalent gave similar results. The calculation of time equivalent for individual BISF/FRS tests is also shown in Table 10. From this information it had been hoped to show reasonable agreement between the experimentally obtained and theoretically derived time equivalent values for fire load densities higher than those used in the Cardington work. Such a comparison was favourable up to a fire load density of 30 kg/m^2 at $^1/2$ ventilation. For the more severe BISF/FRS fires no realistic analysis was possible because the quoted maximum average steelwork temperatures were sometimes greater than the maximum average combustion gas temperatures[34,35]. For example, at a fire load density of 60 kg/m^2 and the $^1/8$ ventilation of one wall the respective temperatures were 1115 and 1170°C. The disparity might be due to erratic combustion conditions. However, from the current information available it is considered that sufficient confidence can be placed in a theoretical calculation of time equivalent to enable the influence of more severe fires on steel temperatures to be determined.

This approach has been used to extend the Cardington data to lower (7.5 kg/m^2) and higher (30 and 60 kg/m^2) fire load densities. A series of limiting section factors for unprotected beams and columns have been determined for different fire severities in a plasterboard lined compartment; Table 11 covers wood burning fires and Table 12 covers wood and polypropylene burning fires. The limiting temperatures of 500 to 700°C in each table relate to the lower flange of beams and the average of flange and web on free standing columns. Thus, if an unprotected beam by virtue of a proposed service stress has a limiting temperature of 600°C and is subjected to a natural wood fire having the equivalent fuel density of 20 kg/m^2 with the $^1/4$ ventilation of one wall the limiting section factor for stability is 100 m^{-1}. The use of universal beam of serial size 610 x 229 mm x 140 kg/m having an H_p/A = 105 m^{-1} for three sided attack would be borderline in this fire situation. The choice of a free standing unprotected steel column to withstand a wood fire having the equivalent density of 15 kg/m^2 with the $^1/4$ ventilation of one wall without exceeding a temperature of 550°C would centre on an H_p/A value of 133 m^{-1}. In this situation a 203 x 203 mm x 71 kg/m section would be acceptable.

The information presented in this way represents an important contribution to the fire engineering analytical approach. It is directly applicable to the real heating conditions from fires within certain types of buildings such as multistorey office blocks where the area of ventilation is comparatively large.

If Tables 11 and 12 are to be used as a general guide to the performance of unprotected steelwork in different fire exposure conditions the following qualifications should be recognised. The Cardington fire tests were based on simultaneous ignition of all the cribs which resulted in a more severe heating rate than is normally experienced in a growing fire. Although the fuels examined were considered to by typical of the combustible materials within modern compartment designs, it was impractical to evaluate a wider range of plastic containing fuels. The use of plasterboard was considered to be a typical form of wall lining but a similar set of design tables could be derived from the test data reported in this document for highly insulating surfaces.

The Cardington compartment had a total volume of approximately 200 m^3 and was rectangular in shape with the ventilation provided in the longer walls. Similar results were obtained when the floor area was reduced by 45% to give a floor area roughly square in plan. It would be reasonable, therefore, to expect the behaviour of unprotected steelwork as measured in the Cardington tests to be similar to that observed in a compartment measuring 10 x 10 x 5 m high which is considered by BS5950:Pt 8 as being the maximum size for realistic application of the time equivalent formula.

5. CONCLUSIONS

A collaborative test programme has been carried out by Swinden Laboratories (BSC) and the Fire Research Station (BRE) to determine the heating rate of unloaded and unprotected steel beams and columns in fires of different but known severities.

Considerable information has been obtained to enable the heating rates of steel members to be calculated from low fire load densities (10, 15 and 20 kg/m^2), a range of ventilation conditions and the use of wood or wood/polypropylene fuels. The principal facts to emerge from this work were as follows:-

1. An increase in fire load density raised the maximum average air/gas temperature which for fires based on wooden fuels ranged from 403^{o}C (10 kg/m^2 - $^1/2$ ventilation) to 966^{o}C (20 kg/m^2 - $^1/4$ ventilation). For each fire load the smaller degree of window opening produced a fire that was hotter and in some cases of longer duration. With the exception of a fire load density of 15 kg/m^2 and the $^1/8$ ventilation of one wall all the fires were fuel load controlled. The rate of combustion inside the compartment during the early stage of a fire of 15 kg/m^2 density and the $^1/4$ ventilation of one wall was similar to the BS476:Pt 8 standard curve.

2. Ventilation provided from two walls instead on one wall for a given opening factor has a comparatively small effect. For a fire load density of 15 kg/m^2 and the total ventilation equivalent to $^1/2$ of one wall an increase in maximum gas temperature of 89C^o occurred as a result of ventilating from two sides of the compartment.

3. A redistribution of the fuel load and a change from simultaneous ignition of all 12 cribs to a growing fire resulting from the ignition of only the front four cribs reduced the total heat content retained by the compartment, although in the latter case the duration of the fire was prolonged. The reduction in maximum average gas temperatures compared to the standard test were respectively 126 and 223C^o.

4. The effect of changing the compartment lining from insulating refractory brick walls and ceramic fibre roof tiles to Gyproc 'Fireline' plasterboard walls with the removal of the ceiling tiles had a marked effect on the combustion gas temperatures. For a fire load density of 15 kg/m^2 and the $^1/4$ ventilation of one wall the maximum average combustion gas temperature was reduced from 851 to 732^{o}C. Similar changes occurred with other fire conditions. The combustion gas heating curve obtained under ventilation controlled conditions inside the compartment with plasterboard lining agreed closely with theoretical studies.

5. The burning characteristics of mixed wood/polypropylene fuels resulted in a rapid rise in temperature during the early stages of the test to a value as high as 1092^{o}C after 5.5 min followed by an equally rapid fall to more conventional temperatures once the plastic had been burnt. Heavy dense black smoke was emitted during these tests which influenced the mechanism of combustion.

6. For fuel load controlled fires a reduction in the compartment volume by 45% had a relatively insignificant effect on the rate of burning. A change in fuel from wood to a mixture of wood plus polypropylene influenced the combustion behaviour in a similar manner to the tests in the full sized compartment.

7. The rise in temperature of the steelwork was clearly influenced by the H_p/A value of the member and its location in the compartment. The maximum average temperatures measured were more dependent on the lower section factors, such that the lighter sections reached near equilibrium conditions.

8. The most severe fire situation occurred in compartments with high insulating boundary surface materials. A maximum average temperature of 550^{o}C was attained by unprotected beams in $^1/4$ ventilation fires having an H_p/A value of 150 m^{-1} (10 kg/m^2), 65 m^{-1} (15 kg/m^2) and 45 m^{-1} (20 kg/m^2), the corresponding values for free standing columns were 150, 68 and 30 m^{-1} respectively.

9. A reduction in maximum combustion gas temperature resulted in a reduction in maximum steel temperatures; hence the redistribution of fuel and the growing fire was beneficial. By changing from simultaneous ignition to growing fire, FSC2 with $H_p/A = 96\ m^{-1}$ recorded a drop in maximum average temperature of 176°C.

10. A change in compartment lining to a more conventional material resulted in a marked reduction in the maximum steelwork temperature and consequently extended the workable range of unprotected steel sections. A maximum average temperature of 550°C was attained by beams in 1/4 ventilation fires having and H_p/A value of 145 m^{-1} (15 kg/m^2) and 65 m^{-1} (20 kg/m^2); the corresponding values for free standing columns were 130 and 65 m^{-1} respectively.

11. The influence of the wood/plastic fires carried out in this programme on steel temperatures was small, despite the initial rise in combustion gas temperature. Based on an equivalent fire load of 15 kg/m^2 and the 1/4 ventilation of one wall the increase in steel temperature as a consequence of burning a wood/polypropylene fuel was between 20-48C°.

12. The effect on the maximum average steelwork temperatures by reducing the volume of the fire test compartment from 200 to 130 m^3 was insignificant.

13. For the design of ventilation control used at Cardington in which the height of the openings remained constant two relationships for calculating the equivalent fire resistance time gave similar results. The observations indicated that a more appropriate relationship for time equivalent must include an allowance for the thermal capacity of compartments in real situations. It is also suggested that the height of the ventilation should be included in the expression as it is known to have a marked effect on the behaviour of fires.

14. It is now recognised that the limiting temperature at which a structural member loses its load carrying capacity is dependent on the level of load, the stress distribution and the arrangement of any protection. A series of limiting section factors for unprotected beams and columns has been determined for a range of limiting temperatures from 500 to 750°C. The data are directly applicable to the real heating conditions from fires within certain designs of building where the area of ventilation is comparatively large.

15. Bowing of the shelf angle floor beam and lateral distortion towards the top of the columns in walls opened up gaps which enabled hot gases to penetrate to the protected area of each.

16. The water filled column required modification during the course of the programme to aid the recirculation of water. Once this had been achieved water cooling was found to be most effective, keeping the steelwork temperature ($H_p/A = 102\ m^{-1}$) below 220°C.

17. The external column placed 630 mm from the centre of one of the openings and in the plastic fires was completely engulfed by flames and smoke. During the most severe fire the maximum temperature reached was 465°C. For a fire load density of 15 kg/m^2 and the 1/4 ventilation of a plasterboard lined compartment the maximum temperature of 263°C was less than that observed in early work.

18. The observations made during the fire test with the compartment lined with plasterboard had certain similarities with the records obtained in the early BISF/FRS tests.

19. This investigation has provided valuable and hitherto unavailable experimental data on the behaviour of steel building elements in natural fires as compared to idealised furnace heating conditions. The information enables the analytical methods for the design of structures to resist fire to be used with greater accuracy, thereby

avoiding the costs of expensive fire tests. The provision of design tables related to the temperature sensitivity of structural steel beams and columns in a wide range of real fire environments highlights those situations where individual steel members have adequate inherent fire resistance. An extension of the use of bare steelwork in buildings, with the added protection afforded by adjacent elements of structure, will have a significant impact in the reduction of fire protection costs of multistorey frames. The information is particularly relevant in view of the current problems being experienced in the use of reinforced concrete as an alternative material for high rise buildings.

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7. ACKNOWLEDGEMENT

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TABLE 1 DIMENSIONS OF UNIVERSAL STEEL SECTIONS INCORPORATED IN COMPARTMENT

Identity	Serial Size mm	Mass/Metre kg	Depth mm	Width mm	Web Depth mm	Thickness mm	
						Web	Flange
Columns FSC1	203 x 203	52	206.2	203.9	160.8	8.0	12.5
FSC2	356 x 368	177	368.3	372.1	290.1	14.5	23.8
FSC3	356 x 406	634	474.7	424.1	290.1	47.6	77.0
CAW1	203 x 203	52	206.2	203.9	160.8	8.0	12.5
CAW2	356 x 368	177	368.3	372.1	290.1	14.5	23.8
CIW1	203 x 203	52	206.2	203.9	160.8	8.0	12.5
CIW2	356 x 368	177	368.3	372.1	290.1	14.5	23.8
WFC	300 x 300	91					
EC	203 x 203	52	206.2	203.9	160.8	8.0	12.5
Beams B1	533 x 210	122	544.6	211.9	476.5	12.8	21.3
B2	254 x 146	43	259.6	147.3	218.9	7.3	12.7
B3	203 x 133	25	203.2	133.4	172.3	5.8	7.8
SAFB	406 x 178	54	402.6	177.6	360.5	7.6	10.9

TABLE 2 THERMAL PROPERTIES OF LINING MATERIALS INSIDE CARDINGTON FIRE COMPARTMENT

Position	Material	Density kg/m^3	Thermal Conductivity at 20-200°C W/m K	Mean Specific Heat J/kg K
Ceiling	'Unifelt' ceramic fibre tiles (38 mm) Concrete slabs (200 mm thick)	50-250 2400	0.06 1.3	1070 1200
Walls	MPK 125 insulating refractory bricks 'Fireline' plasterboard (12.7 mm thick)	650 825-945	0.19 0.24	1046
Shutters lintels	Ceramic fibre blanket	96	0.06	1070
Floor	Insulating concrete (Monocast 115-149)	1570	0.44	1045

TABLE 3 MAXIMUM AVERAGE COMBUSTION GAS TEMPERATURES AND TIMES RECORDED IN FULL SIZE CARDINGTON COMPARTMENT (ADJUSTED FOR AMBIENT TEMPERATURE 20°C)

Test No.	1		5		8		3		7		4		13		11		9		2		6	
Lining	Refractory Bricks																					
Fuel	Wood																					
Fire load density (kg/m^2)	10+		10		10*		15		15		15		15 (G)		15 (U)		15		20		20	
Ventilation	1/2		1/4		1/8		1/2		1/4 (2)		1/4		1/4		1/4		1/8		1/2		1/4	
Compartment Position	Combustion Gas Temperature and Times																					
	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min
Upper level	404	5.5	688	12.9	771	14.0	633	11.5	694	11.1	849	13.0	639	31.0	739	16.5	866	16.5	649	15.6	957	13.0
Lower level	407	5.0	694	12.9	768	14.5	564	11.5	693	11.1	850	13.0	609	31.0	703	16.5	882	17.0	587	15.6	981	13.0
Overall	403	5.5	691	12.9	769	14.0	605	11.5	694	11.1	850	13.0	627	31.0	724	16.5	872	17.0	623	15.6	966	13.0

Test No.	12		10		15		14		16		17		18		19	
Lining	Refractory Bricks								Gyproc Fireline Board Lining							
Fuel	Wood/Plastic								Wood							
Fire load density (kg/m^2)	10 (3:1)		10 (1:1)		15 (3:1)		15 (3:1)		15		15		20		20	
Ventilation	1/4		1/8		1/2		1/4		1/4		1/8		1/2		1/4	
Compartment Position	Combustion Gas Temperatures and Times															
	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min
Upper level	993	5.5	892	7.5	1042	5.6	1081	5.6	721	3.5	757	16.0	621	14.1	838	14.0
Lower level	1026	5.5	884	7.5	1005	5.6	1108	5.6	747	3.5	769	16.5	585	14.6	872	14.0
Overall	1006	5.5	889	7.5	1027	5.6	1092	5.6	732	3.5	761	16.0	606	14.6	852	14.0

(2) - Two walls ventilated
(G) - Only four cribs ignited
(U) - Uneven distribution of fuel

+ - East side only
* - West side only

TABLE 4 **MAXIMUM AVERAGE STEELWORK TEMPERATURES AND TIMES RECORDED IN FULL SIZE CARDINGTON COMPARTMENT (ADJUSTED FOR AMBIENT TEMPERATURE = 20°C)**

Test No.		1		5		8		3		7		4		13		11		9		2		6	
Lining		Refractory Bricks																					
Fuel		Wood																					
Fire load density (kg/m^2)		10+		10		10*		15		15		15		15 (G)		15 (U)		15		20		20	
Ventilation		1/2		1/4		1/8		1/2		1/4 (2)		1/4		1/4		1/4		1/8		1/2		1/4	
Steelwork		Steelwork Temperatures and Times																					
Identity	H_p/A (m^{-1})	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min
Columns																							
FSC1	180	305	16.5	571	16.0	-	-	495	16.5	586	15.6	753	14.5	557	38.0	744	18.5	769	20.0	573	20.1	961	15.5
FSC2	96	-	-	450	17.8	561	20.7	415	19.8	445	19.1	654	18.3	478	42.8	433	28.0	680	22.5	422	22.0	790	18.5
FSC3	31	119	16.5	248	32.6	-	-	243	32.0	257	24.7	378	31.0	301	64.0	315	38.0	445	35.5	274	41.6	546	21.0
CAW1	149	319	16.5	537	15.0	-	-	515	15.5	549	14.6	706	15.0	543	41.0	748	19.0	763	19.5	614	19.6	889	16.0
CAW2	80	204	-	417	18.0	-	-	370	20.0	442	18.1	562	19.0	471	41.0	645	19.5	650	24.5	465	22.6	756	18.5
CIW1	85	-	-	415	16.2	-	-	474	17.1	-	-	613	17.3	-	-	-	-	-	-	435	20.0	-	-
CIW2	52	-	-	395	19.0	513	21.2	373	20.3	419	19.1	592	19.3	433	42.8	385	28.0	640	22.5	380	25.0	756	18.0
WFC	102	-	-	160	12.4	194	14.5	132	14.5	164	12.6	414	27.0	152	32.0	163	16.5	215	16.5	143	16.0	297	42.0
EC	180	-	-	282	16.0	325	17.0	269	17.0	266	16.0	379	18.0	267	39.0	271	22.0	397	19.4	241	22.0	465	18.0
Beams																							
B1	108	-	-	487	18.0	610	18.0	505	17.0	479	20.0	691	18.0	536	42.8	529	22.0	706	22.0	532	20.0	832	18.0
B2	242	389	15.0	622	14.5	-	-	609	14.5	640	14.0	765	16.0	611	38.0	758	18.0	810	18.0	646	18.1	956	15.0
B3	169	343	16.5	582	16.0	-	-	569	17.0	580	16.1	747	15.0	594	42.0	782	20.0	783	21.0	639	19.6	941	17.0
SAFB	85	-	-	524	17.0	651	17.5	570	16.0	557	16.1	721	17.3	537	40.8	500	22.0	761	19.0	540	18.0	876	18.0

Cont'd...

TABLE 4 (Continued)

Test No.		12		10		15		14		16		17		18		19	
Lining		Refractory Bricks								Gyproc Fireline Board Lining							
Fuel		Wood/Plastic								Wood							
Fire load density (kg/m^2)		10 (3:1)		10 (1:1)		15 (3:1)		15 (3:1)		15		15		20		20	
Ventilation		1/4		1/8		1/2		1/4		1/4		1/8		1/2		1/4	
Steelwork		Steelwork Temperatures and Times															
Identity	H_p/A (m^{-1})	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min	°C	min
Columns																	
FSC1	180	570	8.0	733	12.5	551	7.1	781	12.1	630	16.0	684	19.5	476	19.6	755	17.5
FSC2	96	435	17.5	599	14.0	485	16.1	682	15.6	494	18.0	576	22.3	415	21.0	682	18.5
FSC3	31	256	6.0	336	35.5	286	5.6	384	24.1	239	40.5	316	44.0	233	40.1	374	32.2
CAW1	149	585	6.5	701	12.5	635	7.1	760	7.6	605	15.5	660	19.5	539	17.1	764	17.0
CAW2	80	460	6.0	576	13.0	409	6.6	645	14.1	500	17.0	576	20.0	393	18.6	632	18.5
CIW1	85	-	-	-	-	-	-	-	-	428	17.5	546	21.3	-	-	-	-
CIW2	52	353	19.0	496	20.0	456	16.6	569	16.6	410	19.5	503	23.4	356	21.0	610	19.5
WFC	102	212	6.0	212	6.5	172	6.1	220	4.1	157	14.0	172	17.0	129	18.6	186	15.5
EC	180	244	15.0	348	12.0	305	14.0	440	14.1	263	17.0	261	22.3	255	21.5	347	18.5
Beams																	
B1	108	484	15.5	635	14.0	554	15.1	737	14.1	514	18.0	612	23.0	462	20.0	650	19.0
B2	242	690	7.0	844	11.5	714	7.1	882	7.6	611	16.0	695	18.0	569	16.1	746	17.0
B3	169	558	8.0	737	12.5	594	9.0	776	14.0	574	17.0	647	20.0	511	19.0	722	18.0
SAFB	85	568	7.5	720	11.5	671	7.6	759	7.1	538	17.0	611	21.0	523	18.5	696	18.5

(2) - Two walls ventilated
(G) - Only four cribs ignited
(U) - Uneven distribution of fuel

+ - East side only
* - West side only

TABLE 5 WEIGHT LOSS OF FUEL DURING FIRE TESTS

Test No.	5	3	7	4	16	13	11	9	2	6	12	10	15	14
Fire load density (kg/m^2)	10	15	15	15	15 (GB)	15 (G)	15 (U)	15	20	20	10	10	15	15
Ventilation	1/4	1/2	1/4 (2)	1/4	1/4	1/4	1/4	1/8	1/2	1/4	1/4	1/8	1/2	1/4
Fuel	Wood										Wood/Plastic			
Weight (kg)	508	762	762	762	684	762	762 (Av)	762	1016	1016	386W 50P	267W 101P	578W 77P	578W 77P
	Average Rate of Weight Loss of Fuel in the Compartment, kg/s													
From 80-55% of load	0.53	0.75	0.86	0.77	0.64	0.74	0.37-0.97	0.63	0.74	0.85	0.53-0.80	0.28-0.69	0.83	1.00
From 55-30% of load	0.56	0.66	0.74	0.69	0.53	0.65	0.45-0.88	0.67	0.74	0.85	0.35	0.41	0.57	1.10
Overall average loss	0.54	0.71	0.80	0.73	0.58	0.69	0.41-0.92	0.65	0.74	0.85	0.51	0.44	0.70	1.05

(G) - Only four cribs ignited (GB) - Gyproc Fireline board lining
(U) - Uneven distribution of fuel (2) - Two walls ventilated

TABLE 6 MAXIMUM AVERAGE TEMPERATURES AND TIMES AS INFLUENCED BY COMPARTMENT SIZE (ADJUSTED FOR AMBIENT TEMPERATURE = 20°C)

(a) Combustion Gas

Compartment Position	Combustion Gas Temperatures and Times					
	Floor Area, m^2					
	49.4 (Test No. 16)		27.1 (Test No. 20)		27.1 (Test No. 21)	
	Wood Fuel		Wood Fuel		Wood/Plastic (3:1)	
	°C	min	°C	min	°C	min
Upper level	721	3.5	680	15.0	850	6.0
Lower level	747	3.5	674	15.0	921	6.0
Overall	732	3.5	678	15.0	882	6.0

1/4 ventilation

TABLE 6 (Continued)

(b) **Steelwork**

Steelwork		Steelwork Temperatures and Times					
		Floor Area, m^2					
		49.4 (Test No. 16)		27.1 (Test No. 20)		27.1 (Test No. 21)	
Component Identity	H_p/A (m^{-1})	Wood Fuel		Wood Fuel		Wood/Plastic (3:1)	
		^oC	min	^oC	min	^oC	min
FSC1		630	16.0	579	18.5	638	8.5
FSC3		239	40.5	203	38.0	221	33.5
CAW1		579	16.0	524	19.0	564	14.5
		(605)	(15.5)	(554)	(17.0)	(556)	(14.5)
CAW2		442	17.0	412	21.0	434	15.0
		(500)	(17.0)	(470)	(18.0)	(496)	(14.0)
WFC		157	14.1	119	18.5	144	6.0
B2		611	16.0	582	18.0	623	11.0
		(597)	(16.0)	(569)	(17.5)	(650)	(7.5)
B3		574	17.0	543	19.0	578	15.0
		(574)	(16.5)	(543)	(18.5)	(569)	(14.0)

1/4 ventilation

TABLE 7 **PREDICTED AND MEASURED MAXIMUM AVERAGE GAS TEMPERATURE FOR WOOD FIRES**

Location	Cardington Compartment												BISF/FRS Tests	
	Insulated								Plasterboard Lined					
Fire load density (kg/m^2)	10	10	10	15	15	15	20	20	15	15	20	20	15	15
Ventilation	1/2	1/4	1/8	1/2	1/4	1/8	1/2	1/4	1/4	1/8	1/2	1/4	1/2	1/4
Max. average combustion gas temperature (^oC)	403	691	769	605	850	872	623	966	732	761	606	852	480	725
Predicted max. average combustion gas temperature (^oC)	433	568	600	581	739	747	700	865	739	747	700	865	545	701
Temperature difference (^oC)	-30	+123	+169	+24	+111	+125	-77	+101	-7	+14	-94	-13	-65	+24

TABLE 8 **THE BEHAVIOUR OF PARTIALLY PROTECTED STEEL SECTIONS IN A REAL FIRE AND IN THE BS476:PT 8 FIRE TEST (ADJUSTED FOR AN AMBIENT TEMPERATURE = 20°C)**

Details of Section	Time (min)	Steel and Combustion Gas Temperatures, °C									
		Cardington Test No. 16 - Plasterboard 15 kg/m², 1/4 ventilation					BS476:Pt 8 Fire Test				
		Exposed Flange	Exposed Web	Unexposed Web	Unexposed Flange	Combustion Gas	Exposed Flange	Exposed Web	Unexposed Flange	Unexposed Flange	Combustion Gas
CIW1 (Lower level)	3.0	119	38	21	21	583	116	83	26	20	475
	6.0	260	109	23	20	601	198	138	34	22	598
	9.0	337	175	32	21	616	288	208	46	26	628
	12.0	420	240	44	23	798	384	287	59	31	675
	15.0	497	316	58	28	711	475	366	76	38	741
	18.0	492	363	75	34	507	565	448	93	46	783
	21.0	461	369	90	41	394	632	515	110	57	802
SAFB (Back position)	3.0	123	113	135	28	737	85	126	22	21	485
	6.0	262	217	203	46	621	184	221	24	21	615
	9.0	365	306	240	56	630	311	324	27	21	678
	12.0	452	388	284	66	684	426	413	33	22	701
	15.0	521	458	332	81	690	519	490	41	25	740
	18.0	535	477	354	96	514	588	547	49	23	757
	21.0	508	459	357	107	384	620	587	59	24	774

TABLE 9 **THEORETICAL AND MEASURED TIME EQUIVALENT VALUES FOR STEELWORK IN CARDINGTON FIRE TESTS**

Boundary		Insulated compartment													Plasterboard Lined Compartment				Plasterboard Lined Small Compartment	
Fuel		Wood									Wood + Polypropylene				Wood				Wood	Wood+Polypr.
Fire load density and ventilation		10 kg/m²			15 kg/m²				20 kg/m²		10 kg/m²		15 kg/m²		15 kg/m²		20 kg/m²		15 kg/m²	
Steelwork		1/2	1/4	1/8	1/2	1/4	1/8	1/4G	1/2	1/4	1/4	1/8	1/2	1/4	1/4	1/8	1/2	1/4	1/4	1/4
Identity	H_p/A (m^{-1})	Time Equivalent, min																		
Columns																				
FSC1	180	8.3	15.5	-	13.0	28.0	30.0	15.5	16.0	75.0	16.0	25.0	15.0	31.5	18.0	21.0	13.0	25.5	16.0	18.5
FSC2	96	-	16.5	22.0	16.5	28.5	29.5	18.5	16.5	43.0	16.5	24.0	19.0	29.5	19.2	22.5	16.0	29.5	-	-
FSC3	31	11.5	20.5	-	21.0	31.5	36.0	25.0	23.0	46.0	21.5	28.0	23.5	32.0	20.5	26.5	20.0	31.0	17.5	19.0
Beams																				
B1	108	-	18.7	26.0	20.5	31.5	32.5	21.5	21.4	>58.5	18.6	28.0	22.0	37.0	20.6	26.0	18.5	27.5	-	-
B2	242	8.7	16.0	-	15.7	29.0	33.5	15.7	17.5	>63.5	20.0	37.0	21.5	45.0	15.5	20.5	14.0	25.0	14.5	16.0
B3	169	9.5	17.0	-	16.5	30.0	35.0	17.5	19.5	>82.5	16.3	28.8	17.5	36.5	16.5	19.7	14.5	25.5	15.5	16.5
SAFB	85	-	15.5	23.0	17.5	29.5	36.5	16.0	16.0	58.0	17.5	29.5	24.0	36.5	16.0	20.5	15.5	27.5	-	-
Av. experimental time equivalent (min) [1]		9.5	17.1	23.7	17.2	29.7	33.3	18.5	18.6	61.0	18.1	28.6	20.4	35.4	18.0	22.4	15.9	27.4	15.9	17.5
Theoretical time equivalent - Equ. 1 [2]		8.7	12.3	17.3	13.2	18.5	25.9	18.5	17.5	24.6	12.3	17.3	13.2	18.5	18.1	25.4	17.3	24.1	17.4	17.4
Theoretical time equivalent - Equ. 2 [3]		8.5	12.1	17.2	12.7	18.1	25.9	18.1	16.9	24.1	12.1	17.3	12.7	18.1	17.8	25.1	16.6	23.7	17.0	17.0
Mean theoretical time equivalent [4]		8.6	12.2	17.2	13.0	18.3	25.9	18.3	17.2	24.4	12.2	17.3	13.0	18.3	18.0	25.3	17.0	23.9	17.2	17.2
Ratio 1:4		1.1	1.4	1.4	1.3	1.6	1.3	1.0	1.1	2.5	1.5	1.7	1.6	1.9	1.0	0.9	0.9	1.1	0.9	1.0
Approx. Petterson factor		2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.10	1.18	0.95	1.10	1.17	1.17

Equ. 1 $$Te = k \frac{L}{\sqrt{A_v . A_T}}$$ (k = 1, L in kg wood)

Equ. 2 $$Te = 0.067 \frac{q}{\left(\frac{A_v \sqrt{h}}{A_T}\right)^{\frac{1}{2}}}$$ (q in MJ/m²)

TABLE 10 **MAXIMUM AVERAGE STEEL TEMPERATURES AND TIME EQUIVALENT VALUES FOR UNPROTECTED STEEL COLUMN IN THE BISF/FRS TESTS**

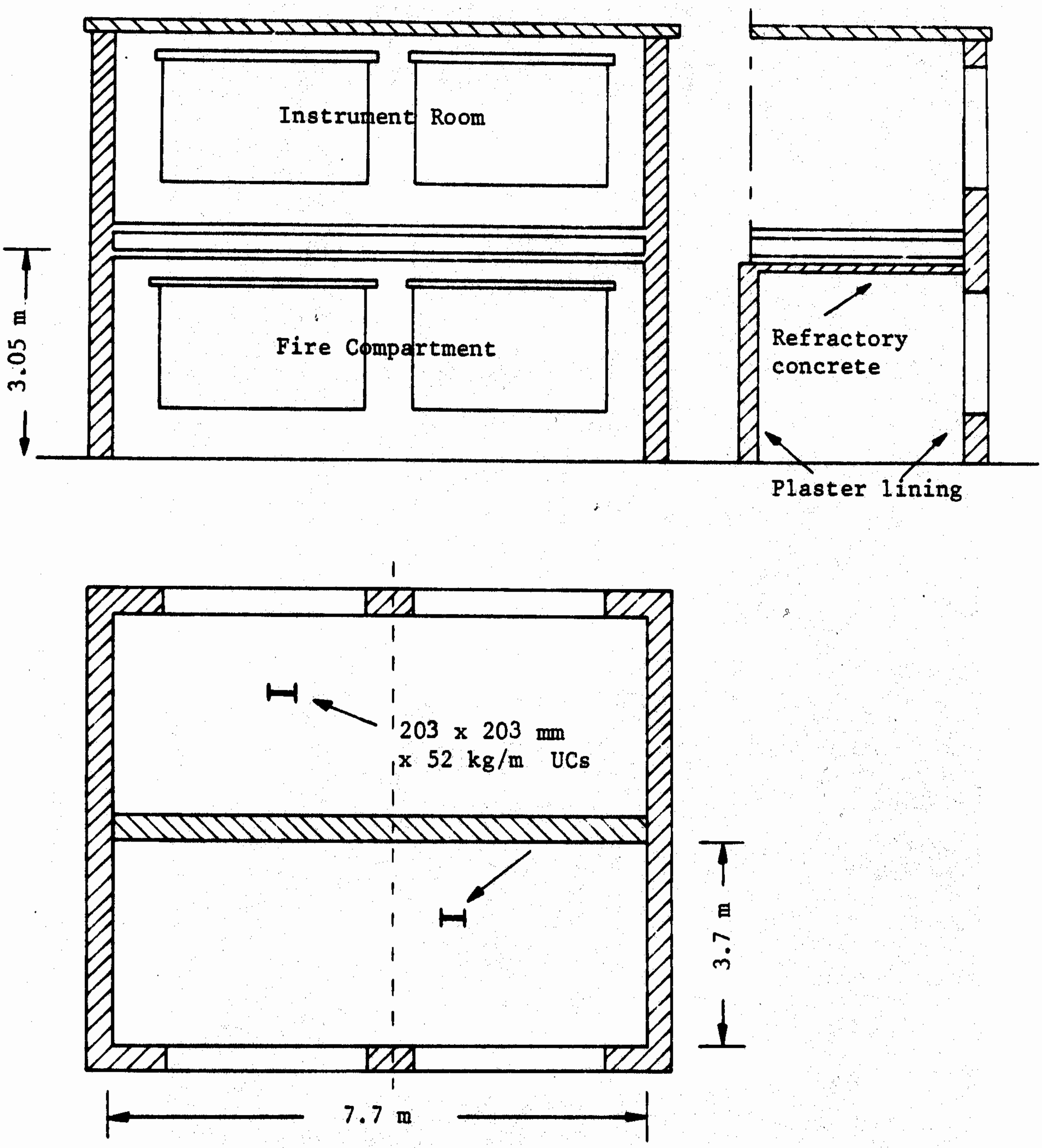
Fuel	Wood							
Fire load density (kg/m²)	7.5		15.0		30.0		60.0	
Ventilation	1/2	1/4	1/2	1/4	1/2	1/4	1/4	1/8
Max. average steel temperature for FSC1 column (°C)	150	245	370	550	742	1010	1160	1170
Av. experimental time equivalent (min)	4.0	6.5	9.5	15.0	26.0	96.5	>100	>100
Theoretical time equivalent Equ. 1 (min)	6.0	8.2	12.0	16.5	24.0	33.0	66.0	92.5

TABLE 11 LIMITING SECTION FACTOR VALUES FOR WOOD BURNING FIRES IN PLASTERBOARD LINED COMPARTMENT

Fire load density (kg/m^2)		7.5		10.0			15.0			20.0			30.0			60.0	
Ventilation of one wall		1/4	1/8	1/2	1/4	1/8	1/2	1/4	1/8	1/2	1/4	1/8	1/2	1/4	1/8	1/2	1/4
Opening factor		0.06	0.03	0.12	0.06	0.03	0.12	0.06	0.03	0.12	0.06	0.03	0.12	0.06	0.03	0.12	0.06
Time equivalent (min)		9.0	11.0	9.5	13.4	18.9	10.5	18.0	22.0	16.0	27.0	30.0	21.0	36.0	44.0	42.0	72.0
Limiting Temperature (°C)		Limiting H_p/A Value															
(1) Three sided attack:	500	>285	278	>285	196	116	>285	126	91	149	69	60	98	<<60	<<60	<<60	<<60
	550	>285	>285	>285	241	138	>285	150	109	180	84	63	115	<<60	<<60	<<60	<<60
	600	>285	>285	>285	>285	166	>285	181	130	222	100	78	138	<<60	<<60	<<60	<<60
	650	>285	>285	>285	>285	206	>285	232	158	288	121	94	169	68	<<60	<<60	<<60
	700	>285	>285	>285	>285	293	>285	>285	215	>285	154	118	232	86	<<60	64	<<60
	750	>285	>285	>285	>285	>285	>285	>285	>285	>285	275	180	>285	121	80	88	<<60
(2) Four sided attack:	500	>300	220	290	168	96	250	108	80	140	60	53	84	40	<30	30	-
	550	>300	275	>300	195	118	300	133	96	175	70	60	101	47	34	36	-
	600	>300	>300	>300	225	144	>300	158	113	192	83	71	120	54	40	43	-
	650	>300	>300	>300	265	182	>300	192	140	220	97	83	150	62	47	48	<30
	700	>300	>300	>300	>300	220	>300	240	80	>300	118	102	190	77	55	60	32
	750	>300	>300	>300	>300	>300	>300	>300	245	>300	170	138	265	96	72	77	42

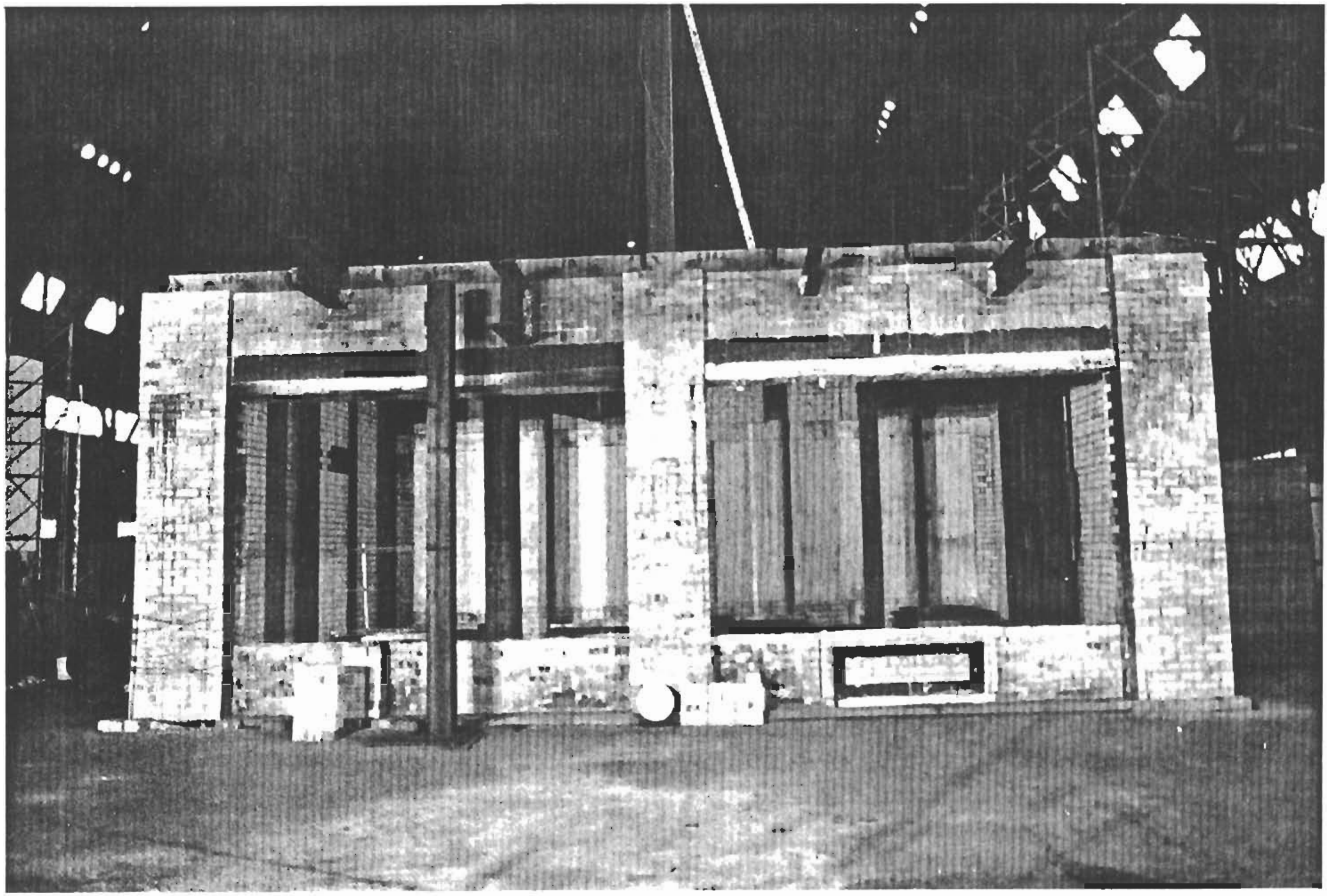
TABLE 12 LIMITING SECTION FACTOR VALUES FOR WOOD + POLYPROPYLENE (75:25) BURNING FIRES IN PLASTERBOARD LINED COMPARTMENT

Fire load density (kg/m^2)		7.5		10.0			15.0			20.0			30.0			60.0	
Ventilation of one wall		1/4	1/8	1/2	1/4	1/8	1/2	1/4	1/8	1/2	1/4	1/8	1/2	1/4	1/8	1/2	1/4
Opening factor		0.06	0.03	0.12	0.06	0.03	0.12	0.06	0.03	0.12	0.06	0.03	0.12	0.06	0.03	0.12	0.06
Time equivalent (min)		9.9	12.1	10.5	14.7	20.8	11.5	19.8	24.2	17.6	29.5	33.0	23.0	39.6	48.4	46.2	79.2
Limiting Temperature (°C)		Limiting H_p/A Value															
(1) Three sided attack:	500	>244	>285	>285	175	100	244	109	79	130	<60	<<60	85	<<60	<<60	<<60	<<60
	550	>285	>285	>285	212	119	>285	129	93	155	66	<60	101	<<60	<<60	<<60	<<60
	600	>285	>285	>285	268	142	>285	154	111	190	80	66	120	<<60	<<60	<<60	<<60
	650	>285	>285	>285	>285	175	>285	192	134	248	96	81	146	<<60	<<60	<<60	<<60
	700	>285	>285	>285	>285	248	>285	274	175	>285	121	102	195	72	<<60	<<60	<<60
	750	>285	>285	>285	>285	>285	>285	>285	>285	>285	181	148	>285	101	<<66	75	<<60
(2) Four sided attack:	500	270	205	250	146	86	220	94	71	108	54	46	76	34	<<30	<<30	-
	550	>300	240	300	180	104	257	114	83	132	60	52	90	41	<<30	31	-
	600	>300	275	>300	204	128	>300	140	94	156	72	60	107	47	35	38	-
	650	>300	>300	>300	249	158	>300	178	118	198	84	72	132	55	40	43	-
	700	>300	>300	>300	>300	193	>300	208	144	245	106	88	170	66	49	52	>30
	750	>300	>300	>300	>300	270	>300	300	210	>300	144	114	228	85	60	67	>30

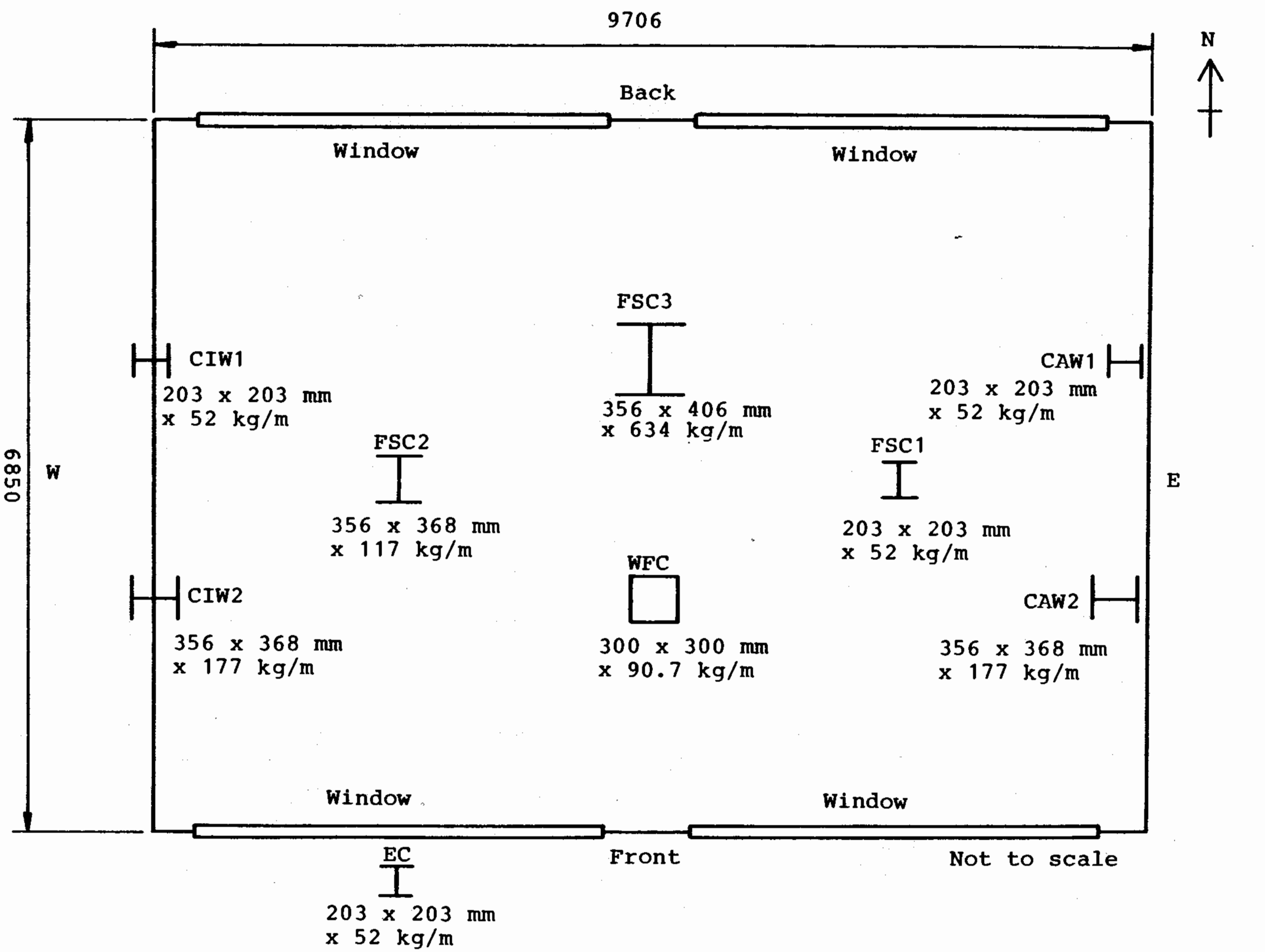


BUILDING USED IN BISF/FRS FIRE TESTS OF 1964

FIG. 1
(R2/1450)

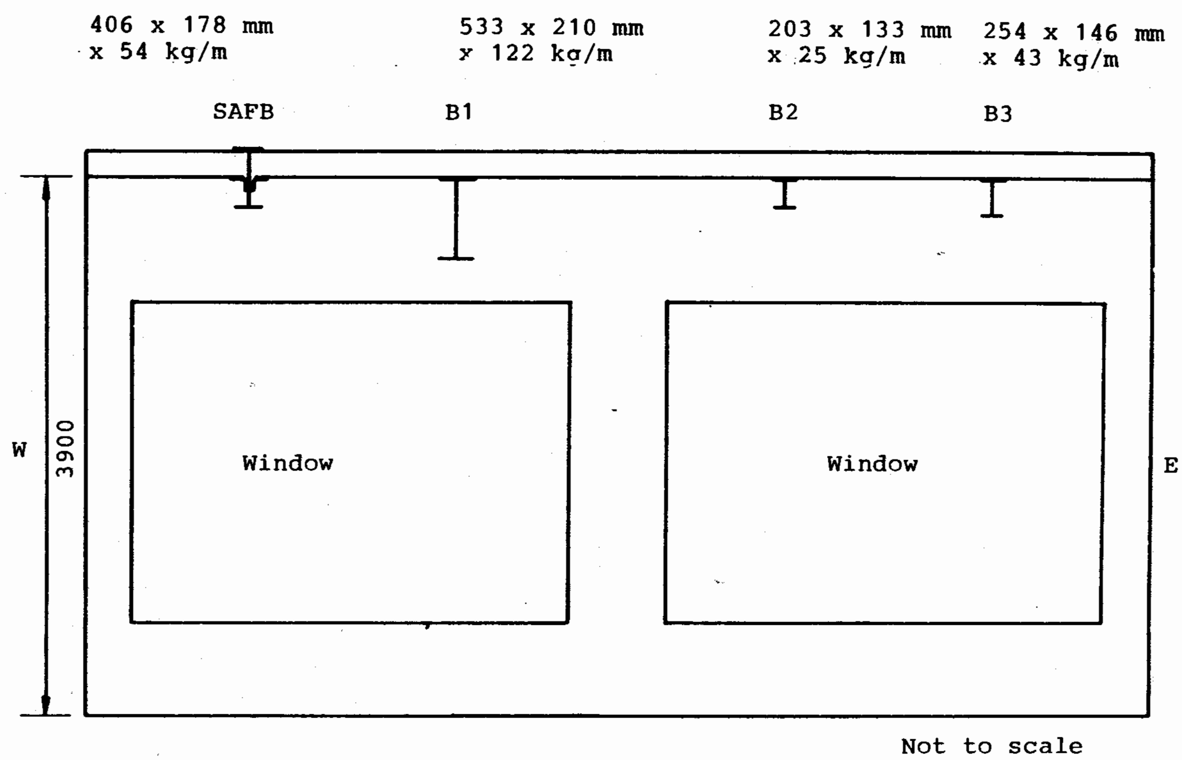


FRONT ELEVATION (SOUTH WALL) OF FIRE TEST COMPARTMENT FIG. 2



PLAN OF THE FIRE TEST COMPARTMENT GIVING DETAILS OF THE COLUMN SIZES IDENTIFICATION AND THEIR LOCATION

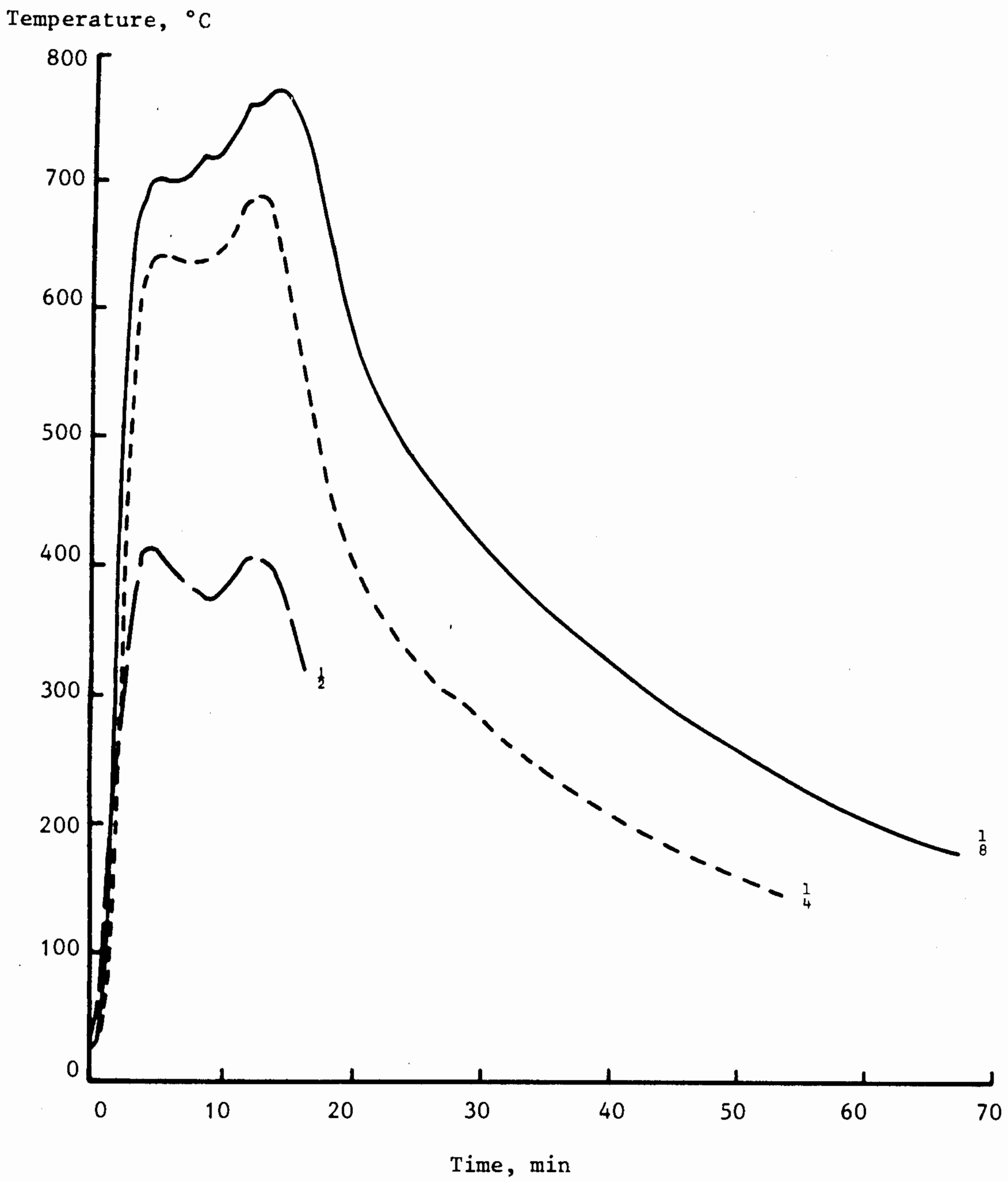
FIG. 3
(R2/4536)



FRONT ELEVATION OF THE FIRE TEST COMPARTMENT GIVING DETAILS OF THE BEAM SIZES IDENTIFICATION AND THEIR LOCATION

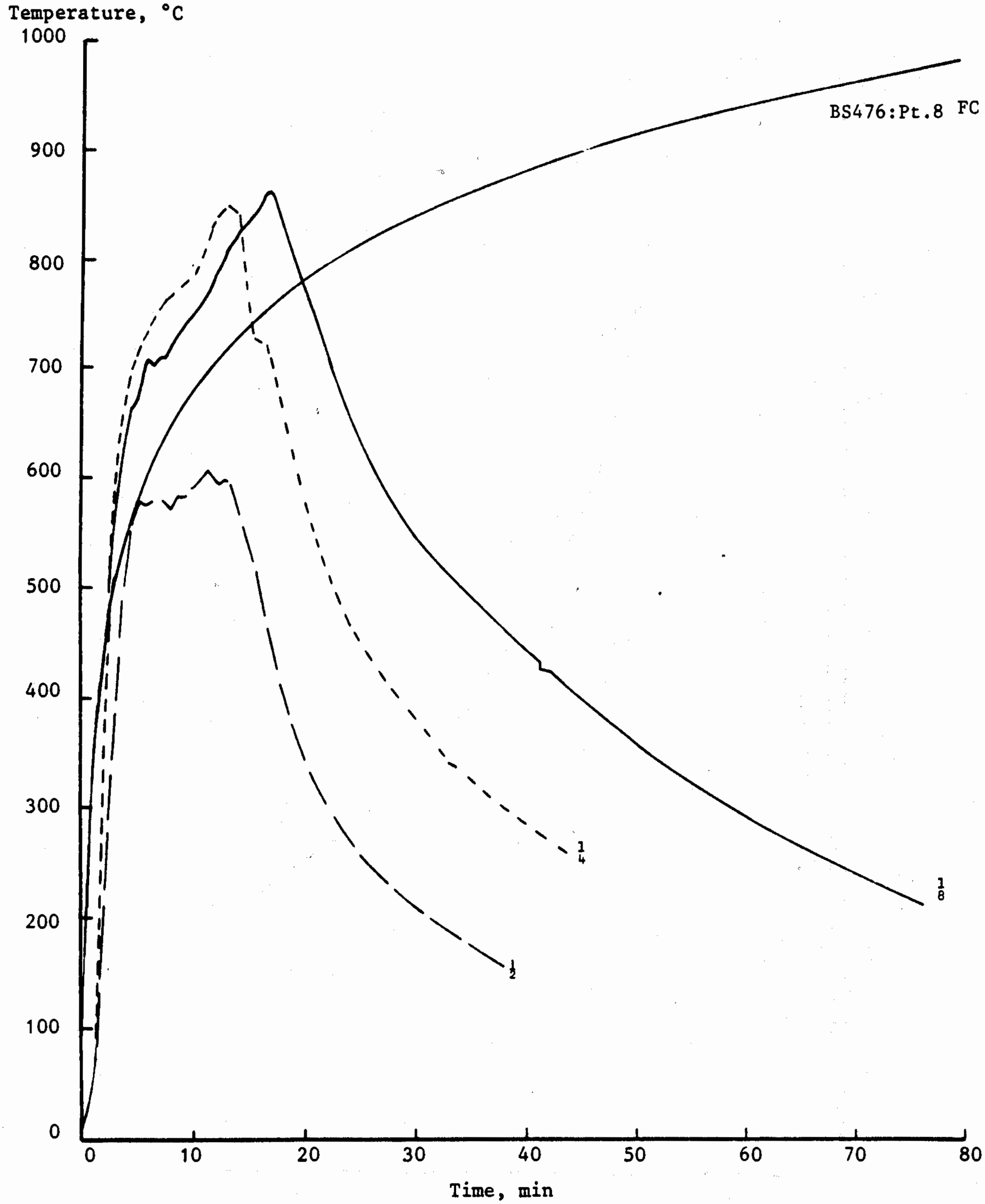
FIG. 4
(R2/4537)

STATE OF COMBUSTION AFTER 8 min FOR A WOODEN FIRE LOAD DENSITY OF 15 kg/m² AND THE ¼ VENTILATION OF ONE WALL   FIG. 5



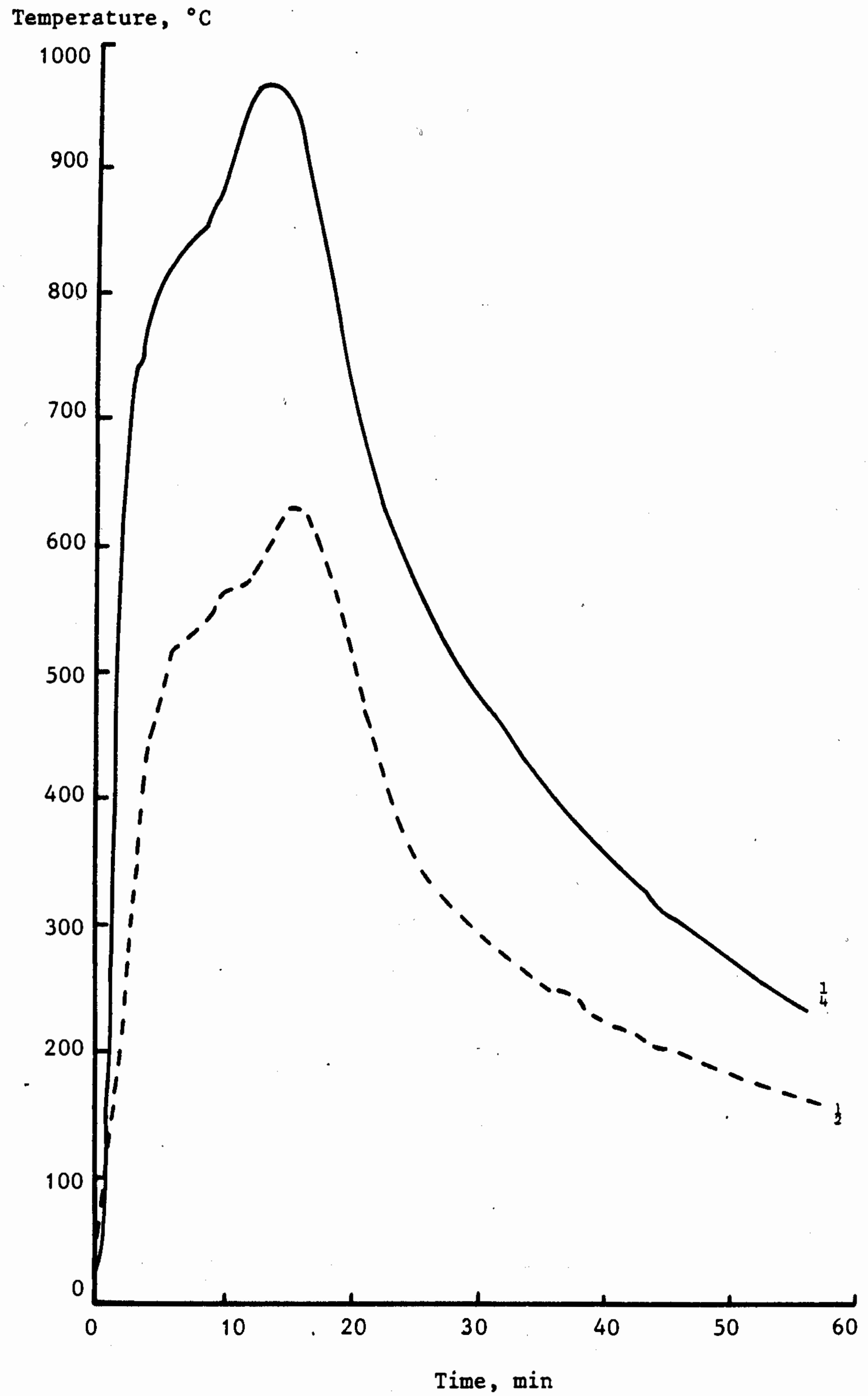
AVERAGE COMBUSTION GAS TEMPERATURES INSIDE COMPARTMENT FOR A WOODEN FIRE LOAD DENSITY OF 10 kg/m² AND DIFFERENT VENTILATION CONDITIONS

FIG. 6
(R2/1451)



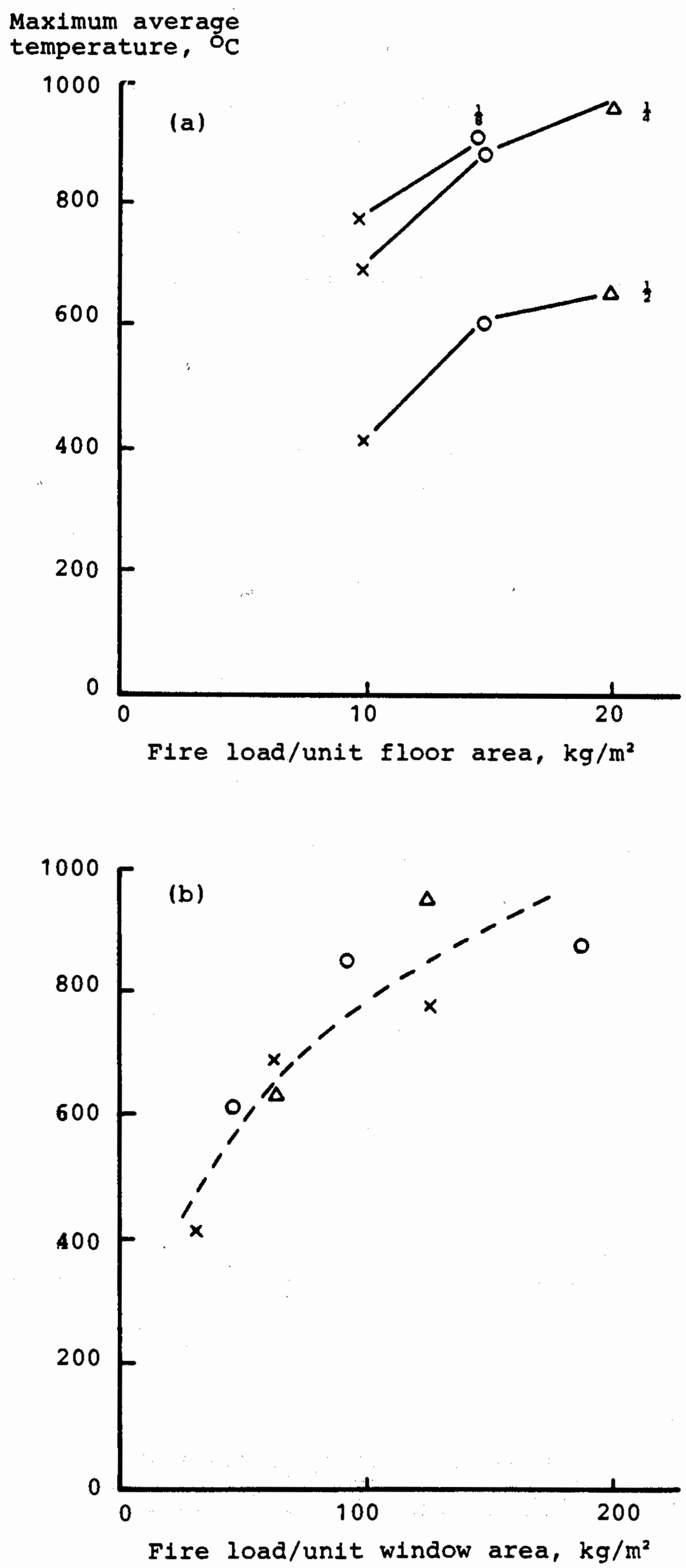
AVERAGE COMBUSTION GAS TEMPERATURES INSIDE COMPARTMENT FOR A WOODEN FIRE LOAD DENSITY OF 15 kg/m² AND DIFFERENT VENTILATION CONDITIONS

FIG. 7
(R2/1452)



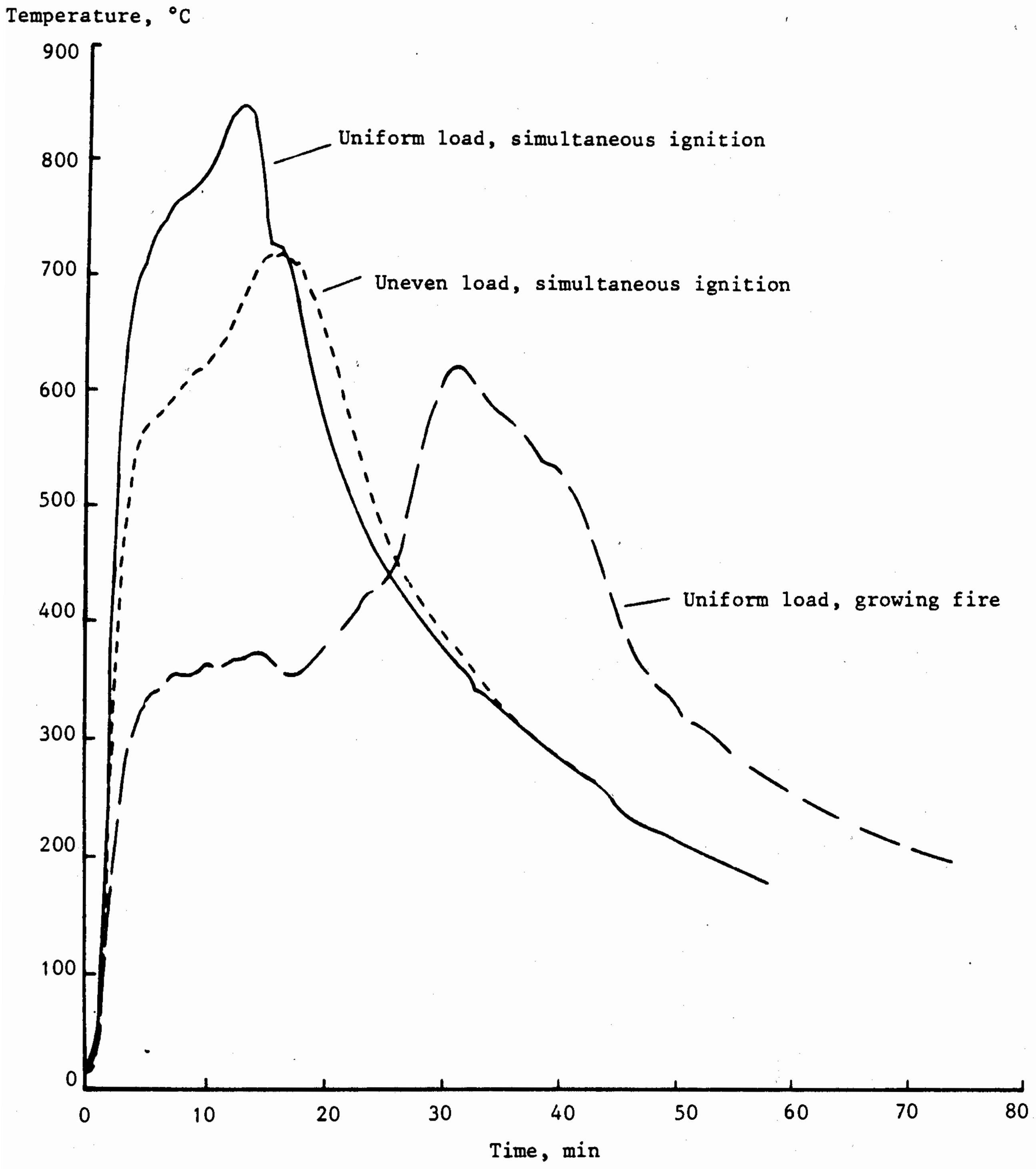
AVERAGE COMBUSTION GAS TEMPERATURES INSIDE COMPARTMENT FOR A WOODEN FIRE LOAD DENSITY OF 20 kg/m² AND DIFFERENT VENTILATION CONDITIONS

FIG. 8
(R2/1453)



<u>THE INFLUENCE OF FIRE LOAD DENSITY ON COMBUSTION GAS TEMPERATURES INSIDE COMPARTMENT</u>

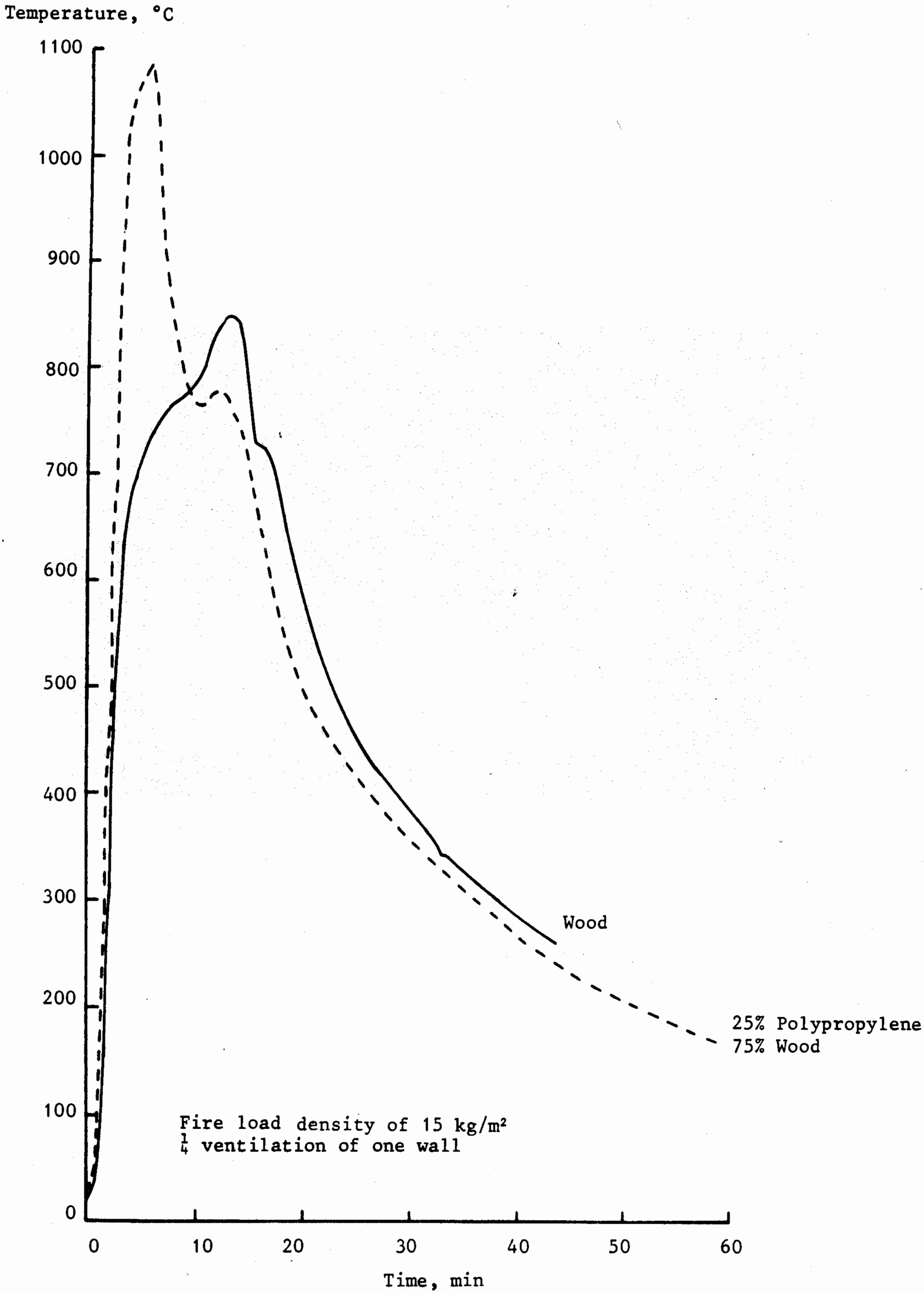
FIG. 9
(R2/4538)



AVERAGE COMBUSTION GAS TEMPERATURES INSIDE COMPARTMENT FOR A WOODEN FIRE LOAD DENSITY OF 15 kg/m² AND ¼ VENTILATION AND DIFFERENT TYPES OF IGNITION

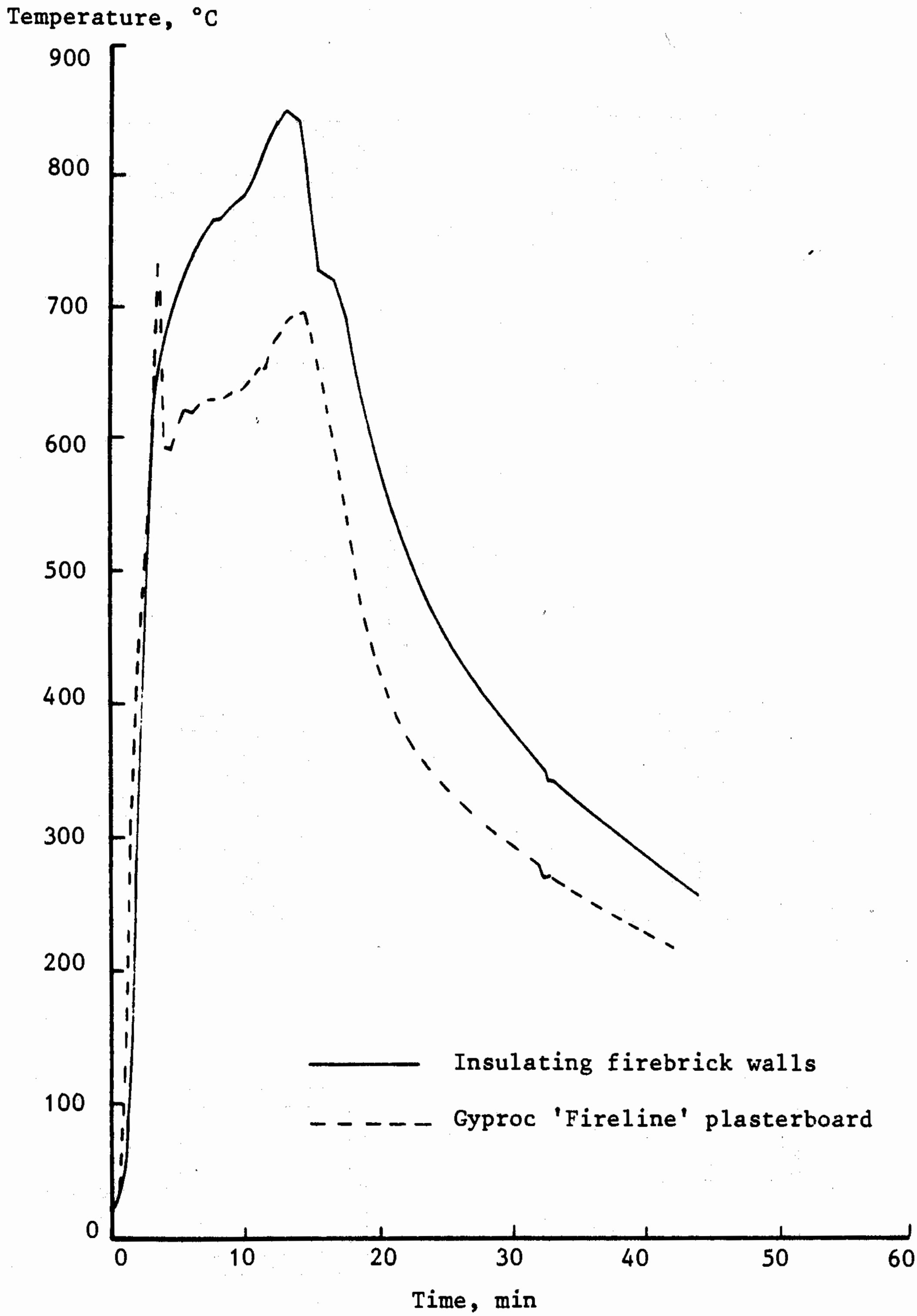
FIG. 10
(R2/1455)

FIRE TEST IN PROGRESS WITH A MIXTURE OF WOOD AND POLYPROPYLENE AS THE FUEL — FIG. 11



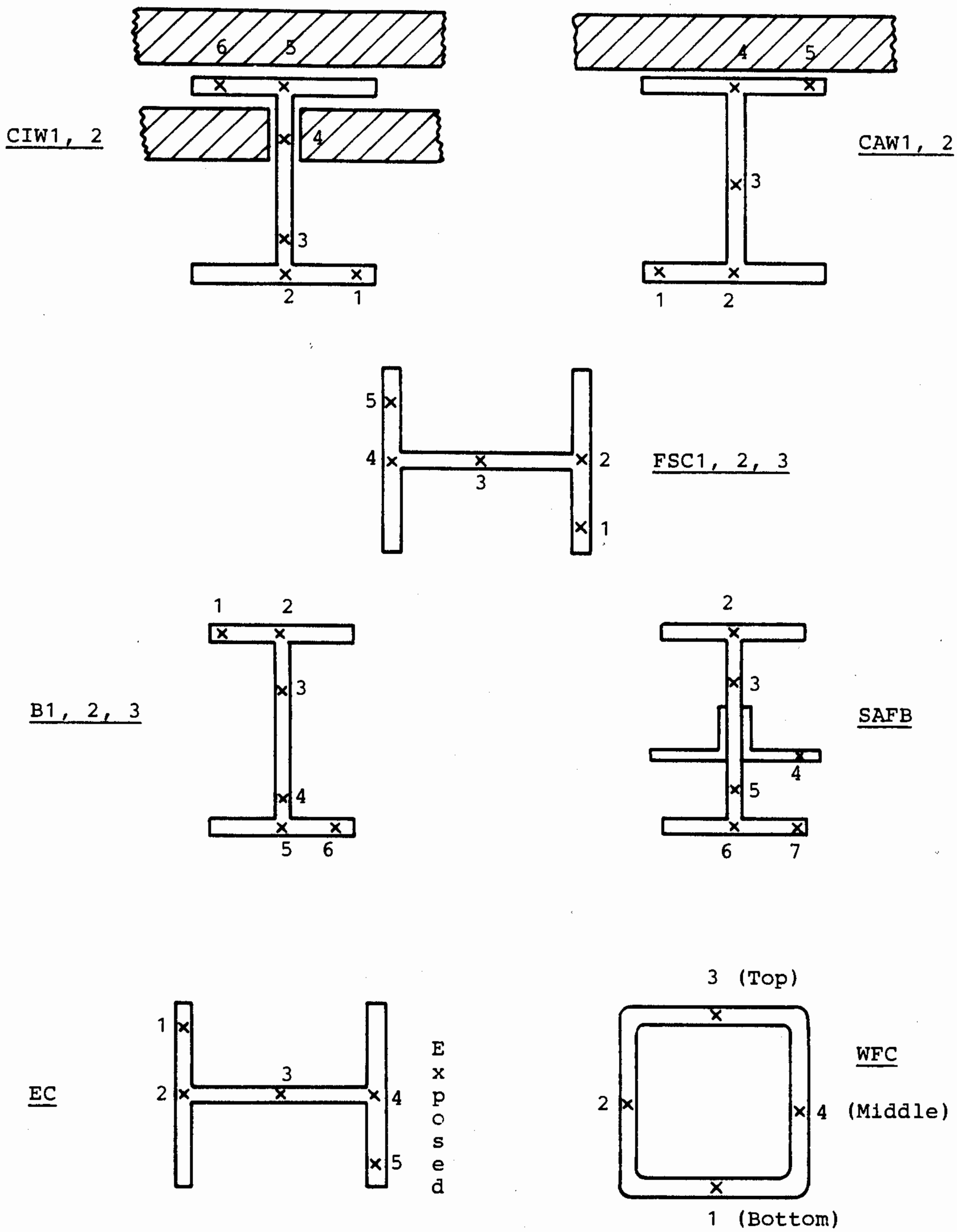
COMBUSTION GAS TEMPERATURE INSIDE COMPARTMENT AS INFLUENCED BY FUEL TYPE

FIG. 12 (R2/1457)

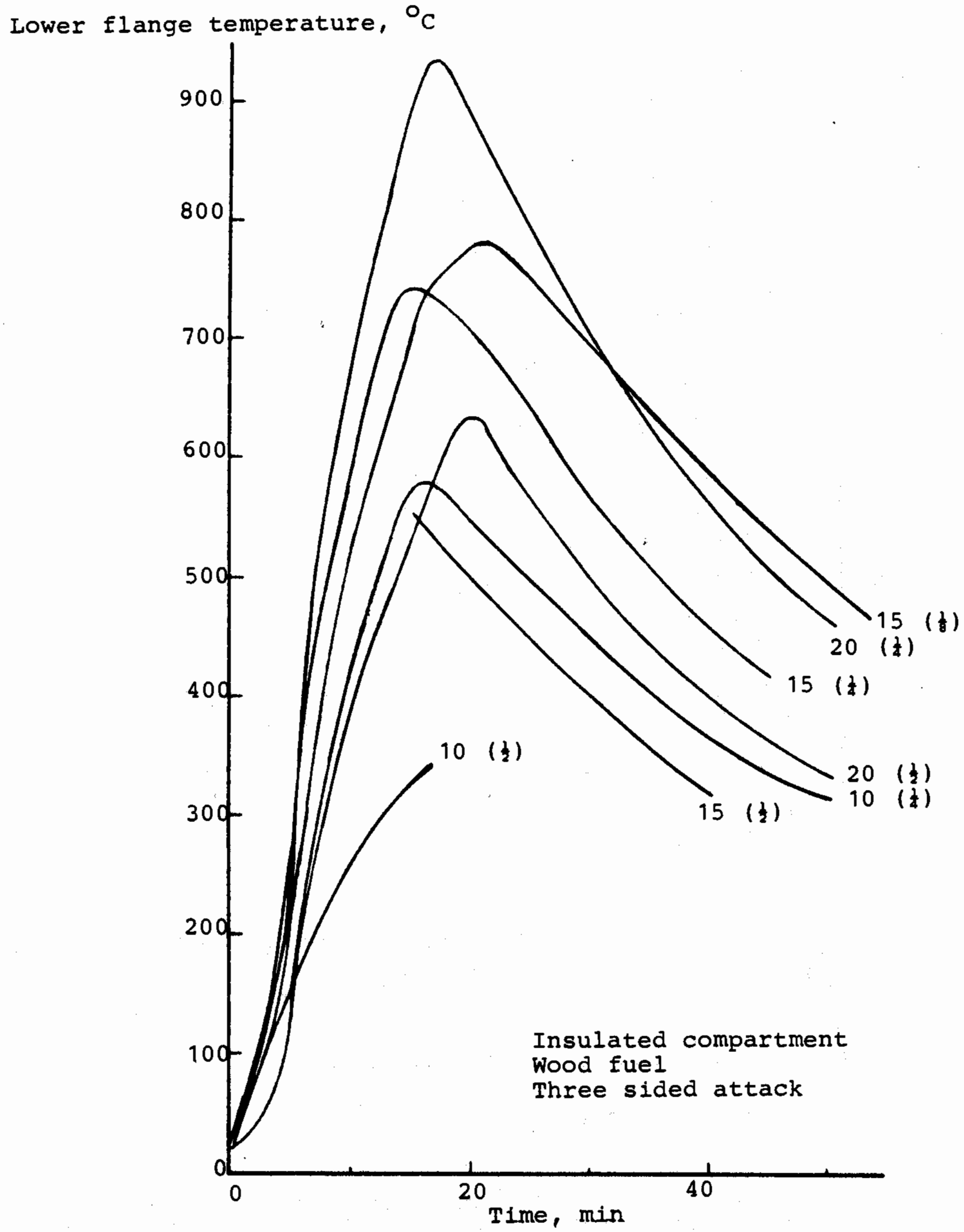


AVERAGE COMBUSTION GAS TEMPERATURES AS INFLUENCED BY COMPARTMENT LINING FOR A WOODEN FIRE LOAD DENSITY OF 15 kg/m² AND THE ¼ VENTILATION OF ONE WALL

FIG. 13
(R2/1456)

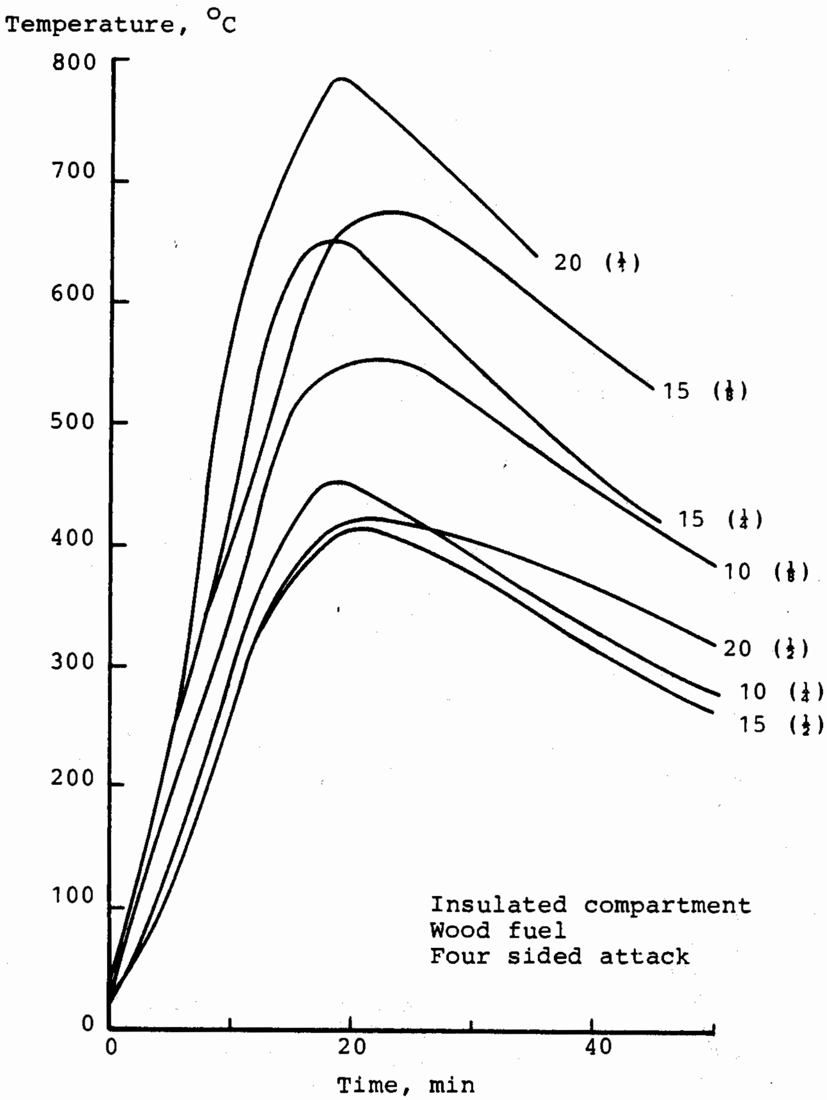


THERMOCOUPLE POSITIONS IN STEELWORK FIG. 14 (R2/4539)



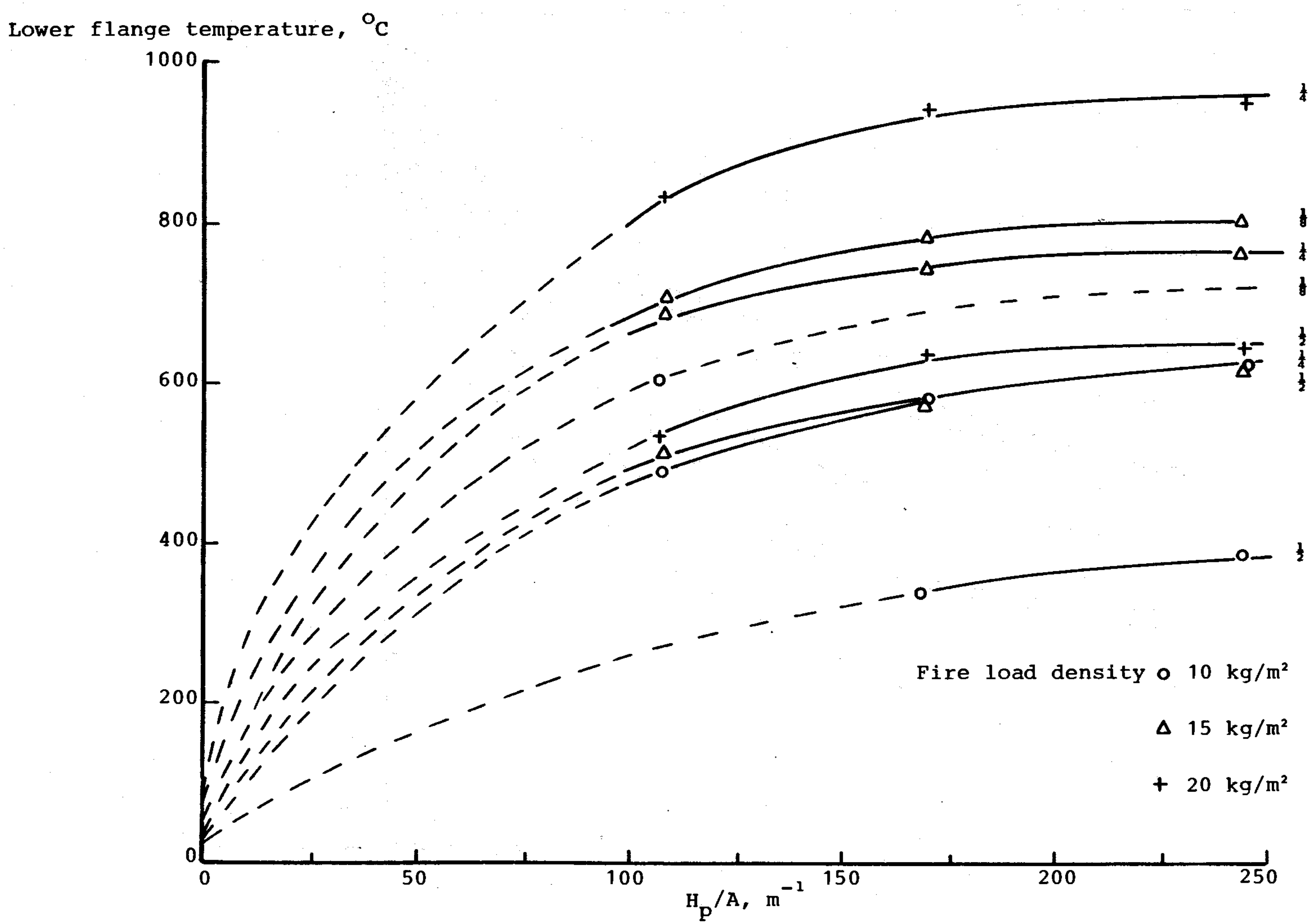
<u>THE EFFECT OF FIRE LOAD AND VENTILATION ON THE TEMPERATURE OF AN UNPROTECTED BEAM WITH AN H_p/A = 169 m^{-1}</u>

FIG. 15
(R2/4540)



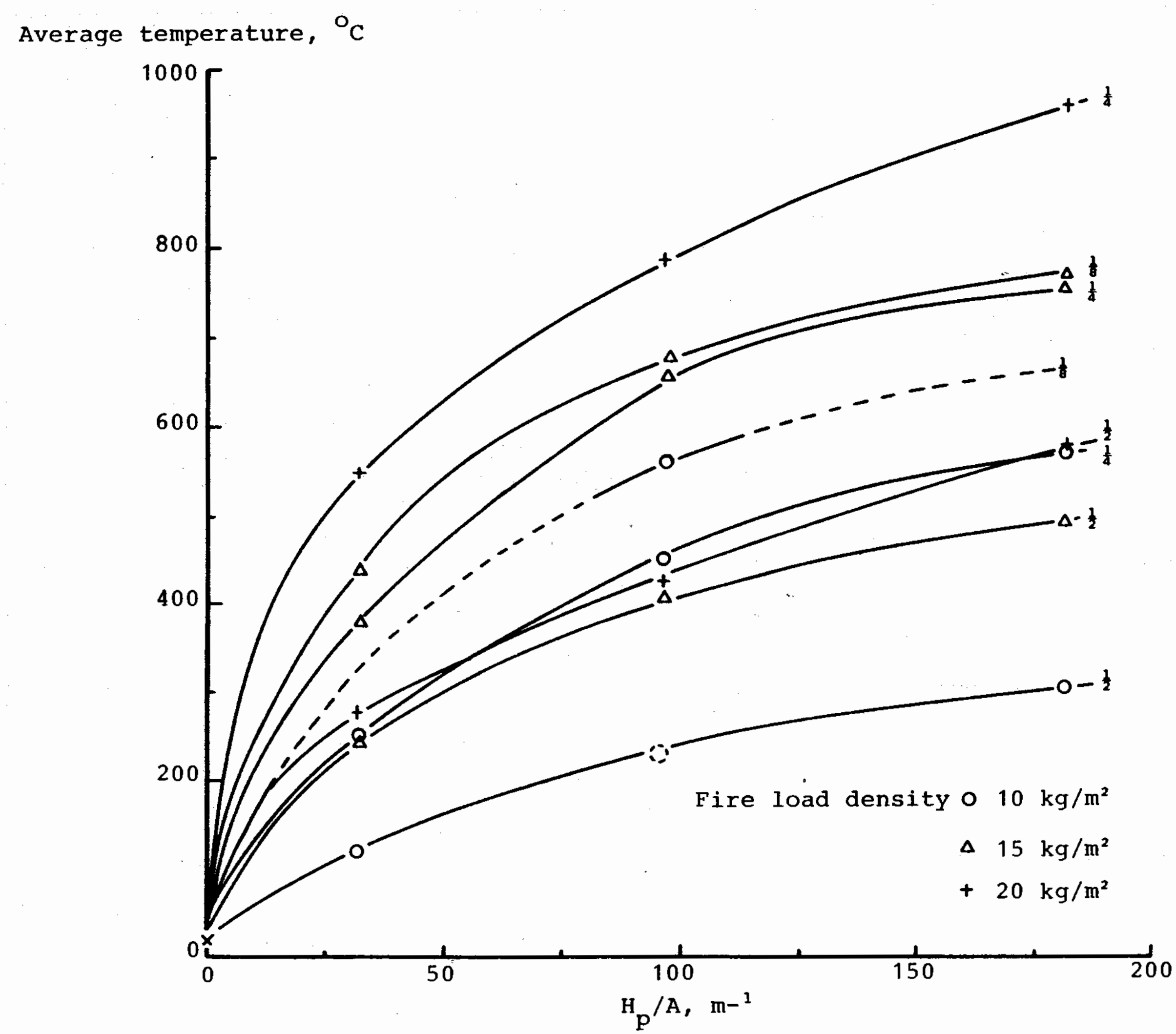
<u>THE EFFECT OF FIRE LOAD AND VENTILATION ON THE TEMPERATURE OF AN UNPROTECTED COLUMN WITH AN H_p/A = 96 m^{-1}</u>

FIG. 16
(R2/4541)



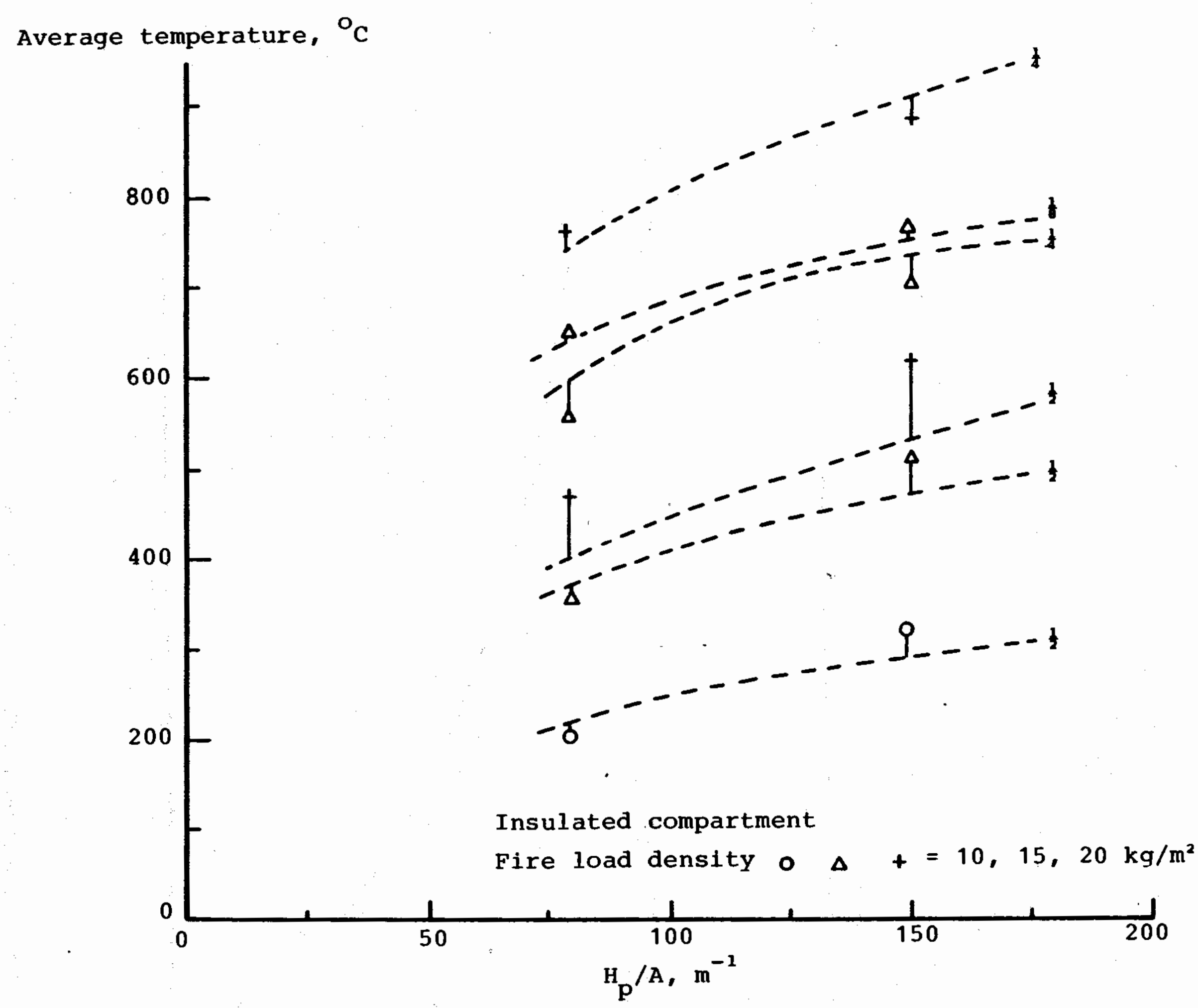
STEEL BEAM TEMPERATURES MEASURED IN WOOD FIRES AND AN INSULATED COMPARTMENT LINING

FIG. 17
(R2/4542)



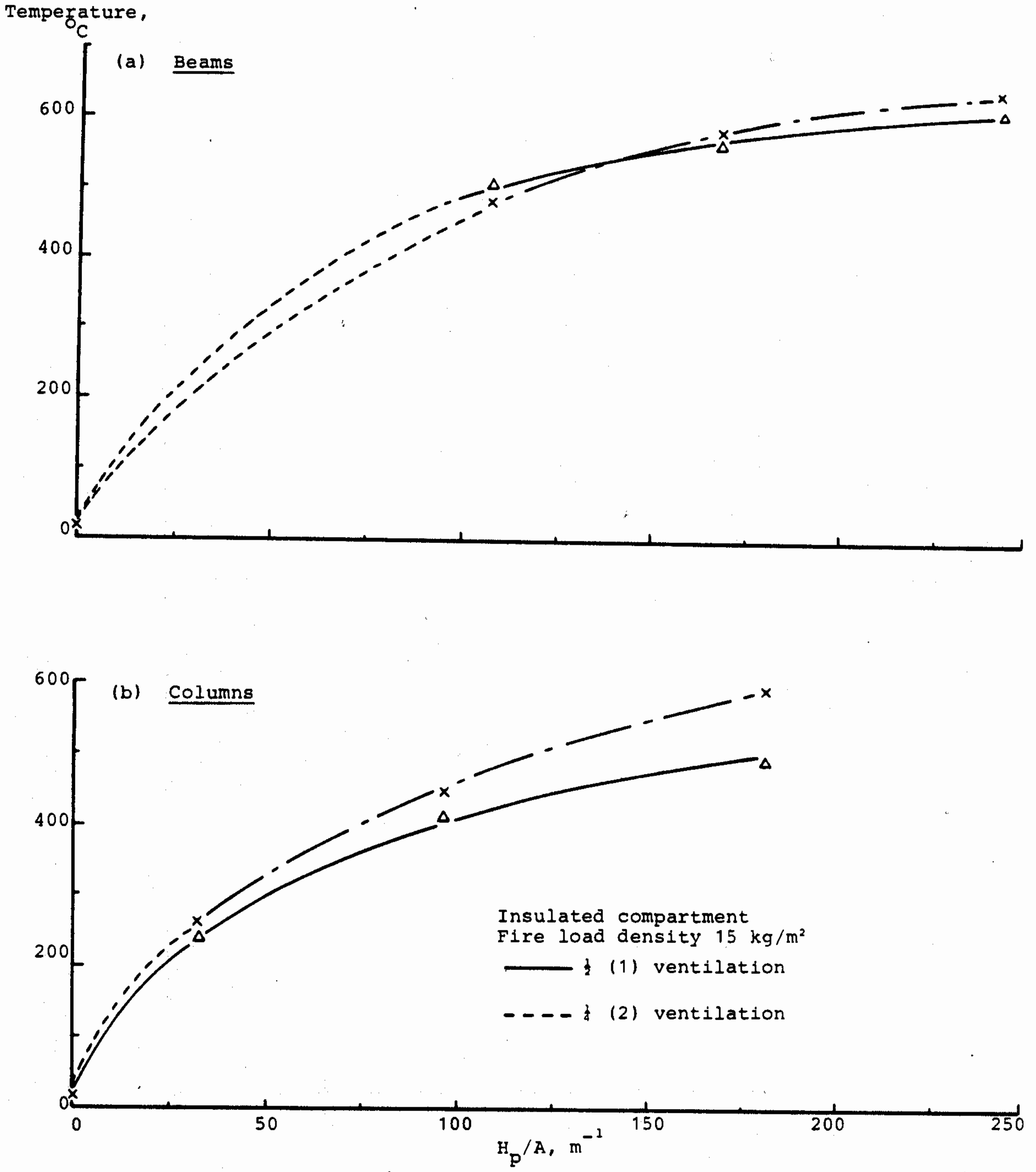
STEEL COLUMN TEMPERATURES MEASURED IN WOOD FIRES AND AN INSULATED COMPARTMENT LINING

FIG. 18
(R2/4543)



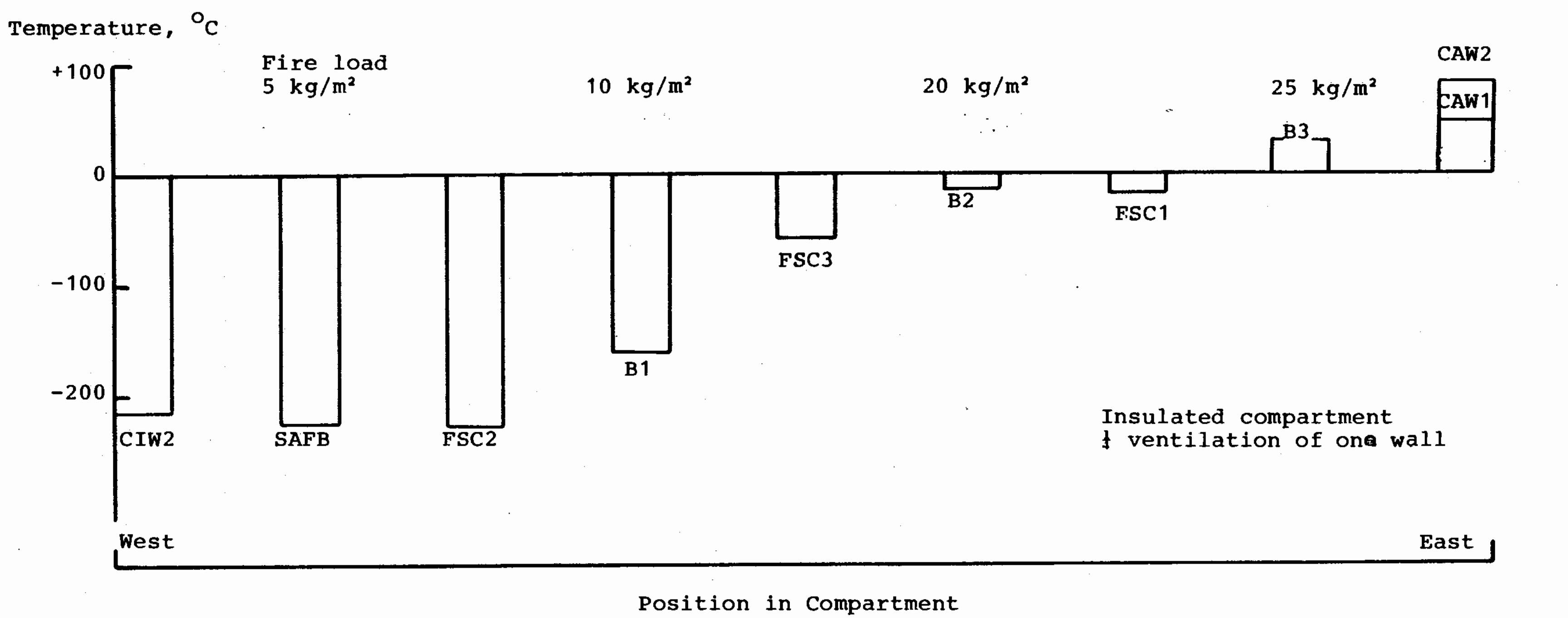
COLUMNS AGAINST WALL TEMPERATURES COMPARED WITH FREE STANDING COLUMNS IN WOOD FIRES

FIG. 19
(R2/4544)



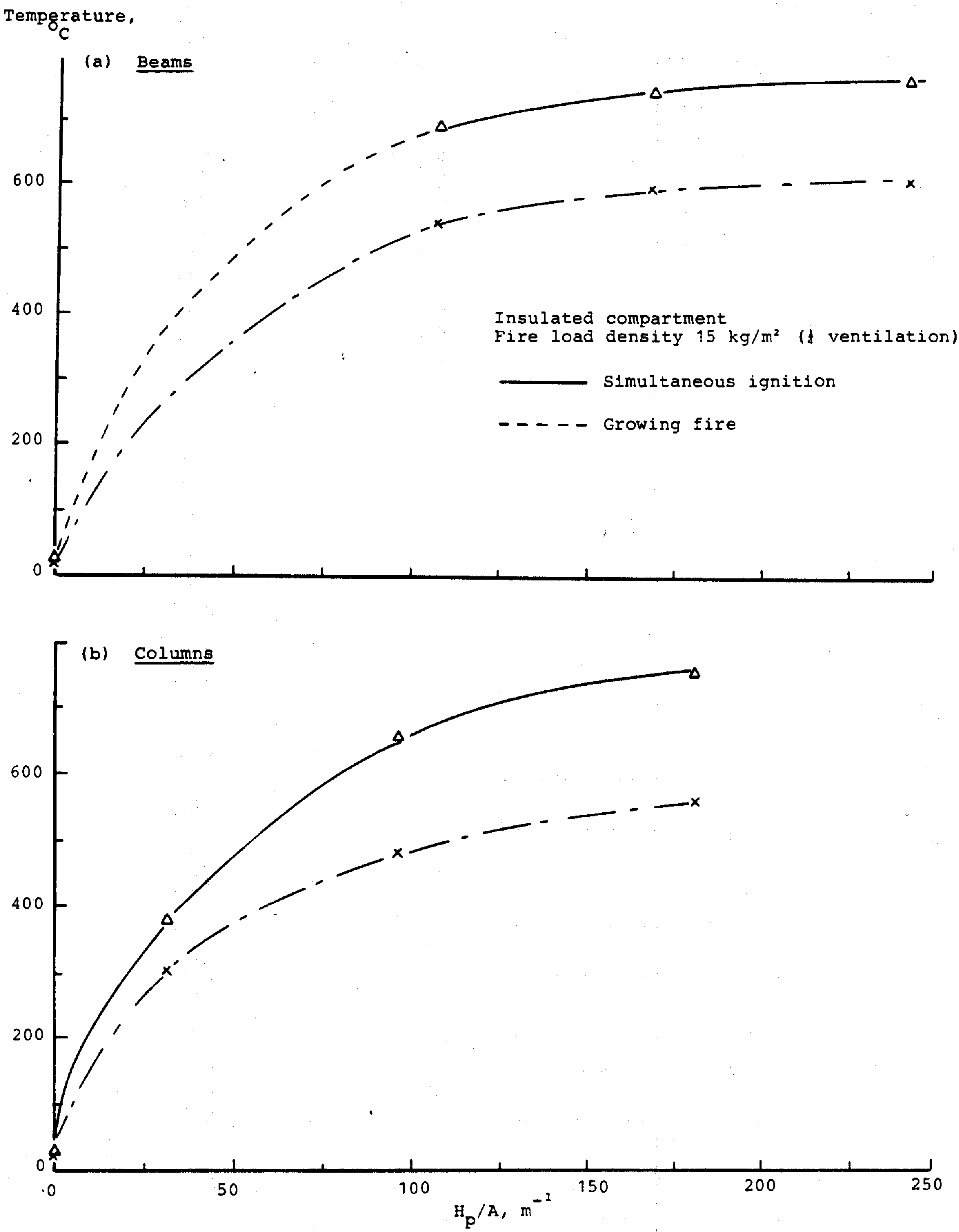
MAXIMUM AVERAGE STEEL TEMPERATURES AS INFLUENCED BY VENTILATION FROM DIFFERENT SIDES OF THE COMPARTMENT

FIG. 20
(R2/4545)



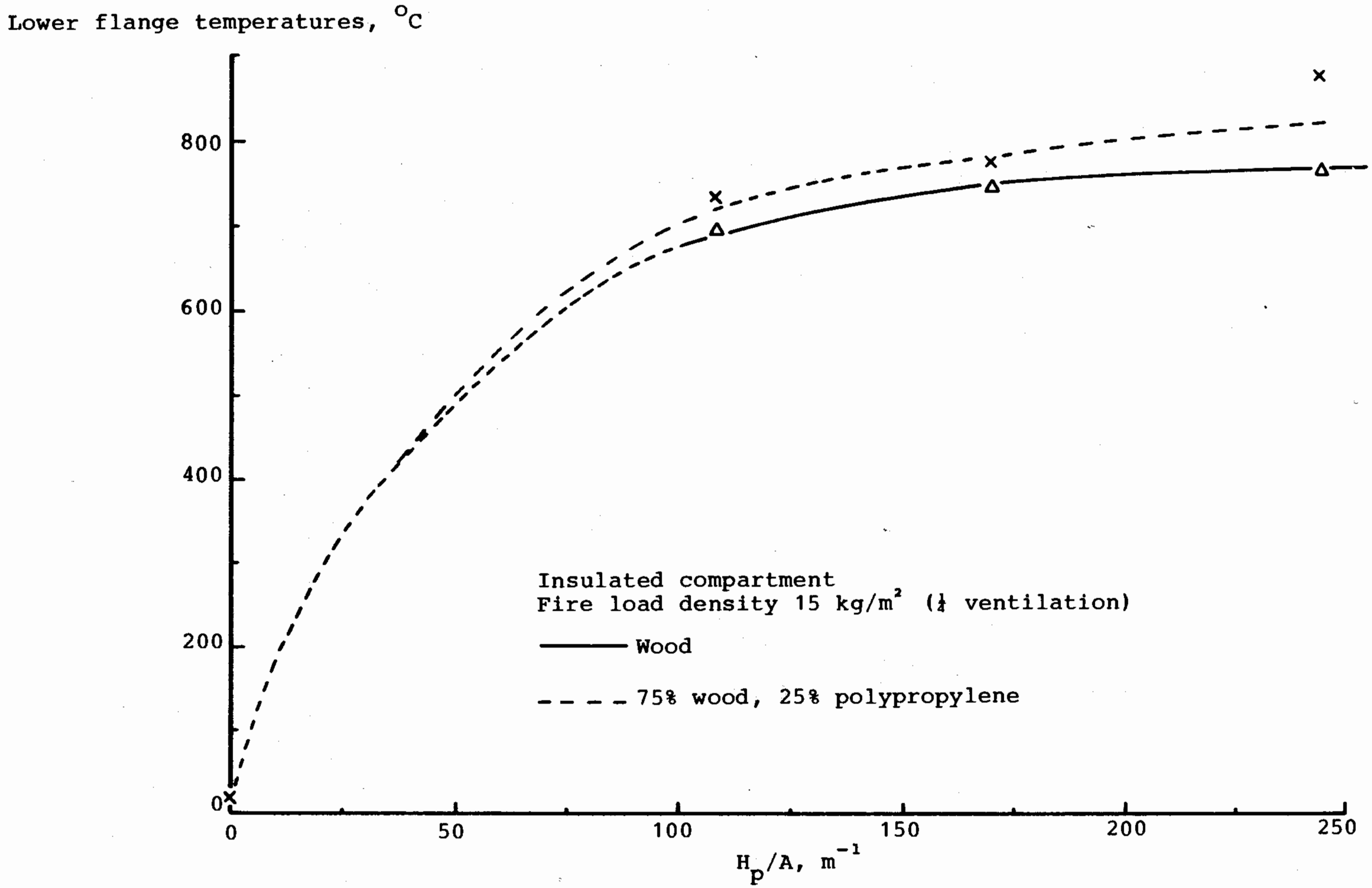
THE DIFFERENCE BETWEEN MAXIMUM AVERAGE TEMPERATURES OF STEELWORK ACROSS THE COMPARTMENT USING AN UNEVEN FIRE LOAD COMPARED WITH THAT OF A UNIFORM FIRE LOAD OF 15 kg/m^2

FIG. 21
(R2/261)



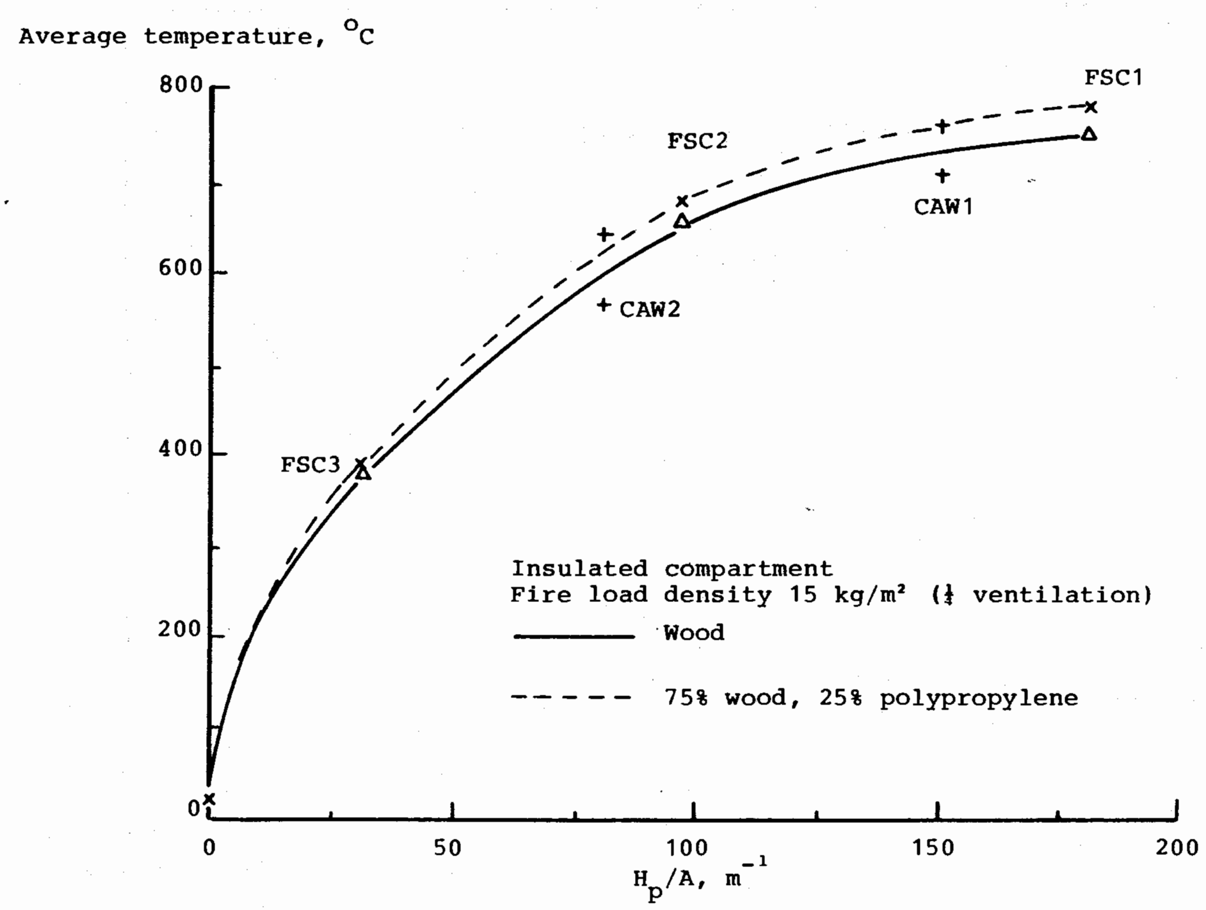
MAXIMUM AVERAGE STEEL TEMPERATURES OBTAINED IN A GROWING FIRE COMPARED WITH SIMULTANEOUS IGNITION

FIG. 22
(R2/4546)



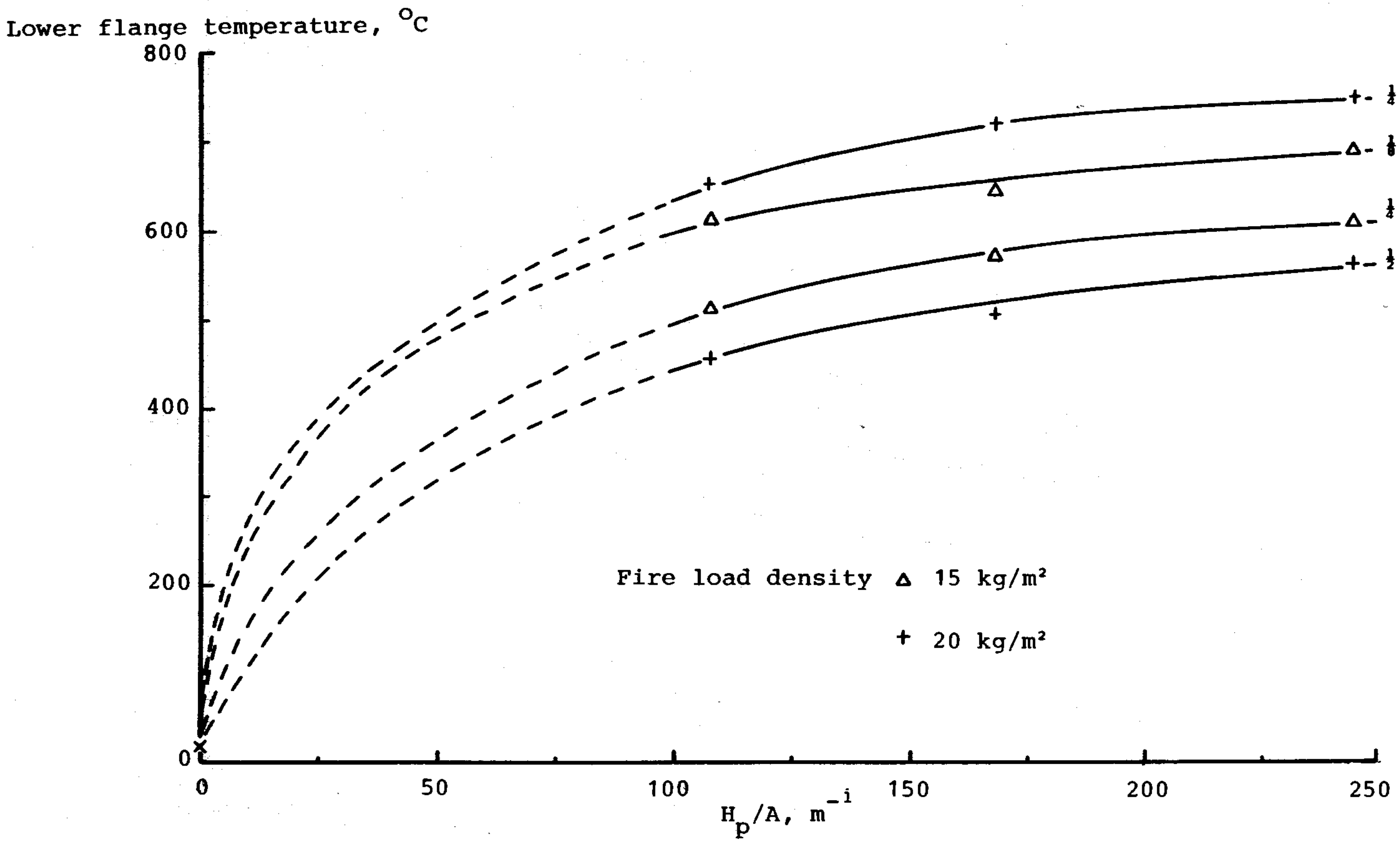
STEEL BEAM TEMPERATURES MEASURED IN WOOD AND WOOD/PLASTIC FIRES

FIG. 23
(R2/4546A)



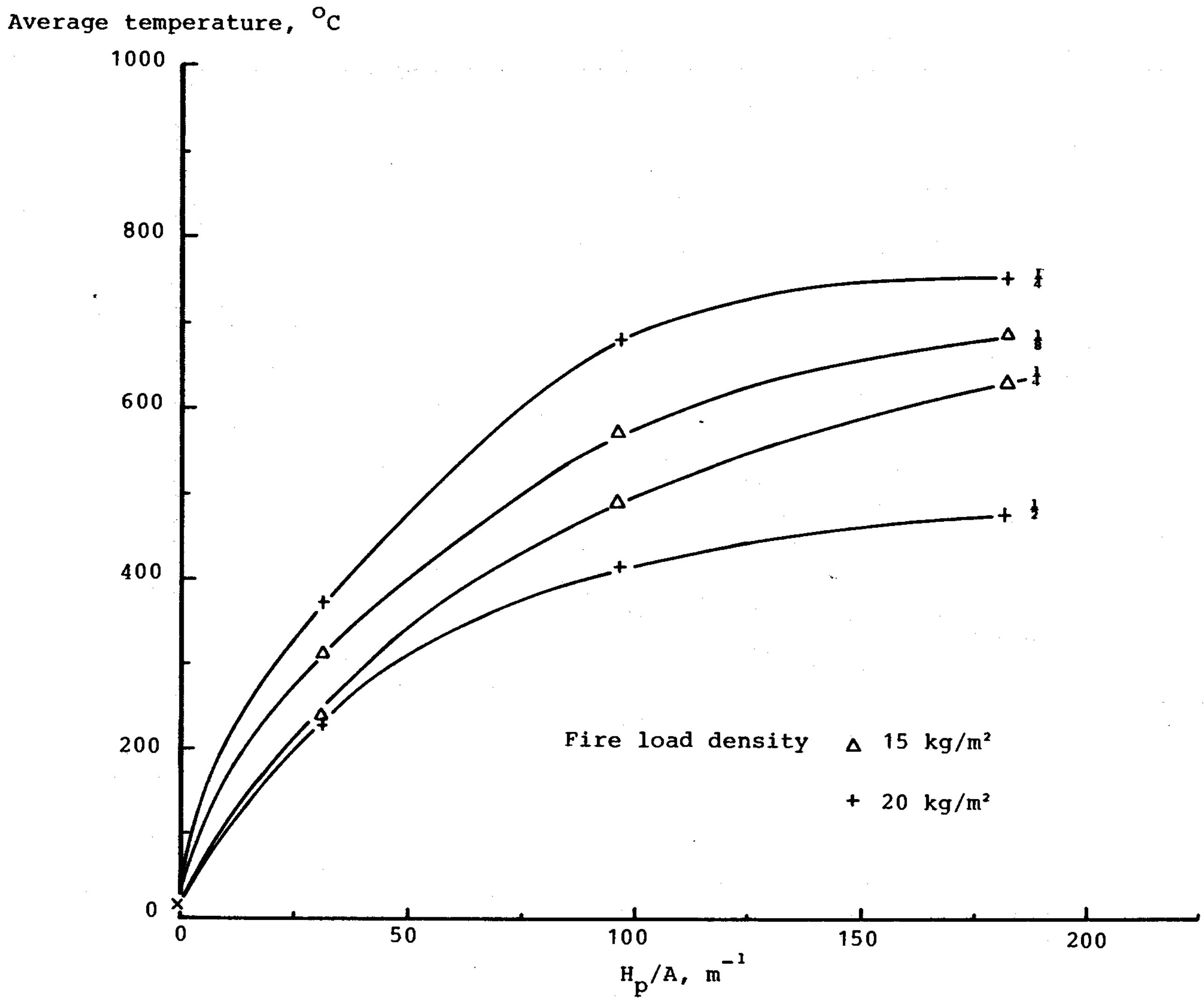
STEEL COLUMN TEMPERATURES MEASURED IN WOOD AND WOOD/PLASTIC FIRES

FIG. 24
(R2/4547)



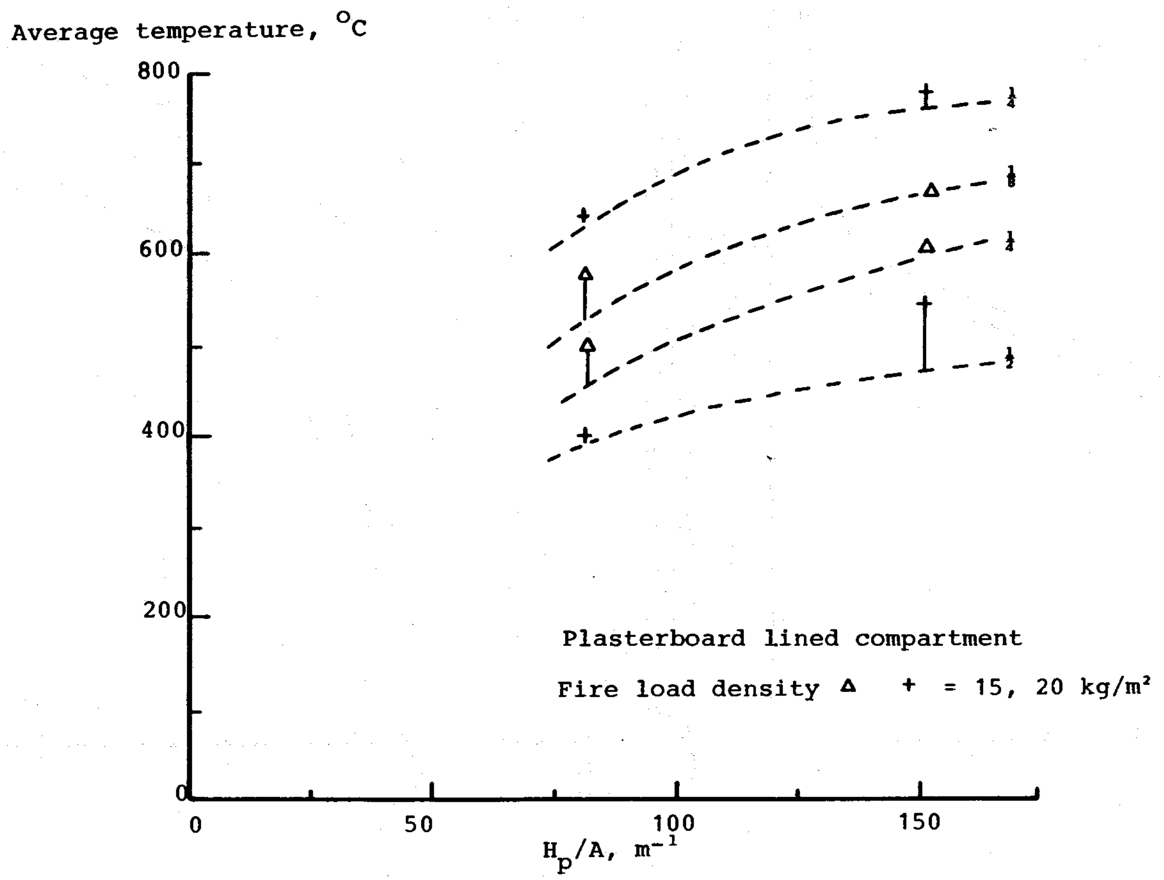
STEEL BEAM TEMPERATURES MEASURED IN WOOD FIRES AND A PLASTERBOARD COMPARTMENT LINING

FIG. 25
(R2/4547A)



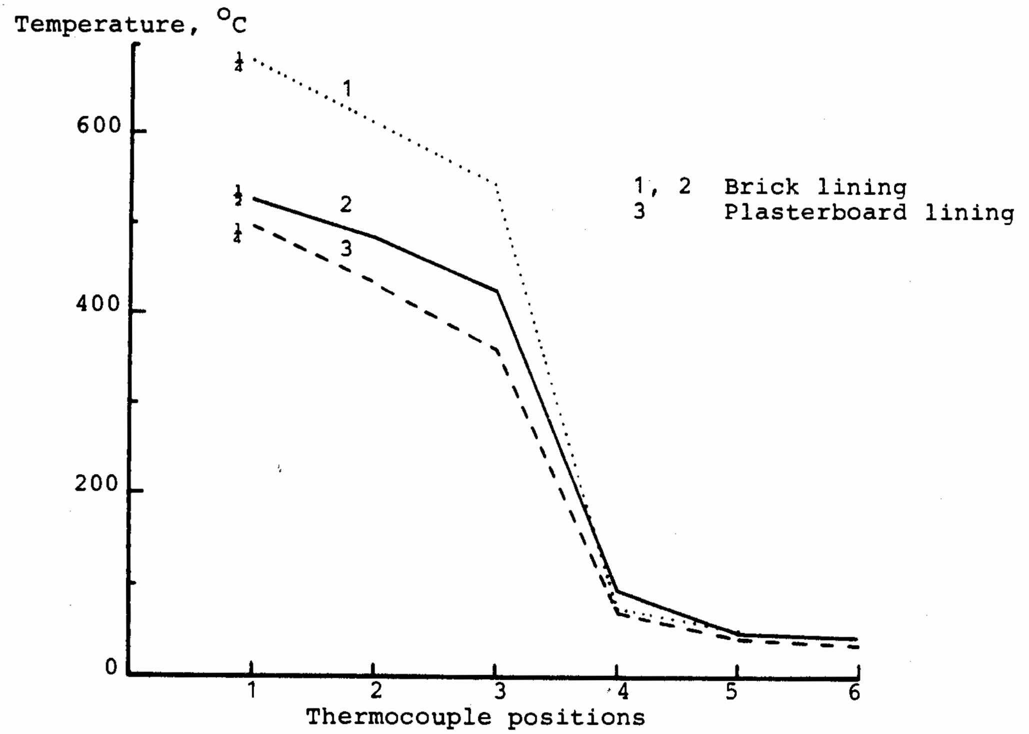
STEEL COLUMN TEMPERATURES MEASURED IN WOOD FIRES AND A PLASTERBOARD COMPARTMENT LINING

FIG. 26
(R2/4548)



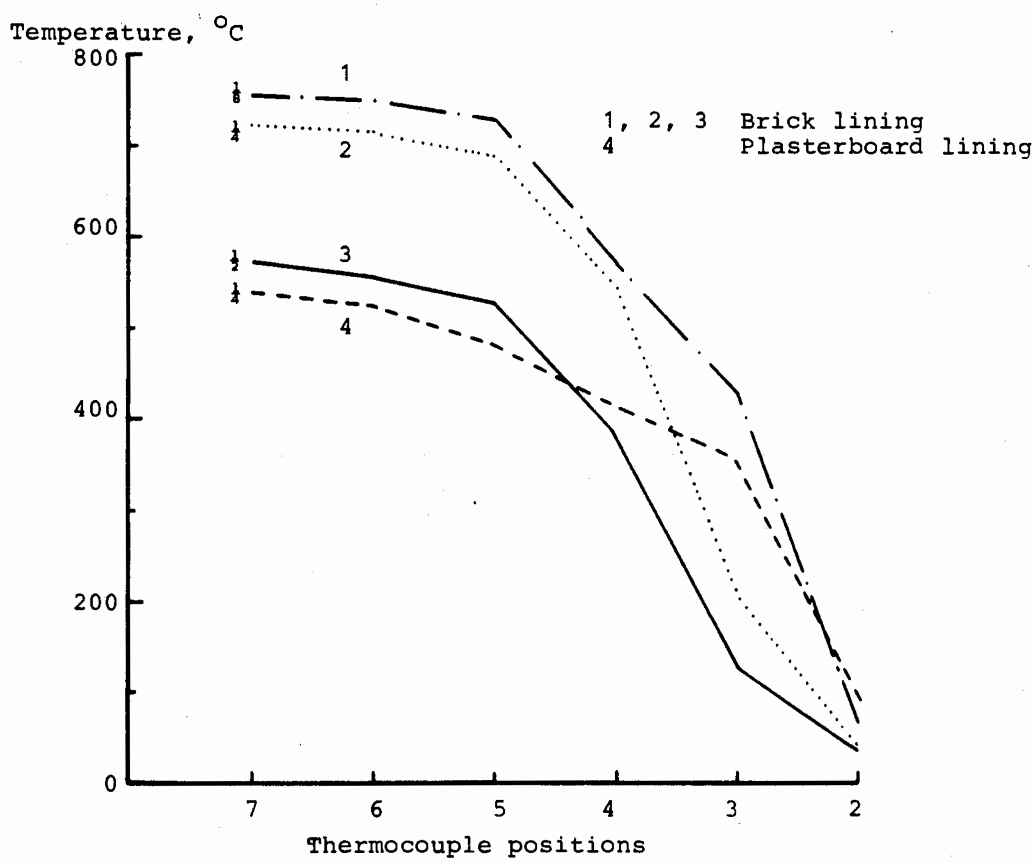
COLUMNS AGAINST WALL TEMPERATURES COMPARED WITH FREE STANDING COLUMNS IN WOOD FIRES

FIG. 27
(R2/4549)



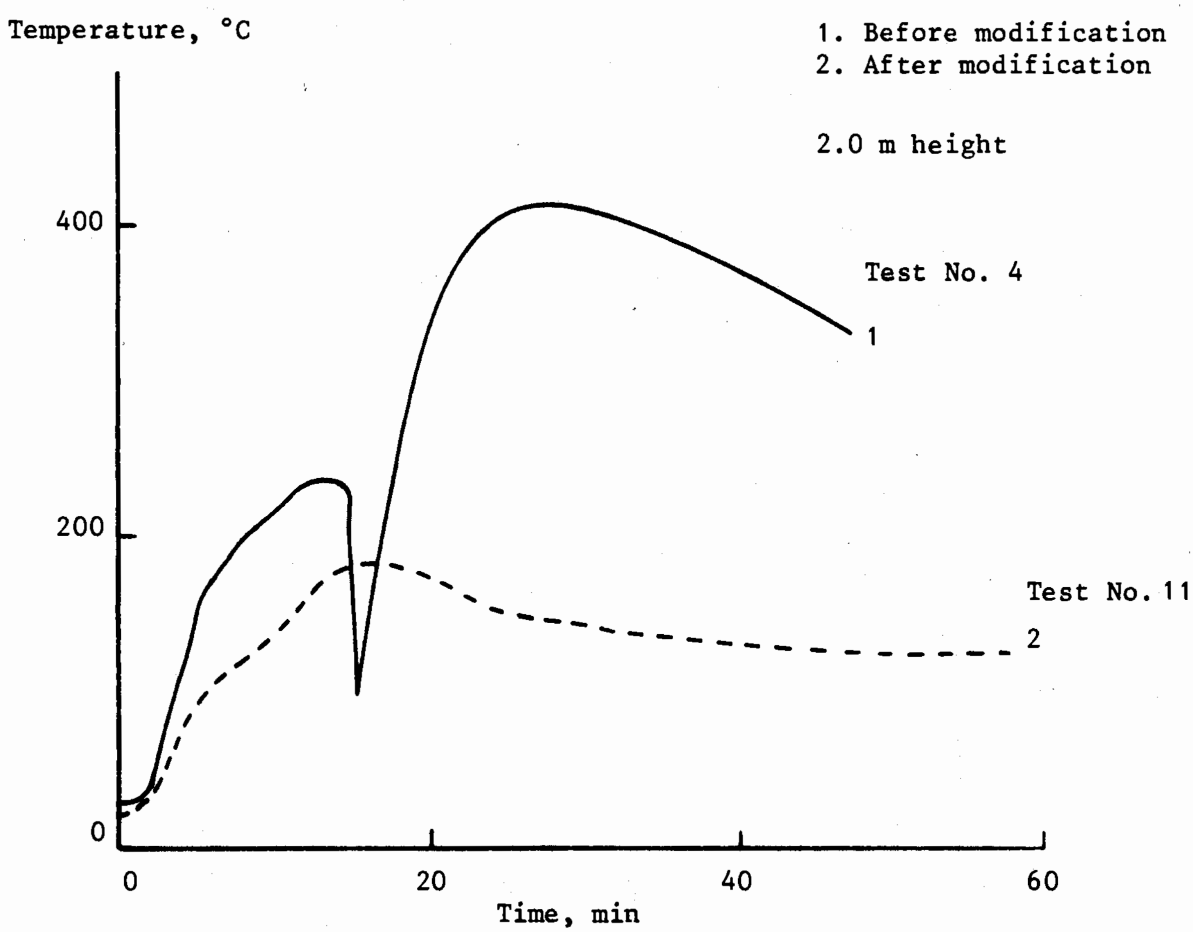
TEMPERATURE PROFILES ACROSS CIW1 AT THE LOWER LEVEL FOR A WOODEN FIRE LOAD DENSITY OF 15 kg/m²

FIG. 28 (R2/4550)



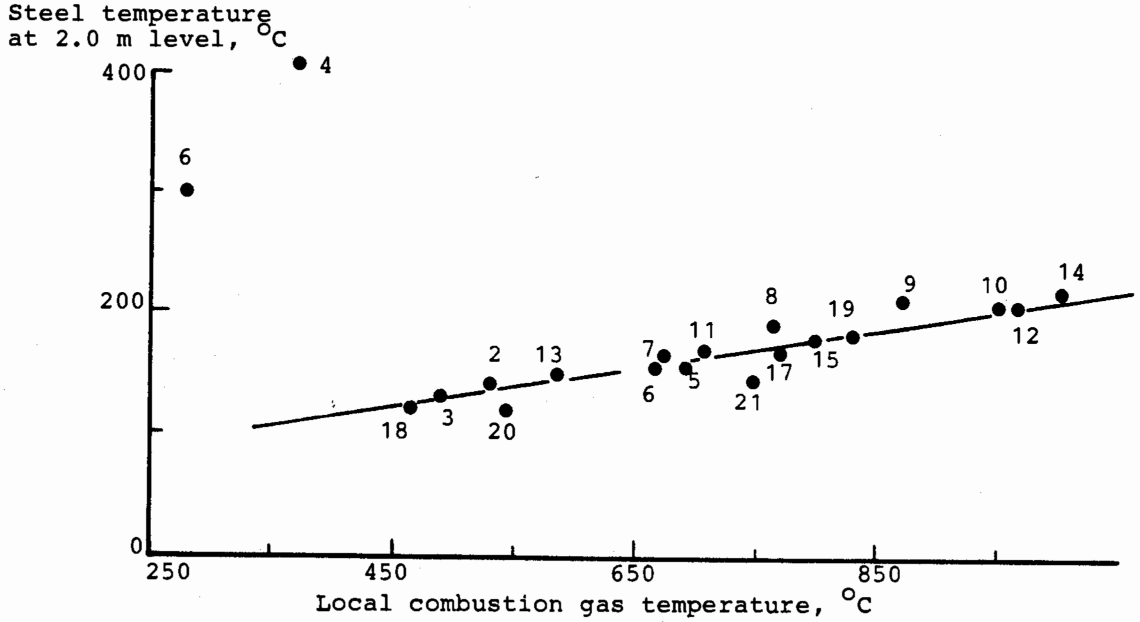
TEMPERATURE PROFILES ACROSS SAFB AT BACK POSITION FOR A WOODEN FIRE LOAD DENSITY OF 15 kg/m²

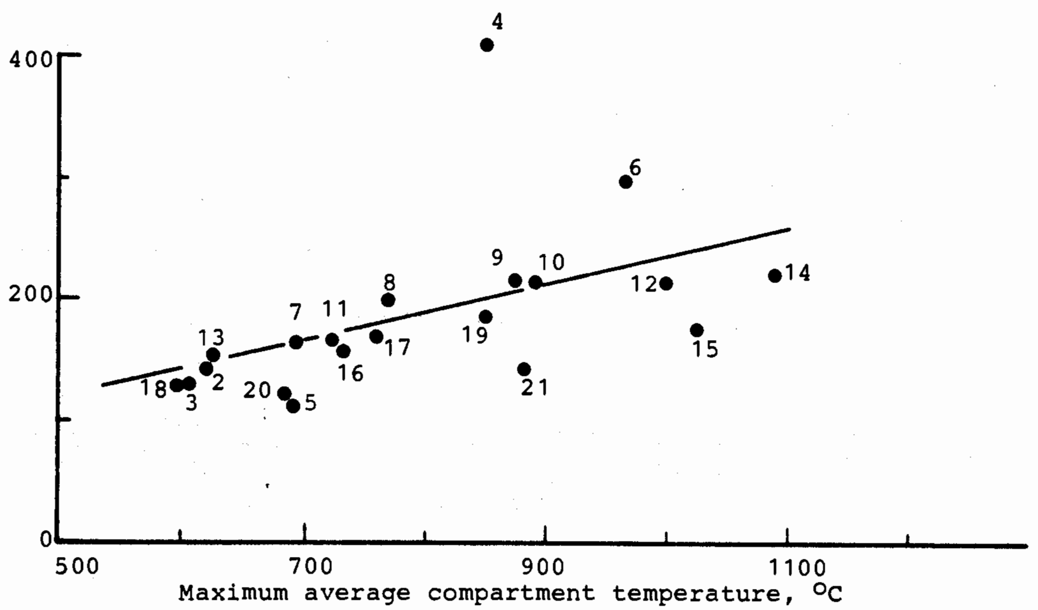
FIG. 29 (R2/4550)



<u>MAXIMUM AVERAGE STEEL TEMPERATURES IN THE WATER FILLED COLUMN FOR A FIRE LOAD DENSITY OF 15 kg/m² AND THE ¼ VENTILATION OF ONE WALL</u>

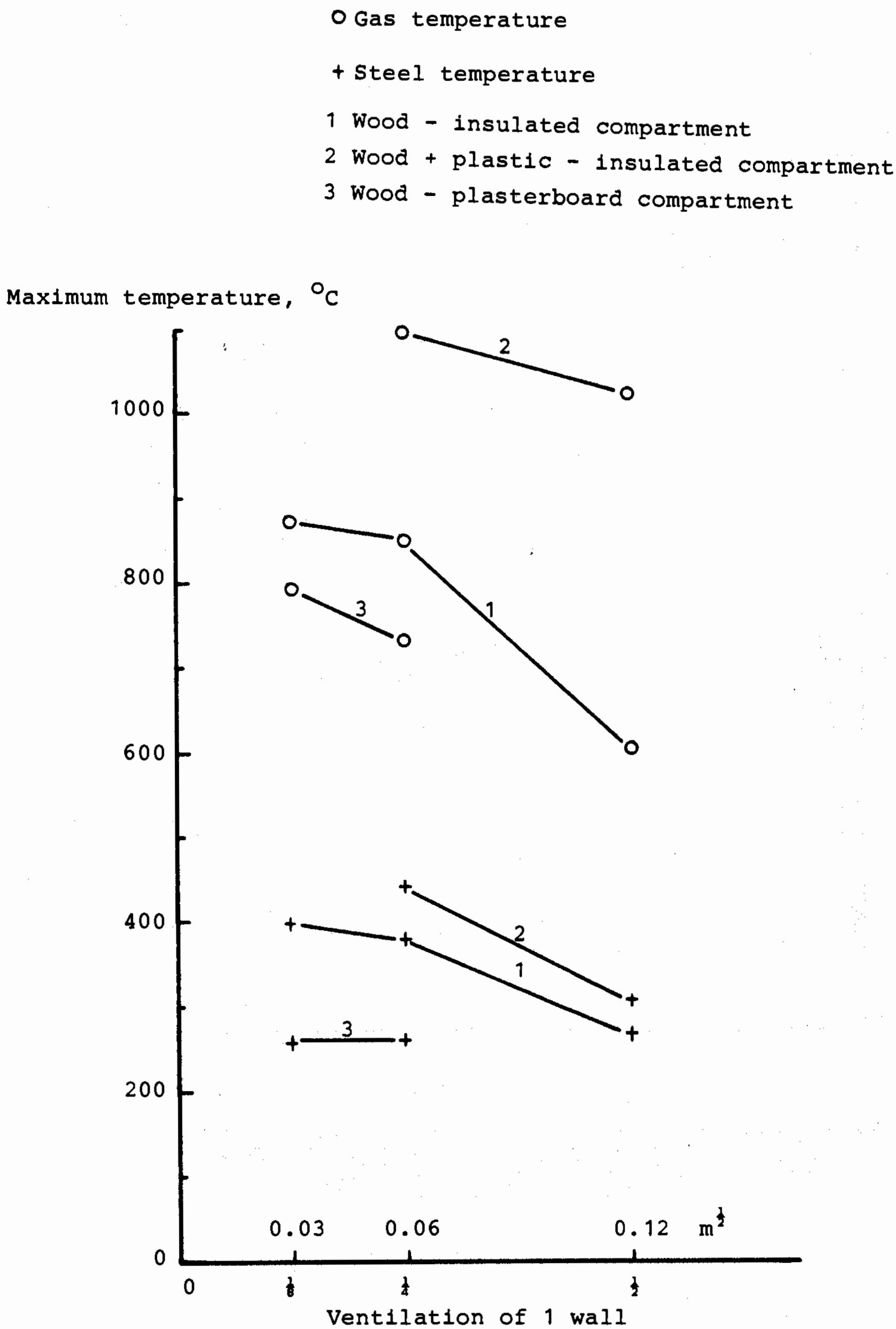
FIG. 30
(R2/1466)





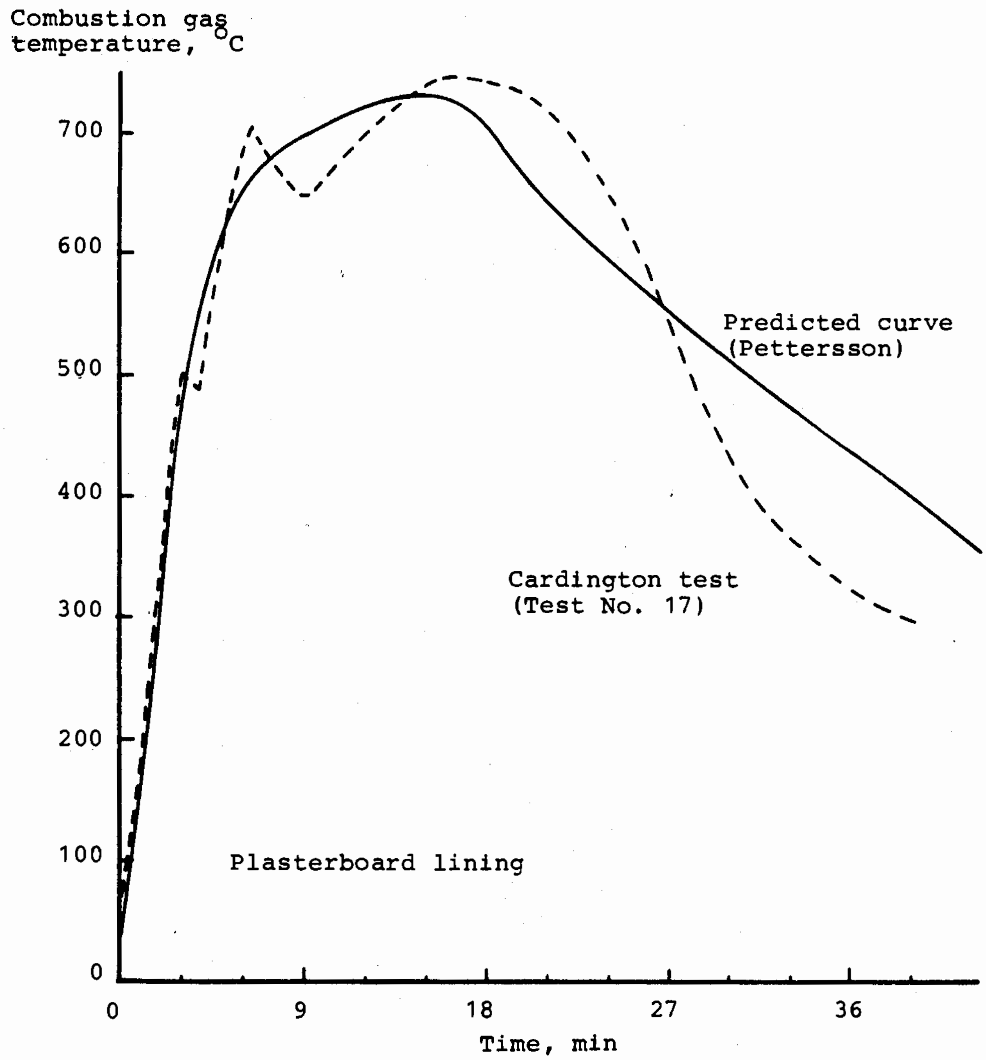
MAXIMUM AVERAGE STEEL TEMPERATURES IN WATER FILLED COLUMN

FIG. 31
(R2/4551)



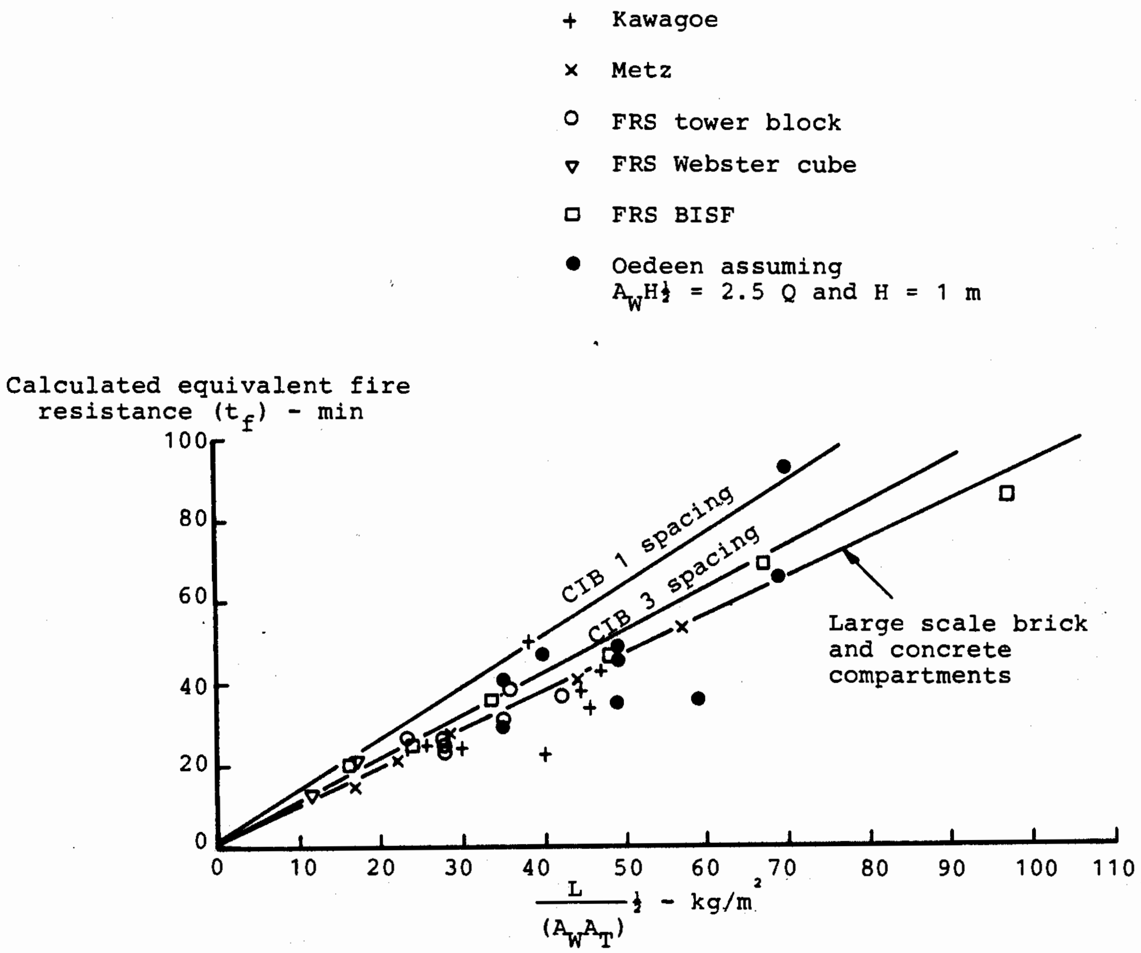
MAXIMUM TEMPERATURES IN EXTERNAL COLUMN FOR FIRE LOAD OF 15 kg/m² AND DIFFERENT VENTILATION CONDITIONS

FIG. 32
(R2/4552)



COMBUSTION GAS TEMPERATURES OBSERVED FOR A FIRE LOAD DENSITY OF 15 kg/m² AND ⅛ VENTILATION COMPARED TO PREDICTED GAS TEMPERATURES

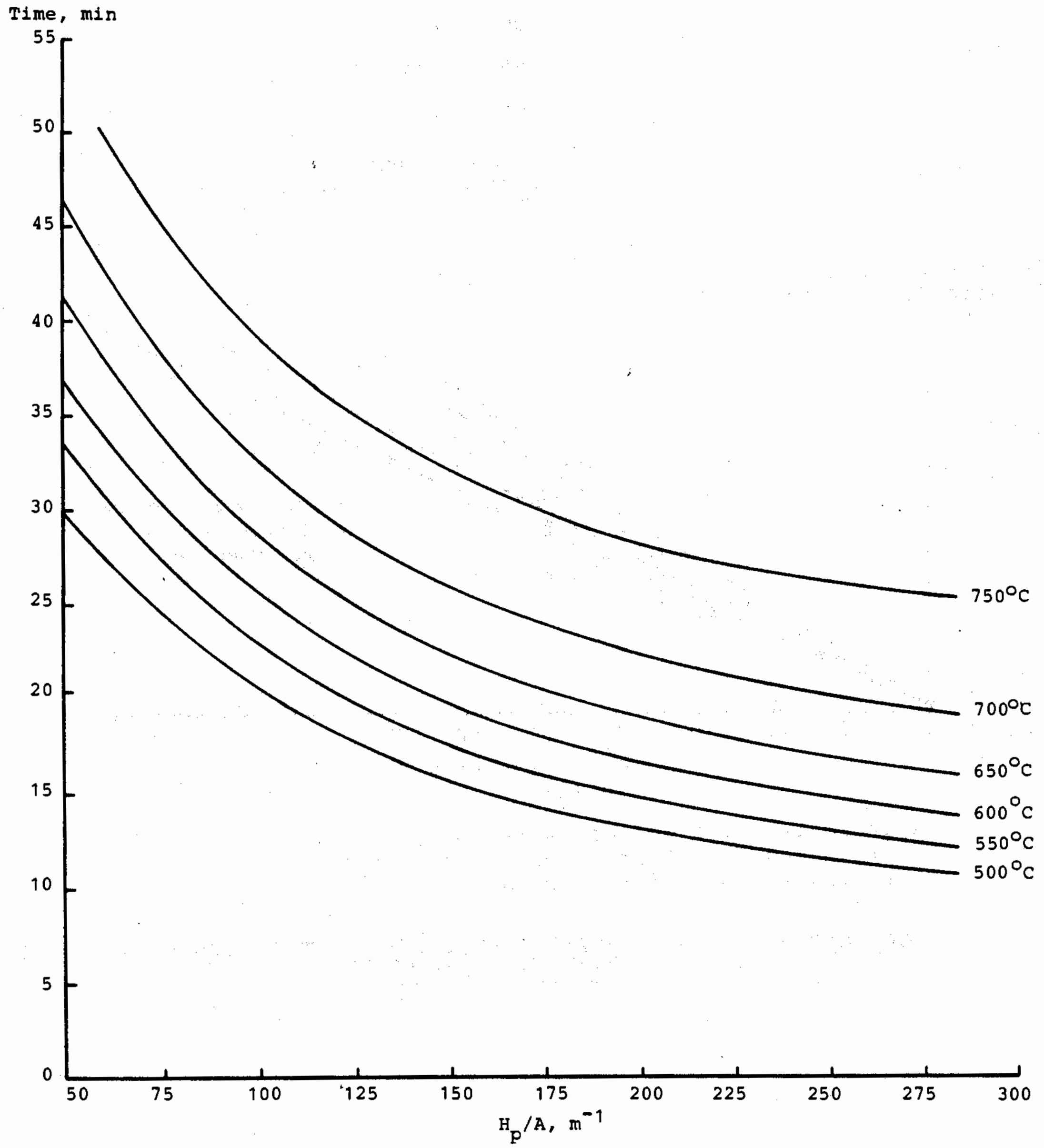
FIG. 33
(R2/4553)



Large scale brick and concrete compartments
t_f estimated from temperature time curves
A_T includes floors for this data

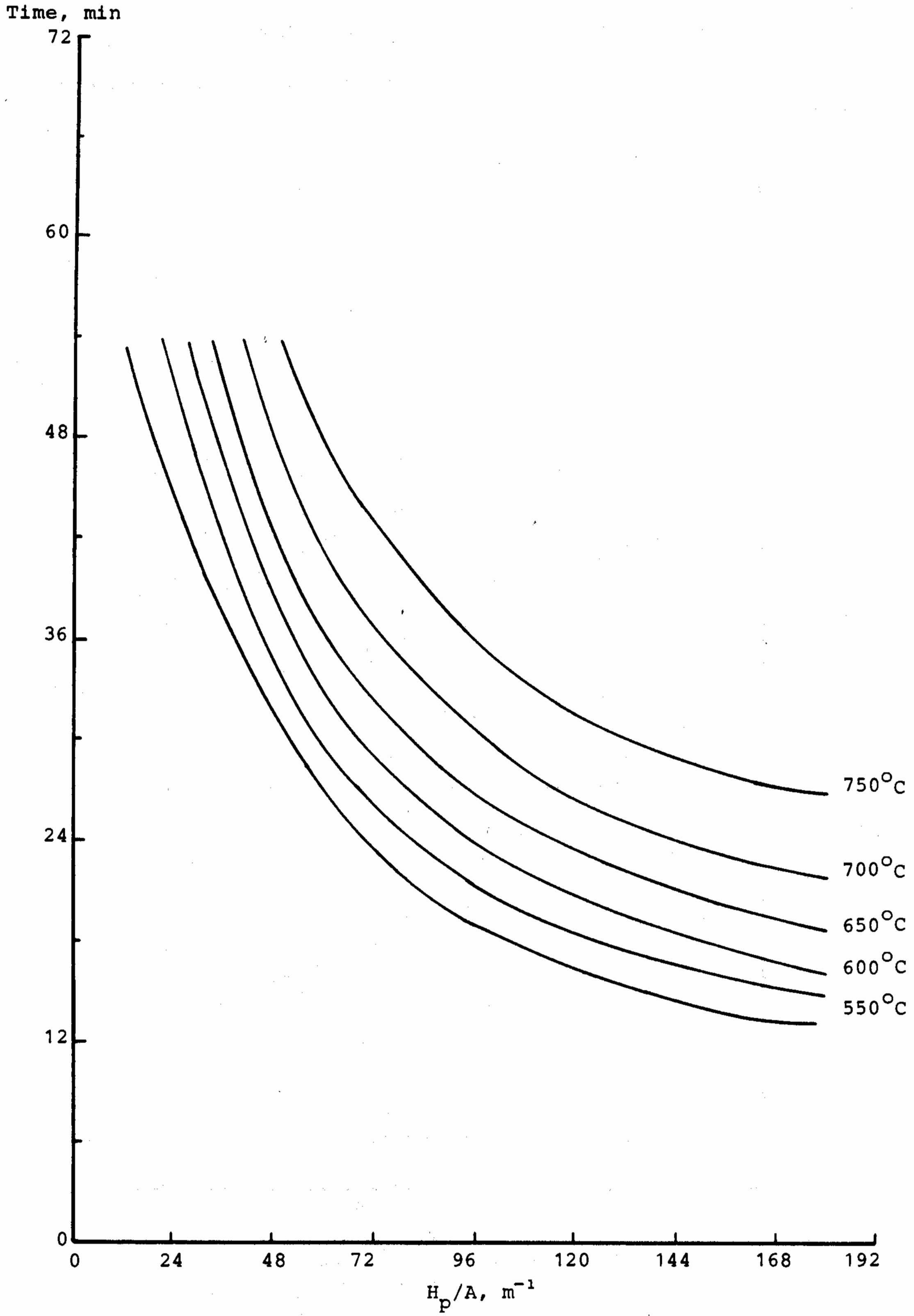
CORRELATION OF LARGE SCALE FIRE TESTS BASED ON PROTECTED STEEL MEMBERS [33]

FIG. 34
(R2/4554)



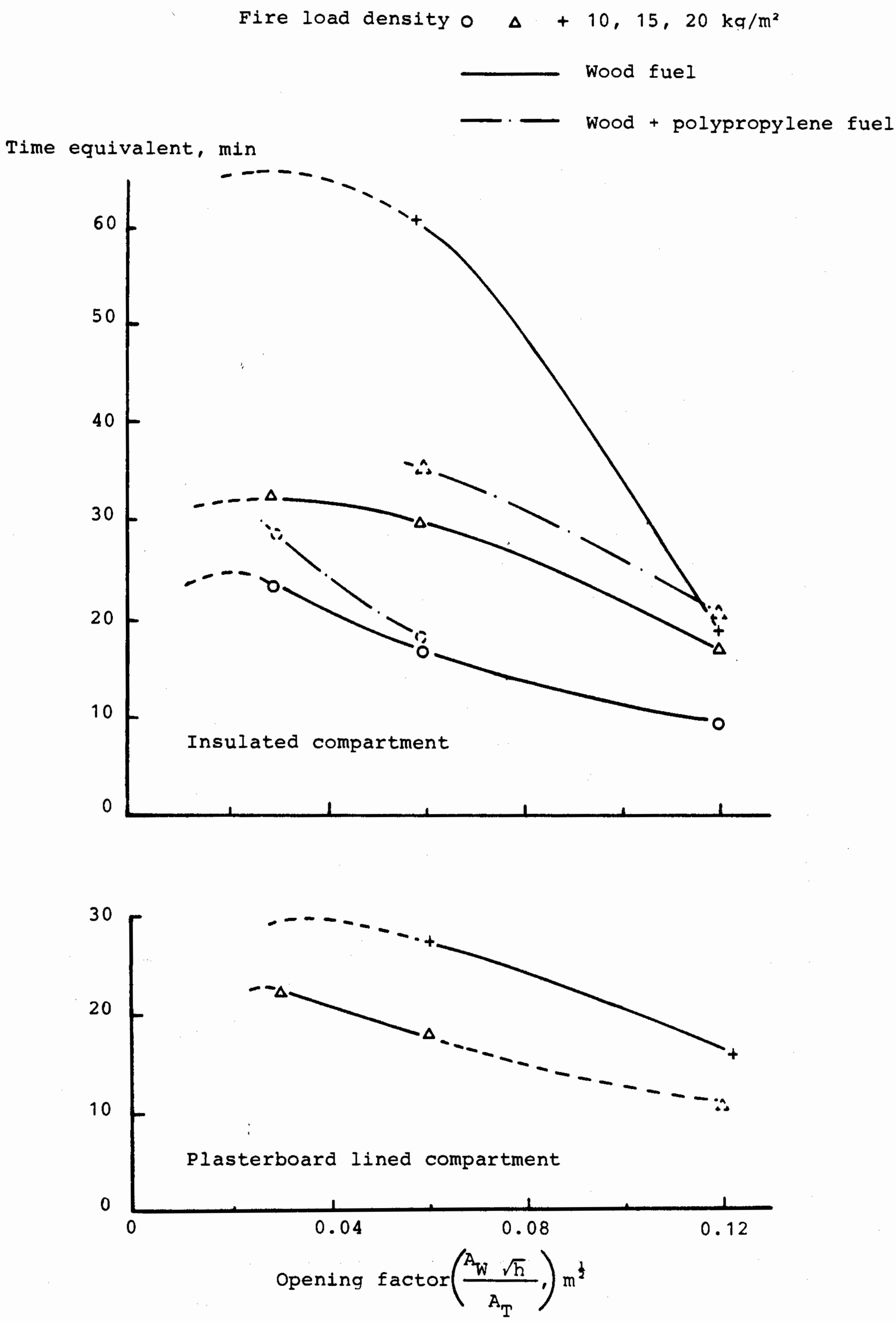
TIMES TO REACH LIMITING LOWER FLANGE TEMPERATURES IN UNPROTECTED STEEL BEAMS IN THE BS476:PT 8 FIRE TEST

FIG. 35
(R2/4555)



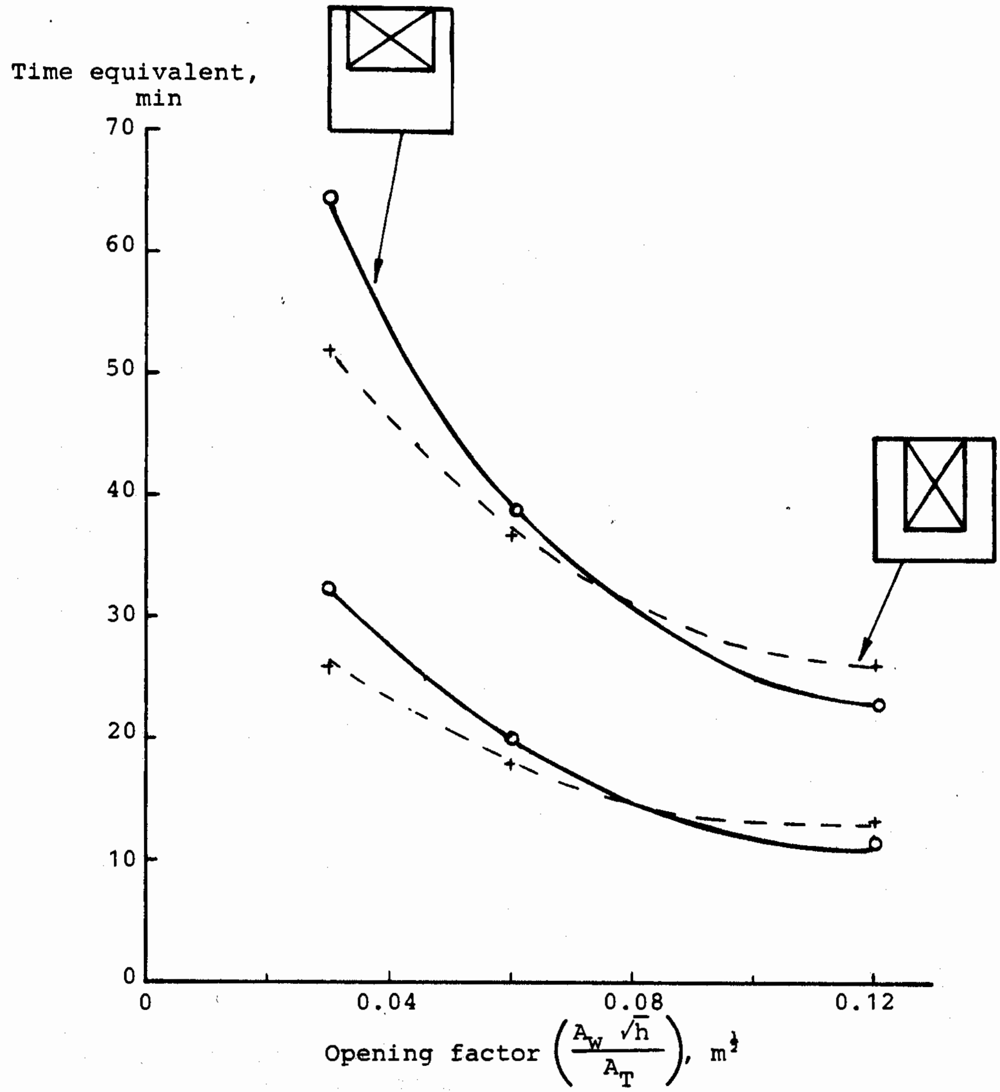
TIMES TO REACH LIMITING TEMPERATURES FOR FREE STANDING UNPROTECTED STEEL COLUMNS IN THE BS476:PT 8 FIRE TEST

FIG. 36
(R2/4556)

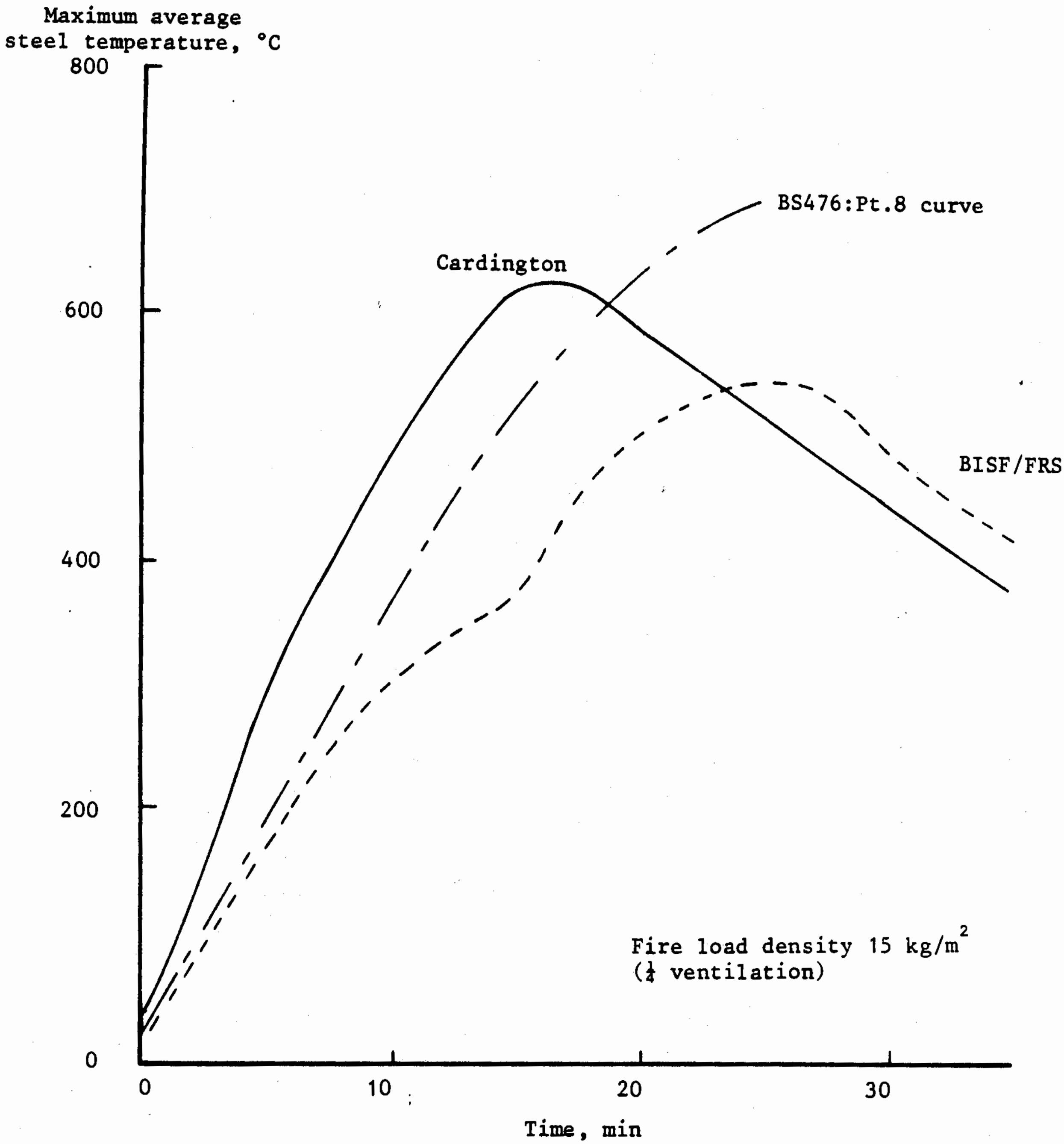


ESTIMATED AND MEASURED TIME EQUIVALENT VALUES FOR COMPARTMENT (SHAPE OF CURVES FOLLOWING DATA DERIVED BY PETTERSSON)

FIG.37 (R2/4557)



THE EFFECT OF VENTILATION ORIENTATION ON TIME EQUIVALENT FIG. 38 (R2/4558)



COMPARISON BETWEEN CARDINGTON AND BISF/FRS FIRE TESTS ON THE TEMPERATURES MEASURED IN UNPROTECTED STEEL COLUMN FSC1 ($^{H}P/A$ = 180 m^{-1})

FIG. 39
(R2/1473)

APPENDIX CARDINGTON COMBUSTION - FIRE LOAD DENSITY 20 kg/m^2, 1/4 VENTILATION

$$\text{Max. } T_f = \frac{6000\ (1 - e^{-0.1\eta})}{\sqrt{\eta}},\ ^{o}C \qquad \text{....(1)}$$

where $\eta = \dfrac{A_t - A_v}{A_v \sqrt{h}}$

$A_t = 213.84\ m^2$

$A_v = 8.33\ m^2$

$h = 2.3\ m,\ \sqrt{h} = 1.52\ m^{\frac{1}{2}}$

$$\therefore \quad \eta = \frac{213.84 - 8.33}{8.33 \times 1.52} = 16.23\ m^{-\frac{1}{2}}$$

$$\therefore \text{max. } T_f = \frac{6000\ (1 - e^{-0.1 \times 16.23})}{\sqrt{16.23}} = 1195^{o}C$$

As the temperature exceeded those measured in the Cardington tests Equation 1 can be modified to take account of low fire loads

$$T_f = \text{max. } T_f\ (1 - e^{-0.05\psi}) \qquad \text{....(2)}$$

where $\psi = \dfrac{L}{\sqrt{A_v}\ \{A_t - A_v\}}$

For particular fire condition, L = 1016 kg

$$\psi = \frac{1016}{(8.33 \times 205.51)^{\frac{1}{2}}} = 24.56\ kg/m^2$$

$$\therefore T_f = 1195\ (1 - e^{-0.05 \times 24.56}) = 845^{o}C$$

Based on ambient temperature of 20^{o}C the predicted maximum average gas temperature = 865^{o}C

Fire Loads Used in Cardington Tests

Fire Load kg	Fire Load Mcal	Fire Load MJ	Fire Load Density kg/m^2	Type of Compartment
508	2235	9342	10	Insulated
762	3353	14015	15	Insulated
1016	4470	18685	20	Insulated
741	3260	13627	15	Plasterboard
988	4347	18170	20	Plasterboard
406	1789	7478	15	Small/Plasterboard

Pettersson Boundary Factors[28]

Type	Enclosing Surfaces	Factor, K_f					
		Actual Opening Factor, $m^{\frac{1}{2}}$					
		0.02	0.04	0.06	0.08	0.10	0.12
B	Concrete	0.85	0.85	0.85	0.85	0.85	0.85
C	Lightweight concrete	3.0	3.0	3.0	3.0	3.0	2.5
G	20% concrete and 80% Gypsum plasterboard	1.50	1.45	1.35	1.25	1.15	1.05

Insulated compartment 76% Type C + 24% Type B
Plasterboard compartment 49% Type B + 51% Type G
Reduced compartment 36% Type B + 64% Type G

APPENDIX

Additional Information not given in the main text of Report RSC/7281/10/86

Reprinted from:
Compendium of Experimental Natural Fire Test Data - Cardington Tests
ECSC Agreement No. 7210.SA/112
2nd Technical Report for the Period 1st January to 30th June 1987

1. INTRODUCTION

During a three year period from 1983-1985, a series of twenty-one natural fire tests were carried out in a purpose built compartment constructed within the No. 2 Hangar at RAE Cardington in Bedfordshire. This work was sponsored jointly by the British Steel Corporation and the UK Department of the Environment and was carried out by research staff from the BSC Swinden Laboratories in Rotherham. The principal aspects of the test data generated are being reported as part of a European survey on experimental natural fires.

The aim of the test programme carried out at Cardington was to obtain heating data for several sizes of unprotected universal steel beams and columns as well as combustion gas atmosphere temperatures, for a variety of fire conditions.

The fire tests were designed to provide information on the following variables:-

(1) Fire load density

(2) Fuel type

(3) Ventilation

(4) Compartment lining materials

(5) Compartment size

(6) Fire development

(7) Distribution of fire load

2. THE FIRE COMPARTMENT

Reference is made to Fig. 1 showing the plan and front elevation of the compartment. Details of the design are as follows:-

2.1 Dimensions (Permanent Structure)

External: 9.706 m x 6.850 m x 4.190 m high
Internal: 8.66 m x 5.87 m x 3.90 m high

(NB. During the test programme, the thermal characteristics of the internal surfaces were modified which slightly altered the internal dimensions given above.)

In two tests a wall was also constructed approximately across the centre of the compartment to provide information on the influence of compartment geometry and size on the rate of rise in steel and combustion atmosphere temperatures.

2.2 Ventilation

Two windows in each of the long walls measuring 3.67 m wide x 2.30 m high provided a maximum ventilation area of 16.88 m² on each side of the compartment. When only one side was fully open, the ventilation available was nominally equivalent to half the surface area of one wall, i.e.

$$\frac{A_v\sqrt{h}}{A_t} \simeq 0.12 \text{ m}^{\frac{1}{2}}$$

By placing vertical shutters symmetrically in the openings, the available ventilation on each wall could be reduced to 8.33 m^2 and 4.14 m^2, i.e. nominally equivalent to ¼ and ⅛ ventilation $\left(\frac{A_v\sqrt{h}}{A_t} \approx 0.06\ m^{\frac{1}{2}} \text{ and } 0.03\ m^{\frac{1}{2}}\right)$ respectively.

With the exception of one test, ventilation was provided only through the front wall.

2.3 Materials

Walls

The walls comprised a double leaf of brickwork.

Spall resistant MPK 125 insulating firebricks having a thickness and bulk density of 114 mm and 670 kg/m^3 respectively, were used for the inner leaf. Details of the specific heat and thermal conductivity at various temperatures for this type of material are as follows:-

Temperature (°C)	500	1000	1500
Specific Heat (kcal/kg per °C)	0.25	0.26	0.27

Temperature (°C)	200	400	600	800	1000
Thermal Conductivity (kcal/m h °C)	0.16	0.17	0.19	0.21	0.22

The outer leaf was constructed using common building bricks along the sidewalls to create a 75 mm cavity with the inner leaf, and with fireclay bricks for the front and back walls to form a solid construction.

In several tests, the thermal characteristics of the internal walls were modified. This was achieved by fixing 25 mm thick wooden battens to the firebricks to which were screwed 2 x 12.7 mm layers of Gyproc Fireline Board. The internal plan area of the compartment was therefore reduced to 8.56 m x 5.77 m. As the thermal properties of Gyproc are permanently affected by fire, this lining was renewed for each test.

Shutters

As far as possible, the materials used in the removable shutters had similar thermal characteristics to the wall linings.

For the unlined compartment in which the internal face of the insulating firebrick was directly exposed to fire, the shutters were constructed using 50 mm thick standard ceramic fibre supported by expanded metal sheet backing. The ceramic fibre used had a bulk density of 96 kg/m^3, a specific heat of 0.25 kcal/kg per °C and the following approximate values of thermal conductivity:-

Temperature (°C)	200	400	600	800	1000
Thermal Conductivity (kcal/m h °C)	0.04	0.07	0.11	0.15	0.19

When the compartment was lined with Gyproc Fireline Board, this same material was used for the shutters.

Roof

The roof was made up from solid reinforced dense concrete floor units 200 mm thick. To create a highly insulating compartment, ceramic fibre tiles 38 mm thick were cemented to the underside of the units thereby reducing the internal height dimension to 3.86 m.

The tiles used had a density of 96 kg/m^3, a specific heat of approximately 0.25 kcal/kg per °C and values of thermal conductivity which varied with temperature as follows:-

Temperature (°C)	200	400	600	800	1000
Thermal Conductivity (kcal/m h °C)	0.05	0.10	0.16	0.22	0.29

Floor

The compartment was constructed on a 75 mm thick reinforced concrete base on which a 15 mm thick refractory cement screed was also laid to primarily prevent major damage to the foundations.

2.4 Steelwork

The following sizes of unprotected steel sections were incorporated in the structure:-

Columns (4 sides exposed - Fig. 2)

Size	H_p/A	Position
203 x 203 mm x 52 kg/m	180 m^{-1}	FSC1
356 x 368 mm x 177 kg/m	96 m^{-1}	FSC2
356 x 406 mm x 634 kg/m	31 m^{-1}	FSC3

Beams (3 sides exposed - Fig. 3)

Size	H_p/A	Position
533 x 210 mm x 122 kg/m	108 m^{-1}	Beam 1
254 x 146 mm x 43 kg/m	169 m^{-1}	Beam 2
203 x 133 mm x 25 kg/m	242 m^{-1}	Beam 3
406 x 178 mm x 54 kg/m (shelf angle floor)	85 m^{-1}	SAFB

The shelf angle floor beam was constructed using 12 mm thick angles bolted to the web leaving a gap of 210 mm with the underside of the upper flange for inserting the concrete units.

2.5 Instrumentation

Steel Temperatures

3 mm diameter chromel/alumel insulated sheath thermocouples were set in holes drilled into the steel members as shown in Fig. 4.

For the column sections the thermocouples were embedded in both the flanges and web at two levels, viz. 0.5 m and 2.0 m below the underside of the ceiling, referred to as upper and lower positions.

Likewise the temperatures in the beam sections were recorded from thermocouples embedded in the lower web (¼ height), lower flange/web junction and lower flange, both at mid-span and 1 m from the back wall. These are referred to as middle and back positions.

In the data sheets reference is made to average steel temperatures. For column sections these relate to the mean between the two flanges and web whereas for beam sections, they are the mean between the lower web and flange only.

Combustion Gas Atmosphere Temperatures

Figure 5 shows the distribution of thermocouples placed inside the compartment. These were located at two levels, viz. 0.5 m and 2.0 m below the ceiling and referred to as upper and lower positions. The distribution of thermocouples placed with respect to the various steel members was planned to enable a correlation to be obtained between steel and local atmosphere temperature/s, see Table 1.

2.6 Fuel Type and Distribution

Two types of fuel were used in the fire tests:

Wood - Western Hemlock (Tsuga Heterophylla) supplied in lengths of 1 m x 50 mm square cross section and kiln dried to 10% moisture content. Calorific value = 4.4 Mcal/kg.

Polypropylene - supplied in lengths of 1 m x 25 mm square cross section. Calorific value = 10.5 Mcal/kg.

The fire load was arranged in 1 m square cribs (see Fig. 6) and apart from one test (see No. 9), was evenly distributed throughout the compartment. In each case the sticks were spaced 1:1 and placed with alternate rows at right angles to each other. For fires which involved both wood and polypropylene, the proportion of plastic used, i.e. 25% or 50%, was based upon its calorific contribution to the total fuel. The plastic sticks were always arranged as the upper layers in the cribs.

Strips of fibre board soaked in paraffin were used as ignition sources. These were placed at the base of each crib and apart from one test (see No. 11), were ignited simultaneously.

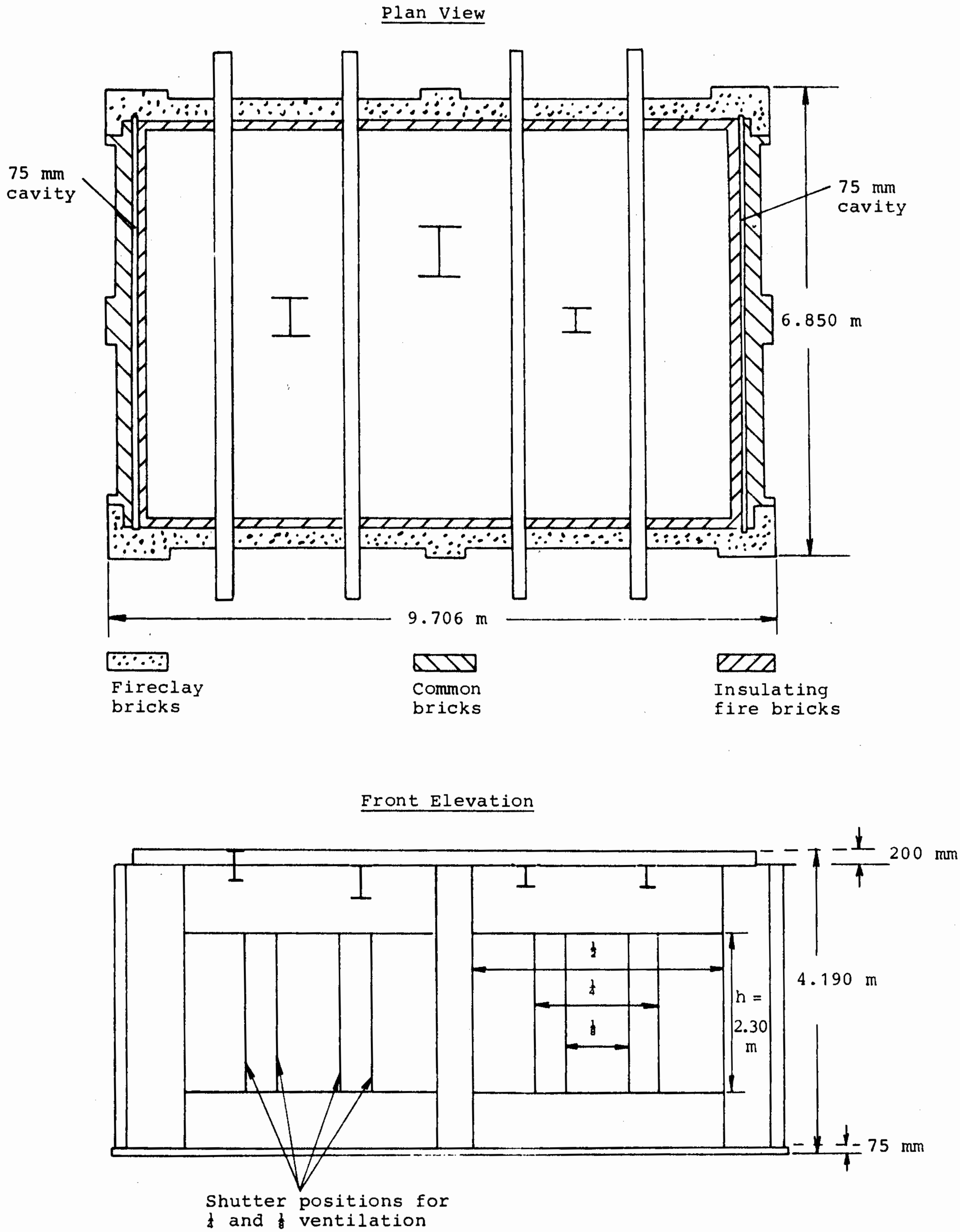
3. TEST DATA

Relevant data for each fire test carried out are provided in the Appendices as a series of tables with details of the particular variables examined.

EJF

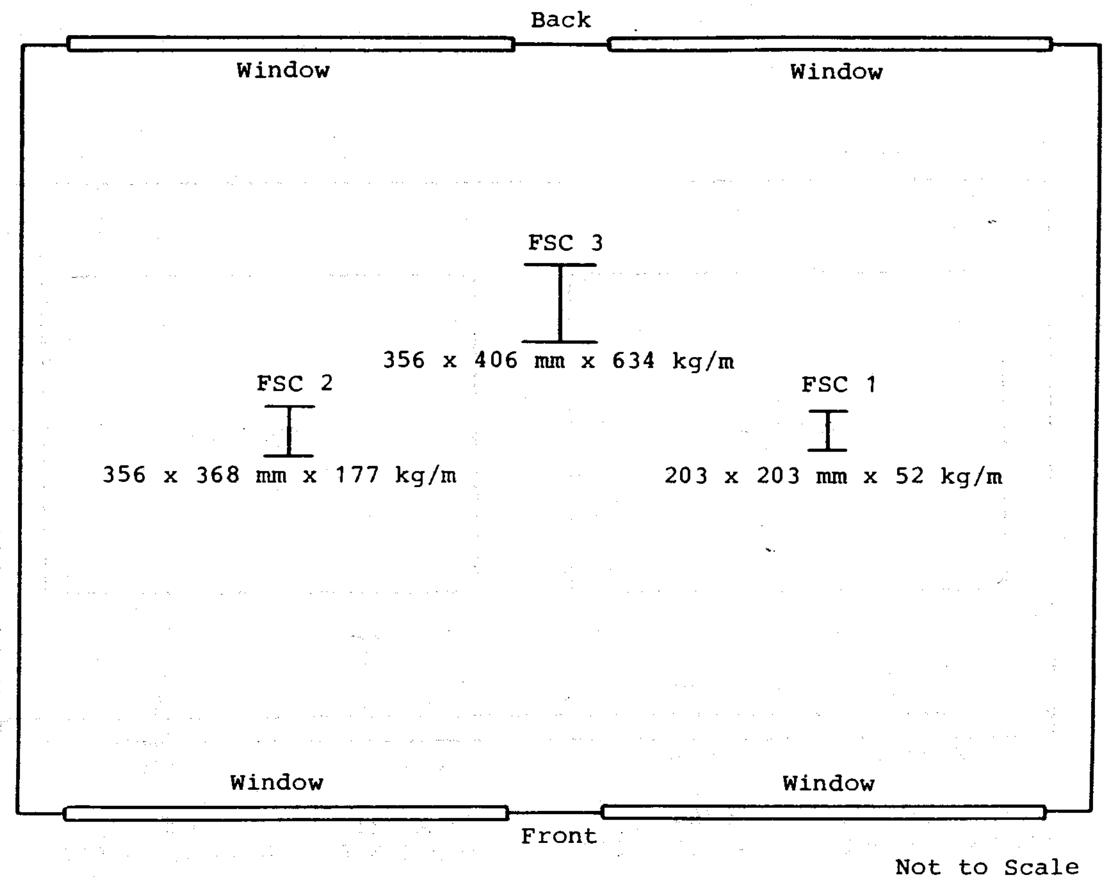
TABLE 1 **IDENTIFICATION OF THERMOCOUPLE/S USED TO DESCRIBE THE LOCAL ATMOSPHERE HEATING RATE FOR EACH LOCATION ALONG THE STEEL MEMBERS**

Component Identity	Upper Level (0.5 m)		Lower Level (2.0 m)
	Back Position	Middle Position	
Beam 1	12	13	-
Beam 2	7	8	-
Beam 3	3	4	-
SAFB	16	17	-
FSC1	(4 + 8)/2		6
FSC2	(13 + 17)/2		15
FSC3	(7 + 8 + 12 + 13)/4		10



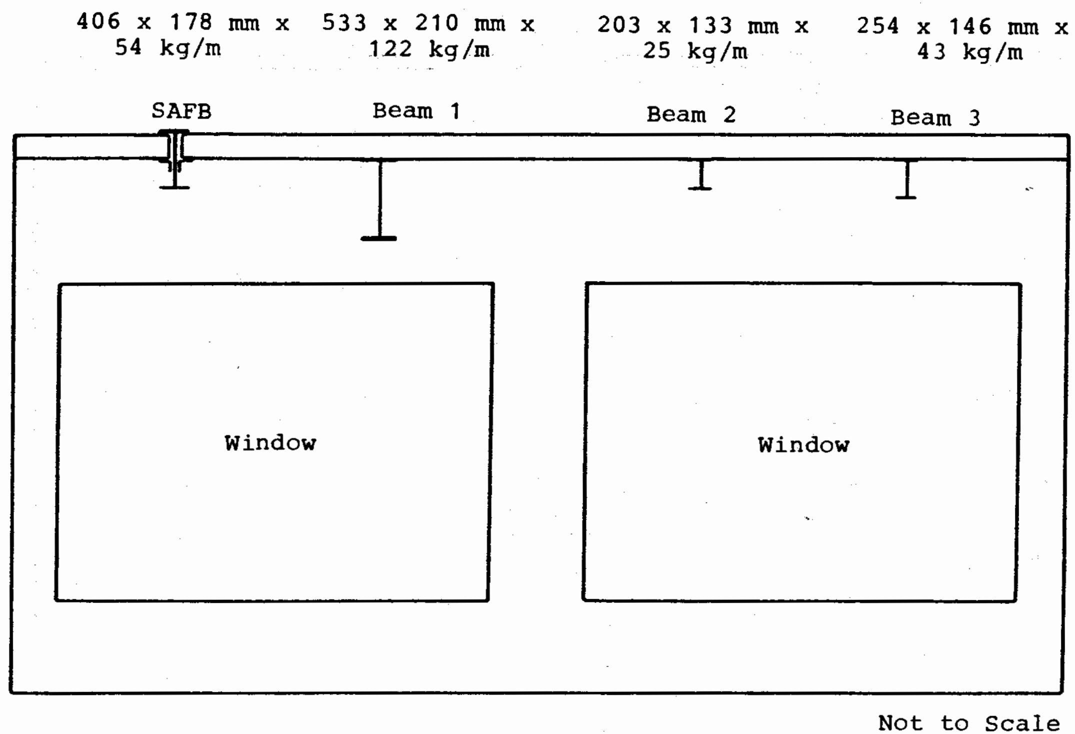
GENERAL ARRANGEMENT OF FIRE TEST COMPARTMENT

FIG. 1
(R2/8230)



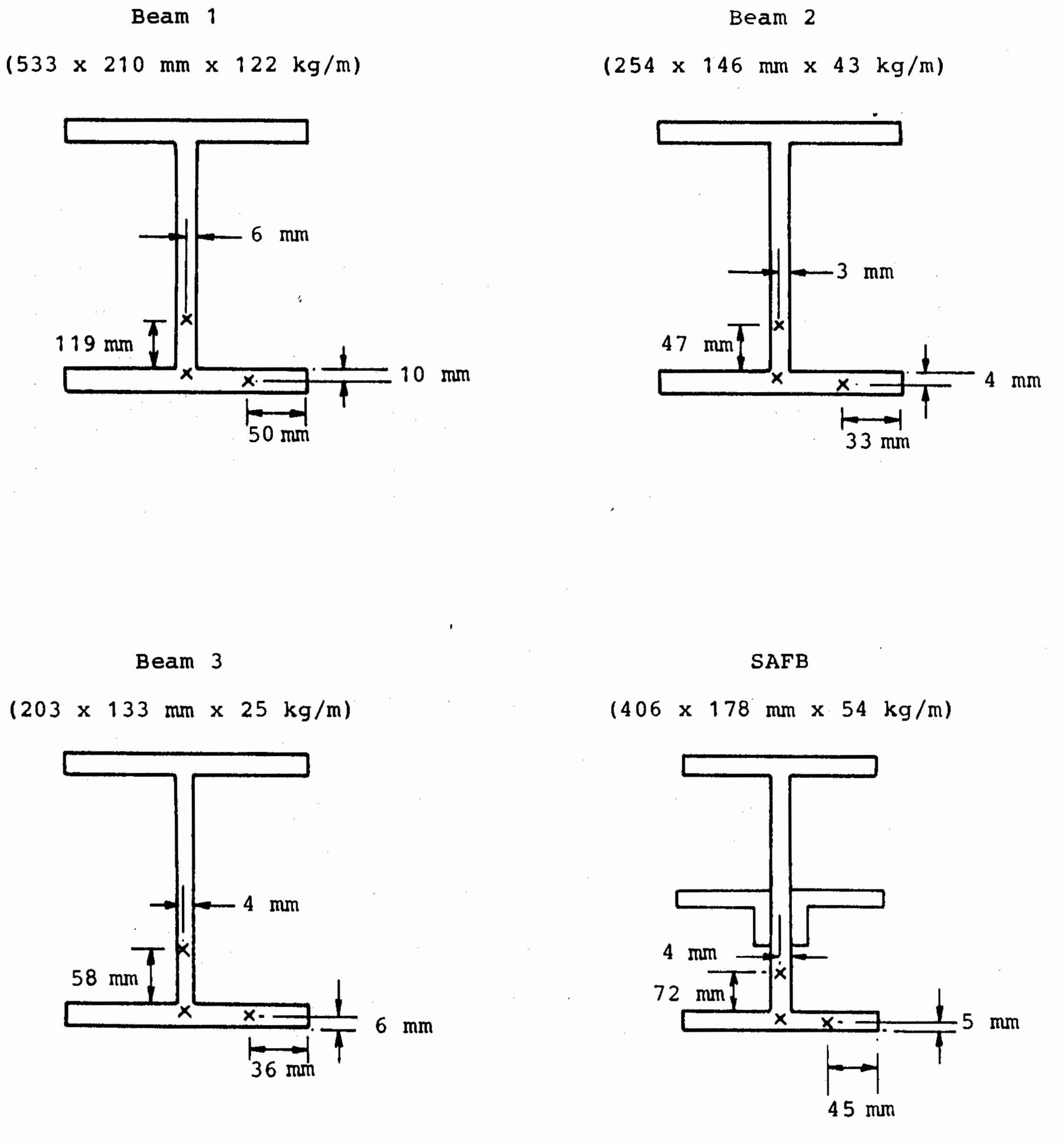
PLAN OF THE FIRE TEST COMPARTMENT GIVING DETAILS OF THE COLUMN SIZES, IDENTIFICATION AND THEIR LOCATION

FIG. 2
(R2/8231)



FRONT ELEVATION OF THE FIRE TEST COMPARTMENT GIVING DETAILS OF THE BEAM SIZES, IDENTIFICATION AND THEIR LOCATION

FIG. 3
(R2/8232)

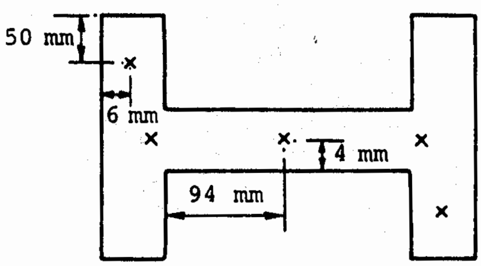


THERMOCOUPLE POSITIONS WITHIN THE FLOOR BEAMS
UPPER FLANGE AND WEB POSITIONS ARE
VERTICALLY SYMMETRICAL

FIG. 4(a)
(R2/8233)

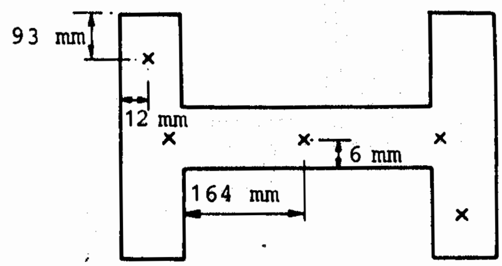
FSC 1

(203 x 203 mm x 52 kg/m)



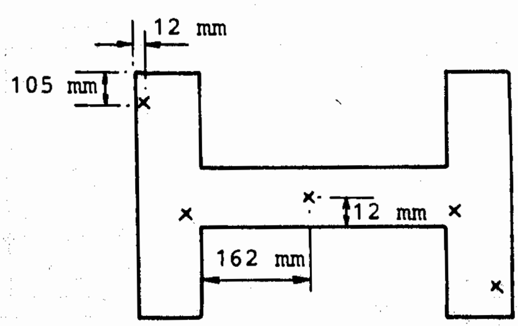
FSC 2

(356 x 368 mm x 177 kg/m)



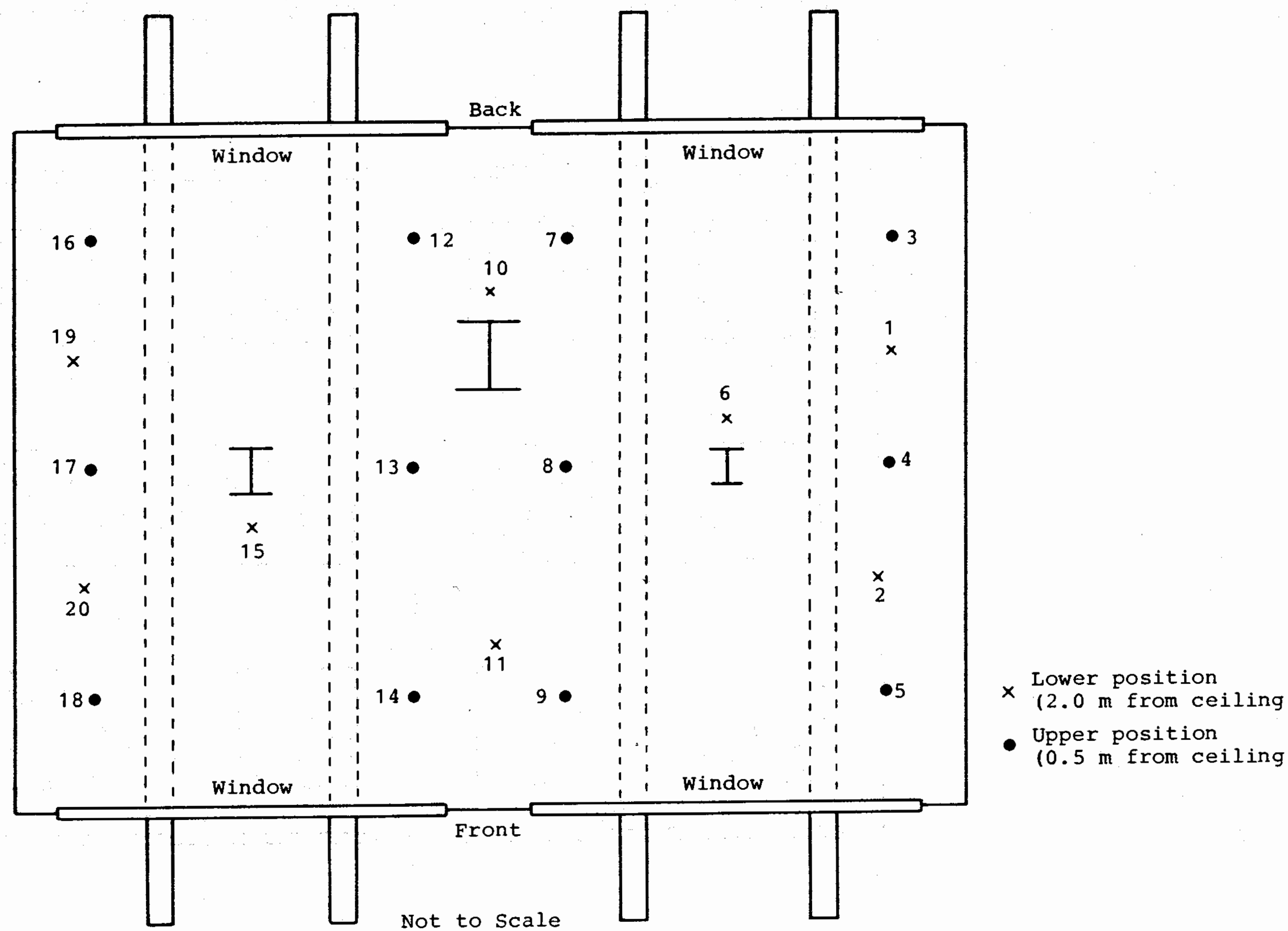
FSC 3

(356 x 406 mm x 634 kg/m)



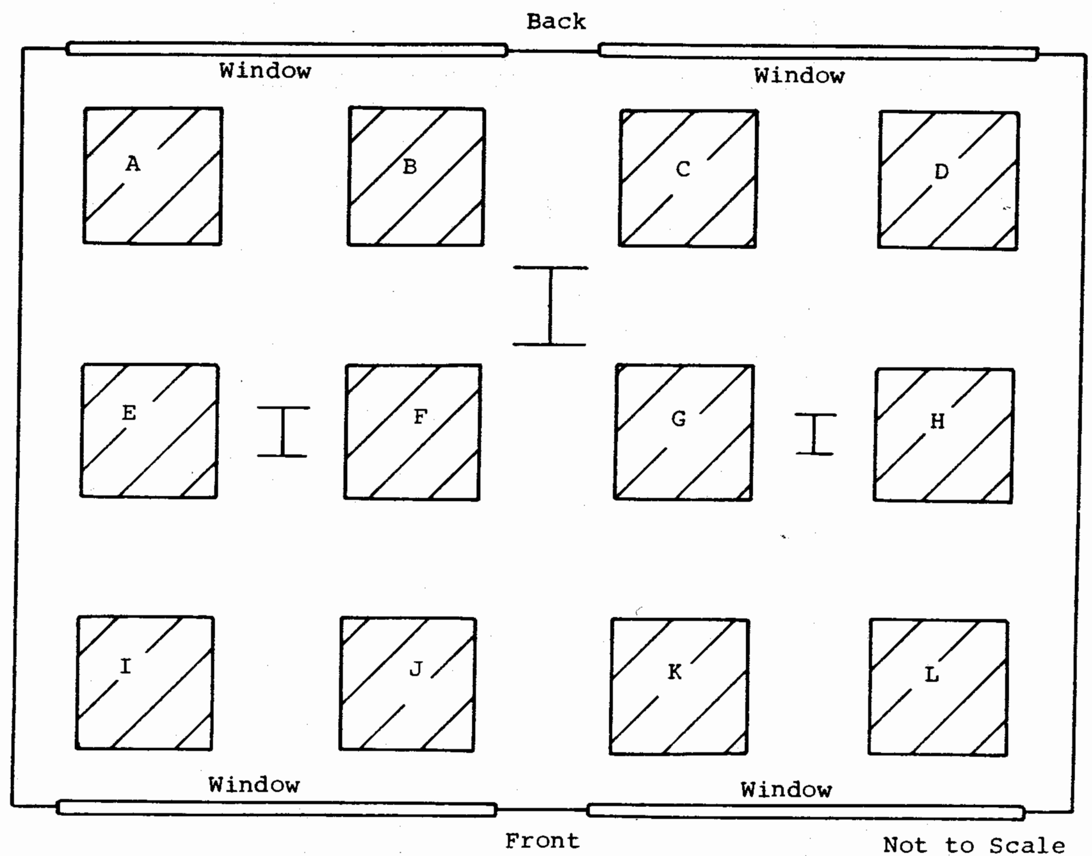
<u>THERMOCOUPLE POSITIONS WITHIN THE COLUMNS</u>

FIG. 4(b)
(R2/8234)



PLAN OF THE FIRE TEST COMPARTMENT SHOWING THE POSITIONS OF THE THERMOCOUPLES WITH RESPECT TO THE STEELWORK FOR MONITORING ATMOSPHERE TEMPERATURES

FIG. 5
(R2/8235)



PLAN OF THE FIRE TEST COMPARTMENT SHOWING THE LOCATION OF THE CRIBS

FIG. 6
(R2/8236)

FIRST NATURAL FIRE TEST ON A LOADED STEEL FRAME AT CARDINGTON

REPRINT OF BRITISH STEEL REPORT RSC/7281/11/86

BRITISH STEEL CORPORATION,
Swinden Laboratories,
Moorgate,
ROTHERHAM.

4th March, 1986.

FIRST NATURAL FIRE TEST ON A LOADED STEEL FRAME AT CARDINGTON

SYNOPSIS

The first of two natural fire tests on a loaded, two dimensional, steel framework is described. The structure comprised an unprotected 406 x 178 mm x 54 kg/m beam which spanned the compartment at ceiling height and was attached at each end by bolted connections to blocked in columns. Maximum design loads were applied to both the beam and the columns in the structure. A fire load density of 20 kg/m^2 of wood at the $\frac{1}{8}$ ventilation of two walls were selected to ensure that the limiting temperature for the load carrying capacity of the beam (as a simply supported member) was attained.

The unprotected beam reached a maximum lower flange temperature, at mid-span of 657°C after 22 minutes. The blocked in columns reached a maximum temperature of 487°C. From the maximum temperatures recorded on the beam and also using evidence from an unloaded indicative column, mathematical analysis suggested that a time equivalent of 20 minutes was appropriate for this fire. Despite the fact that the limiting temperature of the test beam was reached only limited beam deflection occurred emphasising the fact that steel frameworks exhibit a greater fire resistance than their individual steel elements.

The second test should utilise a higher fire load density and be designed to provide a more comprehensive coverage of the deflection characteristics of the assembly.

1. INTRODUCTION

A joint BSC/DoE contract has been carried out to provide an acceptable basis for the preparation of design guidelines detailing the construction of steel frames having adequate structural stability in natural fires. The development of analytical techniques to simulate the performance of steel frames in natural fires is a principal requirement of the project and the initial stage in any mathematical model involves the prediction of the temperature fields generated in the steelwork as the fire progresses by considering the combined effects of radiative, convective and conductive heat flow. A second stage is the determination of deflections in loaded members at any instant during the fire. At present this is being accomplished using FASBUS II which is a non-linear structural analysis program for two dimensional floor systems, however the use of a specialised finite element package from PAFEC Ltd. might offer a greater degree of flexibility and is now receiving some attention.

At present the mathematical model has been used exclusively for predicting the behaviour of elements of structure in the BS 476 : Pt. 8 fire resistance test, such as unprotected beams and columns as well as the response of partially protected beams. The ultimate goal of predicting the performance of steel frames in naturally occurring fires is more difficult to achieve. The problem is being approached in two stages involving initially the simulation of the behaviour, in natural fires, of loaded, but restrained, beams followed by a study of beam/column combinations. Preliminary studies have been based on FASBUS II although the modelling of rotational restraint and the vertical displacement of the beam is complicated Use of the PAFEC 'plate' model may ultimately be more successful, particularly with regard to the second stage. However, whichever method is considered, experimental data are required to check the mathematical predictions.

A large number of natural fire tests have been carried out on unloaded steel sections to measure the steel heating rates in different fire environments. However, in order to assist in the verification of the analysis of frame structures it was considered necessary to subject a loaded framework to a natural fire test and record not only the temperature distribution but also the deflection behaviour of the connected members as the fire progressed.

The present report describes the first of two natural fire tests on a loaded steel framework which formed the Twenty-second experiment in the Cardington series[1]. The structure comprised a 406 x 178 mm x 54 kg/m bare steel beam which spanned the compartment at ceiling height and was attached at each end to a 203 x 203 mm x 52 kg/m blocked in column. Maximum BS 449 design loads were applied both to the columns and the beam. A fire load density of 20 kg/m² of wood and the $\frac{1}{8}$ ventilation of two opposite walls in the compartment were selected on the basis of earlier work, to ensure that the limiting temperature for the load carrying capacity of the beam (as a simply supported member) was attained. The experiment also provided an opportunity to observe the response of both the fire resistant design of a free standing column and also the beam/column connections to a natural fire environment.

2. EXPERIMENTAL PROCEDURE

The fire compartment, which measures 8.6 m x 5.5 m x 3.9 m high has been built within the No. 2 Hangar at RAF Cardington so that tests are almost independent of weather conditions. The constructional materials were selected on the basis that they would withstand repeated exposure to high temperatures without collapsing or changing their thermal characteristics and so some of them would not normally be found in modern buildings.

A total of 21 fire tests had already been carried out in the compartment to measure the heating rates of several unprotected beams and columns as well as a water filled hollow section. The steelwork was evenly distributed throughout the compartment to minimise its effect as a heat sink. Before the loaded framework could be installed these sections had to be removed which necessitated certain repairs to the structure and the removal of the precast concrete roof slabs. Once the new loaded framework had been installed a number of unused concrete planks were placed on the roof. The inner exposed surfaces of the compartment comprised heat resistant brickwork.

2.1 Steel Framework

The steel framework selected for testing under load was typical of that used in a multi-storey building of 2 to 3 storeys in height. The design is detailed in Drawing No. C/01/AO/A but the salient features are given in Figs. 1 to 4.

The test sections comprised a 4.55 m length of 406 x 178 mm x 54 kg/m BS 4360 : Grade 43A universal beam and two 3.53 m lengths of a 203 x 203 mm x 52 kg/m universal column. These serial sizes were chosen because they had previously been included in earlier BS 476 : Pt. 8 fire tests on partially protected members.

The general arrangement of the test frame is shown in Fig. 1. The beam was connected to the columns by M20 Grade 8.8 bolts through welded end plates. The assembly was centrally positioned inside the compartment parallel to the short walls. Each column, which extended above the beam, was pin jointed at the base to 1.5 m lengths of 533 x 210 mm x 92 kg/m section which also formed the base of the loading frame. The webs of each column were protected by lightweight blocks built between the flanges using an ordinary mortar mix followed by a 28 day drying out period. Four 1200 x 550 x 150 mm concrete slabs which formed part of the compartment roof were attached to the top flange of the beam by welded 12 mm diameter threaded bars. The slabs were separated by a gap of 25 mm to prevent composite action with the beam and the gap was filled with ceramic fibre blanket.

A second frame shown in Fig. 2 provided a structure from which the appropriate design loads could be applied to the test assembly beneath. This comprised a 533 x 210 mm x 92 kg/m universal beam as a crosshead, each end of which was attached to two vertical 152 x 89 mm channel sections that straddled the blocked in columns and were fixed to the base sections of the loading frame. These sections were braced and bolted to the concrete floor.

Both frames were held in position by a combination of external bracing and a subsidiary steel framework contained within the compartment. General views of the assembly are shown in Fig. 3. With the exception of the test frame the remainder of the structure inside the compartment, Fig. 4, and lengths of the external braces in front of the ventilators were lagged with ceramic blanket.

2.2 Loading the Frame

A hydraulic ram and load cell were superimposed between the top bearing plate of each blocked in column and the crosshead member to provide the maximum permissible, compressive, design load of 520 kN (BS 449:1972). The beam was loaded at four positions along the span each with a load of 47.6 kN. As the precise loading points on the day of the test were as represented in Fig. 5 the total load represented an 18% increase above the normal maximum design stress in bending of 165 N/mm^2. The loads were maintained throughout the period of the fire test. A general view of the loading arrangement is shown in Fig. 6.

2.3 Instrumentation

The temperature distribution of the combustion gas in the compartment during the fire was monitored by 3 mm diameter chromel/alumel Type K thermocouples with Inconel sheaths and insulated hot junctions. In the vicinity of the test frame, the thermocouples were positioned 300 mm from each flange face of the blocked in columns and at heights of 1200, 2400 and 3330 mm above the floor. Thermocouples were also positioned 100 mm from the test beam and at 6 locations along the length of the lower flange. The combustion gas temperatures were also measured at locations half way between the main frame and each of the short walls of the compartment at heights of 2000 or 3300 mm above the floor. The disposition of the thermocouples is shown in Fig. 7(a).

Similar thermocouples were used to measure the steel temperature gradients in the flanges and webs of the test frame at the positions shown in Fig. 7(b). The tip of each thermocouple was inset into a 3 mm diameter hole drilled into the steel section at the positions shown in Fig. 7(c).

In order to compare the steel temperatures recorded in the test with earlier measurements a 1.6 m length of 203 x 203 mm x 52 kg/m indicative column was placed in the compartment at the same position as that occupied by FSC1[1]. Thermocouples were attached to the flanges and web of this section at a height of 1500 mm above the floor. The 203 x 203 mm x 52 kg/m external column used in the earlier tests was also included in the comparison, the thermocouples were mounted at heights of 1.9 m and 3.3 m from the floor (corresponding to distances of 2.0 m and 0.5 m respectively from the ceiling of the compartment as referred to in earlier reports).

Deflection measurements were made at the centre of the loaded beam using a potentiometric transducer mounted to a fixture on the roof of the compartment. A similar device was located between the crosshead and the top of one blocked in column but no independent measurement of the changes in extension and lateral bowing of this section was attempted during the test.

The temperatures of the top and bottom bolts of the connection were monitored with thermocouples inserted to a depth of 22 mm from the face of the exposed bolt head and to a depth of 12 mm from the end of the threads that were surrounded by mortar and blockwork. In addition, one top bolt was adapted to accept a temperature compensated strain gauge to measure the tensile stresses in the thread during the test. The strain gauge comprised a 6 x 2.6 m Ni-Cr foil element with a gauge factor of 2.3 mounted on a polyimide carrier suitable for use up to 300°C.

The outputs from the separate measuring instruments were fed back to a Compulog 4 computer controlled data acquisition system. The output from the strain gauged bolt was also directed to a visual display unit.

2.3 Fire Load and Ventilation

The combustion of a wooden fire load density of 20 kg/m² with the $\frac{1}{4}$ ventilation of one wall of the compartment was considered to be of sufficient severity to ensure that the loaded beam would reach its limiting temperature during the fire. This decision was based on earlier studies of the temperatures attained by unprotected steelwork in natural fires when the ceiling of the compartment had been lined with ceramic fibre tiles and the walls had, as now, comprised insulating brick. An average time equivalent of 61 minutes had been previously obtained under these conditions. However it was expected that the modifications made to the compartment during the installation of the loaded frame would reduce the severity of the fire, particularly since the concrete ceiling would now be left unprotected. Nevertheless, it was thought that a time equivalent value greater than the 24.6 minutes calculated using the FRS equation might be obtained.

Previous work had also suggested that for a given total ventilation to the compartment the difference in the fire behaviour caused by openings in one wall, or the two opposite walls was small[2]. As it was important to obtain as symmetrical a heating pattern across the loaded frame as possible openings were made in both long walls of the compartment using the appropriate shutters to give $\frac{1}{8}$ ventilation in the area of each wall.

As this fire test represented the first, and possibly the only, experiment on a loaded frame there was some concern as to the likely effect of a too rapid build-up of heat to the maximum combustion gas temperature. It was considered advisable to reduce the rate of burning, as experienced in previous fires of this severity, to allow time for the loads on the beam to be effectively controlled and also to establish a more realistic temperature distribution over the cross section of the blocked in column.

The standard layout of each of the 12 cribs used for simultaneous ignition had been 50 x 50 x 1000 mm dried Western Hemlock sticks spaced 50 mm apart with alternate rows at right angles to each other. Based on relationships between stick size and fire duration[3] it was decided to wire together a number of sticks to a 100 x 100 mm cross section and thereby reduce the rate of burning. A photograph of the crib assembly is shown in Fig. 8; two rows of the 100 x 100 mm stick bundles were placed 100 mm apart at the bottom of the crib to avoid the danger of premature collapse. The photograph also shows the difficulty of crib assembly in the vicinity of the fire protected bracing frame; the original 'columns in walls' suitably lagged appear in the background.

3. EXPERIMENTAL RESULTS - CARDINGTON FIRE TEST NO. 22

Date:	24th October, 1985.
Fire Load Density:	20 kg/m^2 in 12 cribs, total wood fire load = 1016 kg.
Ventilation:	$\frac{1}{8}$ of North wall + $\frac{1}{8}$ of South wall $\equiv$ 0.06 $m^{2\frac{1}{2}}$.

3.1 General Observations

The wooden cribs were ignited simultaneously on a still day. Once the fire became established the intensity was greatest at the centre of the compartment. A considerable amount of moisture was driven from the concrete roof slabs during the tests. In comparison with an earlier natural fire test using the same fire load density and ventilation conditions the rate of heating was reduced and the fire reached its peak 7 minutes later. Representative photographs of the fire test in progress are shown in Fig. 9.

The maximum load applied to both columns and the beam was maintained throughout the fire test but despite this the frame remained stable showing little evidence of rotation at the connections. The deflection behaviour was unexpected; the cross head appeared to bow upwards slightly during the later stages of the test and the loaded beam exhibited only a small deflection.

A maximum tensile load of 6 kN was recorded from the strain gauged bolt in the connection at the start of the test but thereafter the strain gauge failed to respond.

An examination of the loaded frame at the conclusion of the test suggested that the experiment could be repeated once the bolts in the connection and the blockwork in the columns had been replaced.

3.2 Atmosphere Temperature

The atmosphere temperatures in the vicinity of the loaded structure are given in Table 1 and at other positions inside the compartment in Table 2 as a function of time. Reference should be made to Fig. 7(a) for the thermocouple numbering system. A maximum average temperature of 705°C was recorded at the centre of the compartment after 17.5 minutes.

The change in combustion gas temperature with height is shown in Fig. 10 measured in the vicinity of the columns. After 18 minutes the average temperature of 645°C at the 3.3 m level was approximately 50°C cooler than at the lower positions. The average change in combustion gas temperature across the top of the compartment is shown in Fig. 11. The development of the combustion gas temperature with time along the beam is represented in Fig. 12 for a number of time periods throughout the fire test. As a result of equal ventilation from both walls of the compartment the hottest region of the fire occurred at the centre of the beam. Once the peak temperature had been reached the heating became more uniform.

3.3 Steelwork Temperatures

The temperatures recorded during the test are given in the edited Tables 3 to 9 and typical patterns of behaviour in Figs. 13-18. The numbered thermocouple positions used in the presentation of data are depicted at the head of each table.

3.3.1 Loaded Beam

The steel temperatures are presented in Table 3 for the flanges of the beam and in Table 4 for the thermocouple positions on the web. The steel heating rate during the fire was faster at the centre of the beam as shown in Fig. 13(a) and (b) by the individual temperature profiles in the lower flange (Fig. 13(a)) and web (Fig. 13 (b)). For example, the maximum temperature recorded by F1 close to the connection was 557°C reached after 21 minutes whereas F4, closer to the centre of the beam, reached 644°C at the same time. The highest individual temperature of 657°C was recorded by F5 after 22 minutes.

The average changes in both atmosphere and steel temperatures at the ends and at the centre of the beam are summarised in Fig. 14. The maximum combustion gas temperature occurred approximately three minutes before the beam reached its highest temperature.

3.3.2 Loaded Columns

The steel temperatures are presented in Table 5 for the blocked in column at the front of the compartment, nearest to the hangar door and in Table 6 for the blocked in column attached to the other end of the beam. The steel heating rate was faster on the flange facing into the compartment as shown by the thermocouples F1, F3 and F4 in Fig. 15. The difference in temperature with height was not significant except in the proximity of the connection with the beam. For example, the maximum temperature recorded at a height of 2400 mm on the inner facing flange was 487°C and at a height of 3000 mm it was 451°C. The corresponding maximum temperatures on the outer facing flange were 388°C and 370°C. The steel temperatures measured on the flanges of the other blocked in column were similar to those shown in Fig. 15.

The temperatures recorded by individual thermocouples in the webs of each column are shown in Fig. 16. The temperature measurements taken on the front column were very erratic. The highest web temperature on the back column of 288°C was recorded at a height from the floor of the compartment of 1200 mm. The lowest temperature occurred at the intermediate position which also registered a moisture plateau. Clearly the steel temperatures of the web were influenced by the physical changes of the mortar and block work during the fire.

The average changes in both the atmosphere and steel temperatures at the centre of the blocked in column are typified by the curves of Fig. 17 recorded at the back of the compartment. The maximum average flange temperature of 420°C occurred 4 minutes after the fire had reached its peak whereas the corresponding temperature in the web of 260°C occurred a further 10 minutes later.

3.3.3 Bolts

The temperatures measured in the thread of the bolts used for the connections are presented in Table 7 and Fig. 18 shows typical temperature profiles beneath the bolt head and nut. The bolts in the lower part of the connection were the hottest during the fire test. The average maximum temperatures reached by the thread of the bolts beneath the head were 365°C for the lower and 340°C for the upper bolt, recorded after approximately 28 minutes. The drop in temperature along the thread was greatest for the top bolts.

In an earlier indicative BS 476 : Pt. 8 fire test on a similar connection the bottom bolts also exhibited a faster heating rate than the top bolts[4]. After 25 minutes the bottom bolt threads reached a temperature of 336°C below the head and 238°C behind the brickwork. In the present test the corresponding temperatures were 362°C and 325°C for one connection and 355°C and 299°C for the other.

3.3.4 Indicative Column

In an earlier natural fire test using a fire load density of 20 kg/m^2 and the $\frac{1}{4}$ ventilation of one wall the free standing column FSC1 reached a maximum average steelwork temperature of 961°C after 15 minutes. An indicative column having the same $^{HP}/A$ value of 180 m^{-1} was placed inside the compartment and the temperature measurements recorded at the 1500 mm position are presented in Table 8. In comparison with the earlier data the severity of the fire was by no means as great since the column only reached a maximum average temperature of 672°C after 20 minutes.

3.3.5 External Column

The external column with an $^{HP}/A = 180$ m^{-1} reached a peak temperature of 155°C (1900mm) on the exposed flange after 24.5 minutes. The peak temperature recorded on the exposed flange at a height of 3300 mm was 118°C. The results are presented in Table 9.

3.4 Deflection Behaviour

The displacement transducers recorded the change in movement of the loaded columns in Fig. 19(a) and the loaded beam in Fig. 19(b). On completion of the test when the loads were removed and the steelwork cooled down to room temperature the beam had a permanent deflection at the centre of the span of 18 mm and at the mid-point the columns had each bowed inwards by 7.5 mm.

The true behaviour of the assembly was obscured by the fact that the vertical tensile members linked to the crosshead were not sufficiently insulated to prevent significant thermal expansion with the resulting upward movement of this structure. The displacement transducer mounted between the loading frame and the blocked in column showed no relative change during the majority of the test; this observation suggested that the small change in deflection observed near the end of the test was probably caused by bowing of each column due to the temperature gradients being developed across the section.

The displacement transducer on the beam gave a more accurate deflection pattern as it was mounted independently of the loading frame. The apparent reduction in beam deflection during the early stages of the test was due to the expansion of the blocked in columns. After approximately 12 minutes, when the lower flange temperature had reached 520°C, downward movement of the beam commenced and continued until completion of the test.

The expansion of the columns was not measured with accuracy for the reasons given above. However, an approximate indication of behaviour may be obtained from temperature displacement measurements on a fully loaded blocked in column of the same serial size during a BS 476 : Pt. 8 fire test[5]. By making allowance for the difference in length it was estimated that the expansion would be 6.5 mm after 12 minutes and 10.7 mm after 22 minutes. This assumes a temperature profile throughout the length of the blocked in column similar to that observed in the standard test. A comparison of these calculations with the permanent deflection measurements on the loaded frame at ambient temperature suggests that during the course of the fire the beam initially 'hogged' prior to deflecting downwards and the blocked in columns bowed inwards. Such behaviour would be expected from a portal frame construction in a fire.

4. DISCUSSION

In an earlier Cardington fire test with a fuel density of 20 kg/m² and the $\frac{1}{4}$ ventilation of one wall the combustion behaviour was more severe than experienced in the current experiment. For example, the unprotected beam B2 with an $^{HP}/A = 169\ m^{-1}$ reached a maximum average lower flange temperature of 941°C and the respective temperature for the free standing column FSC1 with an $^{HP}/A = 180\ m^{-1}$ was 961°C. However, in the present case the loaded beam with an $^{HP}/A = 192\ m^{-1}$ reached a maximum lower flange temperature of 667°C and the indicative column a maximum average temperature of 682°C. (The steel temperatures have been adjusted to an ambient temperature of 20°C). The difference is due to three factors. Firstly, the original test had been carried out in a highly insulated compartment, since when the ceramic fibre tiles had been removed from the ceiling. Secondly, the release of moisture from the replacement concrete roof slabs reduced the maximum combustion temperature. Finally, the rate of combustion had been reduced in the current work.

As the blocked in columns had previously been found to exceed the ½ h rating and the bolt temperatures in the connection were not excessive, failure was expected to occur in the beam of the loaded frame. The behaviour of the natural fire can be related to an equivalent heating time in the BS 476 : Pt. 8 fire resistance test. The theoretical relationship established by the FRS predicts a time equivalent of 24.6 minutes for the fire load and ventilation conditions used in the present test. This figure relates to a brick plus concrete lined compartment, thereby representing a minimum value for the boundary conditions actually used. A mathematical analysis on the available experimental steel heating rates predicts a time equivalent of 19.5 minutes for the beam in the test frame and 20.5 minutes for the indicative column.

In BS 476 : Pt. 8 tests on fully loaded (BS 449:1972) unprotected steel beams the average lower flange temperature at a deflection of L/30 in the simply supported condition was 650°C, or approximately 620°C for the increased load imposed on the Cardington beam. However, despite a maximum lower flange temperature of 657°C (actual) no significant deflection was observed. Allowing for changes in Young's modulus with temperature it was estimated that the total beam deflection (elastic and plastic behaviour) at the height of the fire was 32 mm; in fire tests on beams having a similar section modulus (e.g., 336 x 171 mm x 67 kg/m : Grade 43A) such a deflection might be expected at a lower flange temperature of 520°C.

The principal reason for the increased stability of the present test beam must have been the degree of end restraint imposed by the connections. From measurements made in a room temperature cantilever test, a bolted connection similar to that used on the test frame exhibited a rotational resistance mid way between a flexible and a fully rigid joint. In the fire, the rigidity of the connection would increase still further due to thermal expansion of the beam and the lack of distortion of the column. A high degree of end restraint is known to be beneficial to fire resistance.

During the fire test, the inward facing flanges of the blocked in columns reached a maximum temperature of 487°C (or 499°C when adjusted to an ambient temperature) and were hotter than the outward facing flanges. In the standard fire test of the composite column under maximum design load the mean exposed flange temperature at failure was 626°C. Therefore, the blocked in columns in the Cardington test had still a significant degree of fire resistance in reserve.

A future test on the loaded test frame should utilise a higher fire load density to raise the steel temperatures still further and provide a more comprehensive coverage of the deflection characteristics of the assembly. The possibility exists that through the combination of end restraint to the unprotected beam and the enhanced fire resistance of the protected columns the test frame as a whole could satisfy a $\frac{1}{2}$ h rating.

5. CONCLUSIONS

A test frame comprising an unprotected 406 x 178 mm x 54 kg/m beam bolted to two 'blocked in' 203 x 203 x 52 kg/m columns was installed in the Cardington compartment. The maximum design load (BS 449 : 1972) was applied to each column but the four point loading of the beam introduced a bending stress 18% higher than the maximum design values of 165 N/mm². The test frame was subjected to a natural fire based on a fire load density of 20 kg/m² and the $\frac{1}{8}$ ventilation of two walls.

The FRS relationship predicted a time equivalent of 24.6 minutes for the fire load and ventilation conditions used. The mathematical model predicted a time equivalent of 20 minutes for the beam in the test frame and 20.5 minutes for an indicative column placed inside the compartment.

The unprotected beam reached a maximum lower flange temperature at the centre of the span of 657°C after 22 minutes which exqeeded the limiting temperature for this section when tested as a simply supported member. The blocked in columns reached a maximum temperature of 487°C on the inner facing flanges in a similar time, the outer facing flanges were about 100°C cooler and the temperatures in the web were influenced by the physical changes of the mortar abd block work during the fire. The bottom bolts of the connections were hotter than the upper bolts with average maximum temperatures in the thread beneath the head of 365°C.

This test demonstrated that steel frameworks do exhibit a greater fire resistance than individual steel elements. A lack of significant deflection of the test beam was due principally to the degree of end restraint imposed at the connections.

A future test should utilise a higher fire load density to raise steel temperatures in the test frame and provide a more comprehensive coverage of the deflection characteristics of the assembly.

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TABLE 1 ATMOSPHERE TEMPERATURE DATA (ADJACENT TO LOADED STRUCTURE)

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

COMPONENT IDENTITY : ATMOSPHERE
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

TIME	ATMOSPHERE TEMPERATURES (deg C)															
	<---- COLUMNS ----							---->	<---- BEAM ----							---->
	1200mm LEVEL				2400mm LEVEL				3300mm LEVEL							
	(s)	(s)	(n)	(n)	(s)	(s)	(n)	(n)	(n)	(n)	(n)	(s)	(s)	(s)	(s)	(n)
(mins)	A9 (+)	A11	A13	A16	A8	A10	A12	A15	A1	A2	A3	A4	A5	A6	A7	A14
0	11	11	12	12	11	11	12	13	13	13	12	12	12	11	11	13
1	61	59	54	54	68	69	76	68	58	64	66	76	78	67	56	72
2	302	285	295	270	320	347	352	325	301	336	342	344	325	313	285	324
3	449	474	495	415	457	512	515	483	447	480	494	518	492	455	430	486
4	502	543	564	478	513	568	567	537	510	531	556	590	547	502	507	528
5	527	569	584	509	541	590	586	553	530	550	576	613	570	531	532	533
6	549	590	587	536	554	608	610	574	550	580	607	640	604	560	543	557
7	559	597	605	514	562	615	613	586	562	570	601	638	616	570	545	572
8	573	601	617	501	573	626	612	600	568	581	607	643	623	579	561	589
9	577	605	621	499	577	624	621	601	583	587	606	634	623	579	565	590
10	583	607	620	488	584	630	626	604	585	595	621	646	623	583	575	588
11	589	619	628	484	589	635	633	613	593	613	640	664	639	596	576	598
12	603	626	635	485	603	649	644	625	597	624	663	685	656	611	590	604
13	606	634	649	479	607	653	659	639	618	639	664	688	654	611	598	613
14	618	646	672	501	621	665	670	645	633	642	680	695	664	621	611	617
15	631	655	682	499	636	675	681	665	646	656	681	692	655	615	625	629
16	652	663	690	507	650	682	694	676	657	671	694	699	665	622	627	638
17	665	674	706	531	658	696	702	693	654	678	699	709	670	633	637	654
18	657	673	701	536	646	688	695	680	648	669	689	704	680	643	636	649
19	651	650	684	519	636	674	684	667	648	661	682	689	667	635	628	645
20	642	634	681	505	616	656	669	649	631	644	650	653	640	618	610	644
21	612	-	626	485	592	631	633	624	610	619	619	620	615	597	585	610
22	575	554	593	477	568	591	598	592	586	596	590	592	591	577	561	572
23	534	527	552	449	540	564	567	557	556	569	566	573	571	552	535	541
24	502	499	509	406	511	542	546	528	535	551	550	553	546	527	510	518
25	489	466	471	377	502	527	530	510	517	533	535	535	531	511	499	496
26	444	430	435	357	480	509	513	493	498	517	521	521	517	497	483	486
27	420	402	414	335	460	488	495	480	482	501	504	501	498	483	464	469
28	396	380	392	320	436	464	473	454	461	479	482	480	473	465	442	451
29	*	356	377	304	420	439	453	436	443	464	463	463	457	447	424	431
30	*	341	358	289	404	422	434	412	424	448	448	448	443	431	409	409
31	*	322	337	278	358	397	415	379	405	427	432	431	426	416	377	391
32	*	302	319	287	349	382	397	341	383	405	412	416	410	402	363	367
33	*	292	299	266	316	356	382	328	369	396	400	403	392	372	333	352
34	*	275	290	271	304	338	365	306	352	381	381	385	380	373	328	333
35	*	264	274	264	283	324	353	290	336	367	369	371	365	354	312	318
36	*	254	251	249	275	311	338	274	322	352	354	357	343	320	295	298
37	*	240	232	230	263	300	324	258	317	344	343	349	332	303	282	291
38	*	229	237	230	256	289	313	253	299	328	333	334	326	312	274	280
39	*	224	226	229	245	277	301	242	293	320	323	323	314	300	262	264
40	*	215	218	220	236	266	295	233	278	307	310	310	300	286	254	252
41	*	208	212	216	226	255	283	228	274	301	304	300	292	285	246	244
42	*	206	211	219	219	249	272	221	261	292	294	290	283	278	242	234
43	*	197	190	204	210	242	264	212	255	283	288	281	279	255	227	229
44	*	186	178	212	204	235	260	207	243	271	277	277	271	244	215	219
45	*	187	180	219	199	225	251	201	236	263	269	264	260	238	215	210
46	*	180	173	211	192	219	244	197	227	254	262	257	252	229	204	204
47	*	172	166	207	184	215	237	192	220	247	253	250	245	222	197	196
48	*	166	167	209	178	207	229	188	211	239	246	246	239	218	188	190
49	*	158	160	202	170	200	222	183	205	231	237	236	232	209	183	183

(+) T/C Faulty from 29 minutes.

(s) = South side of compartment
(n) = North side of compartment

TABLE 2 ATMOSPHERE TEMPERATURE DATA (REMAINDER OF COMPARTMENT)

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

COMPONENT IDENTITY : ATMOSPHERE
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

TIME	ATMOSPHERE TEMPERATURES (deg C)											
	3300mm LEVEL						1900mm LEVEL					
	(e)	(e)	(e)	(w)	(w)	(w)	(e)	(e)	(e)	(w)	(w)	(w)
(mins)	A17	A19	A21	A23	A25	A27	A18	A20	A22	A24	A26 (+)	A28 (#)
0	13	13	12	14	19	14	13	11	12	12	12	12
1	69	76	81	93	92	70	77	49	84	129	64	57
2	351	366	390	391	403	375	448	303	373	470	331	335
3	550	527	547	582	559	530	606	516	545	638	527	517
4	629	591	617	627	599	587	647	591	611	654	595	570
5	639	601	643	636	603	615	657	623	629	622	614	601
6	658	625	652	666	622	647	683	645	640	690	643	637
7	663	638	654	680	633	633	659	649	646	712	650	637
8	669	635	657	691	644	657	685	649	649	739	660	640
9	672	637	655	691	651	649	688	650	650	733	658	650
10	675	639	662	684	644	641	685	655	657	715	647	640
11	691	645	662	693	658	596	706	660	662	715	665	652
12	691	655	674	706	666	659	704	673	675	741	677	663
13	712	672	689	720	664	672	733	684	697	745	683	687
14	708	677	693	705	667	696	744	695	702	731	699	737
15	730	693	706	686	661	676	751	709	727	715	693	698
16	731	701	714	700	673	681	779	720	740	732	703	704
17	734	700	723	699	679	691	773	727	750	741	707	711
18	712	688	706	701	680	702	746	718	723	734	707	708
19	703	671	687	700	671	688	719	693	696	719	*	697
20	673	647	653	678	646	673	703	674	673	699	*	677
21	649	620	632	652	625	649	677	645	643	677	*	656
22	611	591	594	620	598	599	626	613	612	651	*	604
23	575	564	565	585	572	561	582	583	580	608	*	568
24	546	539	544	560	546	524	556	555	549	566	*	539
25	521	520	522	534	524	521	531	535	522	533	*	508
26	501	504	503	511	502	472	500	507	489	499	*	487
27	483	486	481	486	483	453	473	483	464	473	*	466
28	460	465	453	463	465	493	446	458	446	456	*	440
29	443	448	437	449	450	444	417	436	419	438	*	417
30	422	432	421	428	429	432	411	416	397	418	*	374
31	409	417	405	412	416	415	389	401	381	408	*	373
32	394	401	391	395	401	398	374	380	366	390	*	358
33	375	386	376	380	391	409	354	367	350	367	*	365
34	358	368	361	365	365	342	338	355	336	347	*	351
35	346	356	343	349	352	381	316	341	323	329	*	332
36	332	341	327	333	344	340	309	328	302	314	*	321
37	327	330	320	323	332	301	299	319	293	303	*	304
38	313	316	311	309	320	293	286	306	282	293	*	301
39	307	310	303	299	308	284	280	297	273	281	*	291
40	296	296	293	290	298	272	268	286	263	267	*	277
41	287	288	283	280	288	265	259	278	258	258	*	269
42	280	280	278	273	278	294	253	271	248	247	*	266
43	268	269	270	264	273	283	244	264	238	244	*	253
44	262	261	260	258	265	244	234	253	229	232	*	240
45	256	253	253	248	256	267	226	246	222	225	*	239
46	248	248	244	240	249	257	217	237	214	215	*	*
47	242	238	237	234	242	236	215	229	208	212	*	*
48	235	235	232	227	235	217	206	221	203	203	*	*
49	227	228	225	222	227	222	195	212	196	192	*	*

(+) T/C Faulty from 19 minutes.
(#) T/C Faulty from 46 minutes.

(e) = East side of compartment.
(w) = West side of compartment.

TABLE 3 TEMPERATURES IN BEAM FLANGES

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

SECTION : 406 mm x 178 mm x 54 kg/m
NOMINAL Hp/A : 190 /m
COMPONENT IDENTITY : BEAM (FLANGES)
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

```
**  A1        A2        A3              **
**  /         /         /               **
******************10******11*********** (U/F)
**                                      **
** 1   2    3    4    5    6    7    8    9 ** (Web)
**                                      **
***1***2***3***4***5***6***7***8***9*** (L/F)
**                  /         /         /  **
**                 A4        A5        A6  **
Back Column                         Front Column
 (North)                              (South)
```

TIME (mins)	STEEL TEMPERATURES (deg C)										
	LOWER									UPPER	
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10 (+)	F11
0	10	10	11	10	10	10	10	10	10	10	10
1	13	14	16	16	14	13	12	13	12	12	11
2	33	40	49	51	45	42	36	43	36	37	29
3	68	83	100	106	102	93	81	84	71	73	56
4	111	135	155	163	160	148	135	133	110	107	83
5	153	185	205	216	213	200	187	180	151	139	114
6	194	238	264	277	276	257	239	228	189	176	146
7	232	285	311	330	330	311	291	276	226	209	177
8	269	329	356	376	377	357	336	319	263	238	203
9	301	369	397	417	420	400	378	359	294	269	230
10	332	405	433	454	456	436	415	395	326	297	255
11	361	440	466	485	488	469	449	428	354	325	280
12	389	471	497	516	520	501	481	460	382	353	305
13	416	500	525	542	544	528	508	487	409	375	325
14	441	527	549	566	567	551	533	512	433	398	346
15	465	549	569	586	589	574	557	537	457	418	368
16	489	572	590	606	606	592	576	557	478	439	386
17	510	568	608	622	622	612	596	577	499	455	405
18	528	606	621	635	635	625	611	593	517	468	420
19	542	618	631	643	647	636	622	605	530	477	433
20	552	625	635	648	651	638	627	611	537	488	437
21	557	626	634	644	652	637	627	612	540	491	442
22	557	622	628	638	657	630	623	609	540	502	450
23	552	614	619	626	650	621	616	603	538	499	451
24	545	604	608	617	638	610	605	594	532	494	449
25	538	594	597	603	609	599	595	585	525	*	444
26	530	582	585	591	611	589	586	576	519	485	444
27	521	571	574	579	603	578	576	566	511	479	440
28	512	559	562	567	553	564	561	553	501	459	431
29	501	547	551	554	578	552	549	541	492	462	429
30	492	535	537	541	546	541	540	531	484	*	423
31	482	523	525	528	531	528	527	519	474	*	417
32	472	510	512	513	519	516	515	508	464	*	411
33	462	499	501	504	507	504	504	496	454	*	404
34	452	487	491	493	511	493	493	485	445	421	399
35	443	476	477	482	472	483	483	475	436	405	392
36	434	465	467	468	461	472	471	462	426	396	385
37	425	454	458	460	472	461	460	452	416	399	379
38	416	444	447	450	460	451	451	443	408	393	374
39	408	434	438	439	448	442	441	432	399	384	366
40	400	424	427	428	435	432	431	422	391	377	360
41	392	415	418	419	425	423	422	413	383	370	354
42	384	406	409	411	410	414	413	404	375	353	348
43	376	397	400	400	404	405	405	396	367	*	343
44	369	389	392	395	397	399	398	389	361	352	338
45	362	380	384	386	385	389	388	379	354	335	332
46	355	371	377	380	378	381	382	373	347	331	328
47	347	363	368	368	370	374	373	363	340	*	321
48	340	356	360	363	364	366	367	356	334	328	317
49	334	348	352	357	356	359	360	350	327	*	312

(+) T/C Intermittent fault from 25 minutes.

TABLE 4 TEMPERATURES IN BEAM WEB

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

SECTION : 406 mm x 178 mm x 54 kg/m
NOMINAL Hp/A : 190 /m
COMPONENT IDENTITY : BEAM (WEB)
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

TIME (mins)	STEEL TEMPERATURES (deg C)								
	WEB								
	W1	W2	W3	W4	W5 (+)	W6	W7	W8	W9
0	10	10	11	11	3	10	10	10	10
1	14	17	20	19	29	19	14	17	12
2	41	59	78	72	54	78	53	69	39
3	91	117	142	140	116	145	113	127	82
4	150	178	205	206	201	208	176	186	130
5	201	234	257	266	256	263	233	238	179
6	248	295	323	335	323	327	294	291	220
7	291	344	370	386	388	381	350	343	259
8	332	389	414	431	424	421	395	386	296
9	366	426	449	467	472	459	435	422	326
10	395	457	480	497	494	487	466	452	355
11	420	486	506	522	520	514	494	478	379
12	444	511	531	546	545	540	520	504	404
13	470	536	554	568	564	556	539	523	427
14	491	553	571	586	583	575	558	542	446
15	509	571	585	599	596	590	576	560	468
16	529	587	601	614	610	603	588	572	483
17	547	601	613	626	622	616	603	587	500
18	559	610	621	633	632	622	612	596	514
19	567	616	625	638	640	627	619	602	522
20	572	616	624	634	640	621	616	599	525
21	570	610	617	626	634	613	611	594	525
22	565	602	608	616	627	609	605	586	521
23	555	589	594	602	613	596	594	577	515
24	543	576	580	588	599	582	580	563	506
25	532	563	567	574	600	566	566	549	496
26	520	549	553	560	568	555	556	539	488
27	508	536	540	547	554	542	543	527	478
28	495	522	527	533	541	524	525	511	467
29	483	509	513	519	526	513	514	499	457
30	472	496	500	506	525	500	503	488	448
31	460	483	487	493	514	487	489	475	437
32	447	470	473	480	500	474	477	463	428
33	437	459	462	468	485	463	466	451	418
34	427	446	449	456	461	452	455	440	409
35	418	435	439	446	446	441	445	430	401
36	407	425	428	434	435	430	434	418	391
37	398	415	418	423	*	419	423	407	381
38	389	404	407	414	*	410	414	400	374
39	380	395	398	404	*	401	405	389	366
40	373	386	389	395	*	392	396	380	359
41	365	378	380	386	*	383	387	372	352
42	357	369	372	378	*	375	379	364	346
43	350	361	364	370	*	367	371	356	339
44	342	353	355	361	*	360	364	350	333
45	334	345	347	354	*	352	356	342	327
46	328	338	340	347	*	346	350	336	322
47	320	329	332	339	*	338	342	327	315
48	313	322	325	332	*	331	335	322	310
49	307	315	318	325	*	324	329	316	304

(+) T/C Faulty from 37 minutes.

TABLE 5 **FLANGE AND WEB TEMPERATURES IN BLOCKED-IN COLUMN AGAINST SOUTH WALL**

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

SECTION : 203 mm x 203 mm x 52 kg/m
NOMINAL Hp/A : ------
COMPONENT IDENTITY : COLUMN (SOUTH)
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

	Exposed Flange		Web	Unexposed Flange		
		*	W5	* F9		--- 3675 mm
		*		*	A7	--- 3300 mm
	F4	*	W4	* F8		--- 3000 mm
A10	F3	*	W3	* F7	A8	--- 2400 mm
	F2	*	W2	* F6		--- 1800 mm
A11	F1	*	W1	* F5	A9	--- 1200 mm

TIME	STEEL AND ATMOSPHERE TEMPERATURES (deg C)																		
	EXPOSED FLANGE						UNEXPOSED FLANGE								WEB				
(mins)	F1	F2	F3	F4	A11	A10	F5	F6	F7	F8	F9	A9 (+)	A8	A7	W1 (#)	W2	W3	W4	W5
0	9	9	9	9	11	11	9	9	9	9	9	11	11	11	9	8	8	9	9
1	15	17	16	17	59	69	10	10	11	11	13	61	68	56	9	10	10	9	9
2	62	64	67	65	285	347	20	23	26	23	36	302	320	285	10	9	8	9	9
3	107	118	139	114	474	512	36	44	49	45	75	449	457	430	10	10	9	10	9
4	138	159	198	144	543	568	52	61	75	71	110	502	513	507	15	15	16	14	10
5	209	197	237	197	569	590	70	79	101	92	129	527	541	532	20	20	18	19	12
6	242	224	264	221	590	608	102	115	130	115	145	549	554	543	27	27	25	26	15
7	266	246	286	240	597	615	125	139	151	136	159	559	562	545	39	40	40	36	18
8	287	268	307	258	601	626	144	158	170	155	171	573	573	561	50	50	47	46	23
9	307	284	322	274	605	624	164	178	188	173	187	577	577	565	64	63	63	57	29
10	323	302	337	290	607	630	181	196	206	190	198	583	584	575	77	76	77	69	34
11	340	321	355	307	619	635	199	214	222	207	209	589	589	576	90	89	97	81	40
12	363	343	376	327	626	649	220	234	242	226	221	603	603	590	107	104	105	94	47
13	388	364	392	345	634	653	237	253	259	242	229	606	607	598	121	118	112	107	55
14	398	383	410	364	646	665	255	271	276	258	239	618	621	611	137	133	131	121	62
15	420	407	430	386	655	675	276	293	297	278	254	631	636	625	151	150	144	136	73
16	439	425	447	400	663	682	297	314	315	294	263	652	650	627	166	163	155	146	80
17	459	447	467	421	674	696	320	338	337	314	274	665	658	637	177	178	169	164	89
18	472	460	479	433	673	688	337	355	352	330	285	657	646	636	194	190	180	175	97
19	483	472	487	445	650	674	353	372	367	345	296	651	636	628	211	203	192	187	108
20	485	476	488	448	634	656	365	383	377	355	302	642	616	610	227	213	204	197	117
21	485	478	486	451	241	631	373	391	383	362	303	612	592	585	240	224	216	206	121
22	478	475	481	449	554	591	378	396	387	366	305	575	568	561	260	240	259	214	133
23	474	472	476	448	527	564	382	399	389	370	306	534	540	535	229	250	269	223	143
24	465	464	467	443	499	542	381	398	388	368	302	502	511	510	229	257	276	229	150
25	458	458	461	439	466	527	381	397	388	368	304	489	502	499	211	257	245	235	156
26	448	454	456	436	430	509	380	395	387	368	305	444	480	483	219	271	286	241	164
27	441	448	450	432	402	488	379	392	385	367	306	420	460	464	225	276	289	246	171
28	427	438	439	423	380	464	372	388	380	362	302	396	436	442	210	267	232	248	174
29	422	431	432	418	356	439	368	383	376	358	298	*	420	424	205	282	294	252	181
30	413	426	428	415	341	422	366	379	374	357	297	*	404	409	187	201	269	255	186
31	404	418	419	407	322	397	360	373	368	352	294	*	358	377	185	282	270	257	190
32	396	410	411	401	302	382	354	368	362	347	290	*	349	363	200	284	272	260	194
33	387	402	404	394	292	356	350	362	356	342	285	*	316	333	187	285	274	261	198
34	383	397	397	388	275	338	346	357	351	338	281	*	304	328	*	288	295	263	203
35	379	391	392	383	264	324	344	353	346	334	278	*	283	312	*	287	265	265	205
36	368	382	383	375	254	311	337	347	339	327	273	*	275	295	*	285	268	265	207
37	359	376	376	368	240	300	331	342	334	322	269	*	263	282	*	287	286	265	211
38	351	372	370	364	229	289	325	338	330	319	267	*	256	274	*	288	283	266	213
39	349	363	364	357	224	277	321	332	324	313	262	*	245	262	*	287	281	266	214
40	341	358	357	352	215	266	316	327	319	309	259	*	236	254	*	286	280	266	216
41	335	352	352	346	208	255	312	322	314	305	256	*	226	246	*	285	279	265	217
42	330	347	346	341	206	249	309	318	309	300	253	*	219	242	*	282	275	264	217
43	324	341	340	335	197	242	303	313	304	296	250	*	210	227	*	282	275	263	218
44	319	337	336	331	186	235	299	310	301	293	248	*	204	215	*	283	277	264	220
45	314	331	329	325	187	225	295	305	296	288	245	*	199	215	*	279	272	262	219
46	311	327	325	321	180	219	290	302	293	286	244	*	192	204	*	279	272	262	221
47	303	319	318	315	172	215	286	296	287	279	239	*	184	197	*	276	271	260	220
48	297	315	313	310	166	207	281	292	283	276	237	*	178	188	*	276	271	259	220
49	293	309	309	306	158	200	278	288	288	272	234	*	170	183	*	274	268	257	220

(+) T/C Faulty from 29 minutes.
(#) T/C Faulty from 34 minutes.
NOTE :- Web temperatures erratic - Possibly affected by loss of free water / chemical changes occurring in blockwork / cement / steel interface.

TABLE 6 FLANGE AND WEB TEMPERATURES IN BLOCKED-IN COLUMN AGAINST NORTH WALL

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

SECTION : 203 mm x 203 mm x 52 kg/m
NOMINAL Hp/A : ------
COMPONENT IDENTITY : COLUMN (NORTH)
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

	Unexposed Flange		Web	Exposed Flange		
A14	F18	*	W10	*		--- 3675 mm
				*		--- 3300 mm
	F17	*	W9	* F13		--- 3000 mm
A15	F16	*	W8	* F12	A12	--- 2400 mm
	F15	*	W7	* F11		--- 1800 mm
A16	F14	*	W6	* F10	A13	--- 1200 mm

TIME	STEEL AND ATMOSPHERE TEMPERATURES (deg C)																		
	EXPOSED FLANGE						UNEXPOSED FLANGE								WEB				
(mins)	F10	F11	F12	F13	A13	A12	F14	F15	F16	F17	F18	A16	A15	A14	W6	W7	W8	W9	W10
0	9	9	9	9	12	12	9	9	9	9	9	12	13	13	9	9	9	9	9
1	12	11	12	13	54	76	13	10	11	11	20	54	68	72	9	9	9	9	9
2	32	27	28	29	295	352	36	17	24	21	70	270	325	324	8	9	9	9	9
3	68	55	60	49	495	515	71	32	39	38	124	415	483	486	8	9	9	10	9
4	107	89	90	74	564	567	96	51	59	58	149	478	537	528	13	13	11	12	10
5	140	120	119	113	584	586	115	70	77	79	161	509	553	533	18	18	13	17	13
6	170	150	146	148	587	610	136	94	118	108	185	536	574	557	26	26	18	25	16
7	197	176	169	172	605	613	155	123	139	129	202	514	586	572	38	35	23	35	20
8	223	202	192	195	617	612	174	143	158	149	217	501	600	589	53	46	31	45	26
9	245	225	213	216	621	621	191	163	176	168	229	499	601	590	68	59	40	56	33
10	268	240	234	236	620	626	208	182	194	186	240	488	604	588	83	72	51	66	41
11	291	271	254	257	628	633	226	201	213	203	253	484	613	598	94	86	76	79	48
12	314	294	276	278	635	644	244	220	233	220	262	485	625	604	106	100	100	94	56
13	336	318	298	300	649	659	262	240	252	239	275	479	639	613	122	114	102	106	65
14	359	341	320	321	672	670	282	260	272	259	283	501	645	617	135	128	102	120	75
15	382	365	342	342	682	681	303	282	293	277	295	499	665	629	147	143	103	137	86
16	404	389	364	365	690	694	323	305	314	295	306	507	676	638	160	156	104	148	95
17	430	415	387	386	706	702	347	329	337	317	318	531	693	654	174	170	122	162	101
18	452	437	406	404	701	695	367	352	357	336	332	536	680	649	188	184	134	174	111
19	469	453	422	420	684	684	383	370	372	351	337	519	667	645	201	197	145	186	122
20	483	466	435	432	681	669	395	386	385	364	338	505	649	644	215	209	156	198	131
21	489	472	442	439	626	633	400	395	392	372	337	485	624	610	228	221	166	209	140
22	487	474	445	442	593	598	402	401	396	378	335	477	592	572	240	232	177	218	148
23	486	473	445	443	552	567	402	404	398	380	332	449	557	541	249	242	188	227	157
24	481	470	443	442	509	546	399	404	398	380	329	406	528	518	257	250	198	235	164
25	475	466	441	440	471	530	395	403	397	379	326	377	510	496	263	258	207	242	171
26	468	462	439	438	435	513	390	401	396	378	327	357	493	486	268	264	215	248	178
27	460	457	435	435	414	495	385	399	394	377	324	335	480	469	273	270	222	253	184
28	451	451	431	431	392	473	378	395	390	374	322	320	454	451	279	274	228	258	189
29	443	445	426	426	377	453	372	391	387	371	317	304	436	431	282	278	233	261	194
30	436	439	422	422	358	434	368	387	384	368	314	289	412	409	283	281	238	265	199
31	428	432	416	417	337	415	363	382	379	365	311	278	379	391	286	284	242	267	204
32	420	426	411	412	319	397	358	377	374	360	307	287	341	367	287	285	245	269	208
33	412	419	406	406	299	382	352	372	370	356	302	266	328	352	286	287	249	270	212
34	405	413	400	401	290	365	347	367	364	350	299	271	306	333	287	287	252	270	216
35	396	406	395	396	274	353	341	362	360	347	295	264	290	318	288	289	254	271	219
36	389	400	389	390	251	338	335	357	354	343	269	249	274	298	288	289	256	271	222
37	382	393	384	385	232	324	329	351	349	337	285	230	258	291	286	289	258	270	224
38	375	387	379	380	237	313	324	347	344	333	282	230	253	280	285	290	260	271	227
39	367	381	373	374	226	301	320	342	339	328	277	229	242	264	284	289	261	271	228
40	360	375	368	369	218	295	314	336	334	324	272	220	233	252	283	289	261	271	230
41	355	370	363	364	212	283	310	332	330	320	268	216	228	244	282	288	262	270	231
42	349	364	358	358	211	272	306	327	324	316	264	219	221	234	280	287	262	270	232
43	343	358	353	353	190	264	301	322	320	312	261	204	212	229	278	286	262	270	233
44	338	352	348	348	178	260	297	318	316	307	257	212	207	219	277	285	262	269	234
45	332	346	343	343	180	251	293	313	310	303	253	219	201	210	275	284	262	268	234
46	327	341	338	338	173	244	288	309	306	298	250	211	197	204	273	283	262	267	235
47	321	336	333	333	166	237	285	304	302	295	245	207	192	196	273	281	261	266	235
48	315	331	328	328	167	229	281	301	298	291	242	209	188	190	271	280	261	265	235
49	311	325	324	323	160	222	277	296	294	287	238	202	183	183	269	278	260	264	235

TABLE 7 TEMPERATURES MEASURED IN BOLTS OF EACH CONNECTION

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

COMPONENT IDENTITY : BOLTS
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

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      **                          **
TH    B1                          B1   TH
TT    B2                          B2   TT
      *************************
BH    B3                          B3   BH
BT    B4                          B4   BT
      **                          **
Back Column               Front Column
 (North)                    (South)
```

TIME	STEEL TEMPERATURES (deg C)							
	NORTH				SOUTH			
(mins)	B1	B2	B3	B4	B1	B2	B3	B4
0	10	10	11	10	9	9	9	9
1	11	10	11	10	9	9	10	9
2	23	11	21	11	16	10	21	11
3	40	17	37	17	29	15	38	16
4	56	25	50	28	42	23	52	25
5	72	34	65	40	57	32	71	36
6	92	45	85	54	73	41	88	47
7	108	57	102	70	90	54	105	62
8	120	71	118	88	106	67	123	75
9	133	84	135	103	120	77	139	89
10	157	95	154	119	136	89	157	103
11	178	109	171	133	153	101	174	117
12	199	122	189	149	169	114	191	133
13	217	133	210	165	185	126	209	146
14	233	145	225	181	199	137	226	160
15	250	160	241	192	216	152	243	177
16	267	173	258	205	230	163	260	190
17	284	187	275	224	246	178	277	207
18	299	200	292	239	260	189	294	220
19	315	213	308	257	274	202	310	236
20	327	225	322	272	283	213	321	249
21	337	237	334	286	293	224	331	261
22	345	247	344	298	303	233	341	272
23	350	256	351	309	310	243	348	283
24	353	263	357	317	314	249	352	291
25	356	271	362	325	316	256	355	299
26	358	276	365	331	320	262	359	306
27	358	281	367	336	322	267	361	311
28	358	284	369	339	322	270	359	316
29	357	286	370	342	322	273	361	320
30	356	289	370	345	323	276	361	323
31	354	290	370	347	322	278	360	325
32	351	291	369	347	321	279	359	327
33	348	292	368	349	320	280	358	329
34	345	291	366	348	318	281	356	330
35	343	293	365	349	318	282	356	330
36	339	291	362	348	315	281	352	330
37	335	290	359	346	312	280	350	330
38	332	290	357	346	310	281	347	330
39	327	288	354	343	307	279	344	328
40	324	288	352	342	305	278	341	326
41	321	286	349	340	302	277	338	325
42	317	285	345	337	300	275	335	323
43	313	283	342	334	297	274	332	321
44	310	281	338	332	295	273	330	319
45	306	280	334	329	292	271	326	317
46	303	279	331	325	290	271	324	316
47	297	276	327	323	286	268	319	312
48	294	274	324	320	283	267	316	309
49	290	272	320	317	280	265	313	307

TABLE 8 TEMPERATURES IN INDICATIVE COLUMN

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

SECTION : 203 mm x 203 mm x 52 kg/m
NOMINAL Hp/A : 180 /m
COMPONENT IDENTITY : COLUMN (INDICATIVE)
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

```
*           *
1           *
*           *
*           *
* * * 3 * * *
*           *
*           *
*           2
*           *
```

TIME (mins)	STEEL TEMPERATURES (deg C) 1500mm LEVEL 1	2	3
0	10	10	11
1	13	17	16
2	39	62	54
3	89	121	117
4	146	183	171
5	209	241	231
6	264	295	285
7	313	348	334
8	362	394	379
9	402	438	421
10	442	473	456
11	477	509	490
12	508	539	519
13	534	563	544
14	565	594	569
15	589	616	597
16	614	637	617
17	632	666	641
18	648	681	656
19	655	685	662
20	666	683	668
21	662	678	665
22	649	665	648
23	648	654	647
24	631	641	620
25	621	627	611
26	609	611	604
27	593	596	566
28	579	579	586
29	563	564	548
30	548	547	532
31	532	532	517
32	518	519	503
33	504	504	439
34	491	490	523
35	478	476	487
36	467	463	452
37	454	450	427
38	442	438	419
39	430	426	410
40	420	415	401
41	409	404	392
42	399	395	392
43	389	385	373
44	380	374	367
45	372	366	364
46	362	355	354
47	353	348	344
48	344	338	334
49	336	330	327

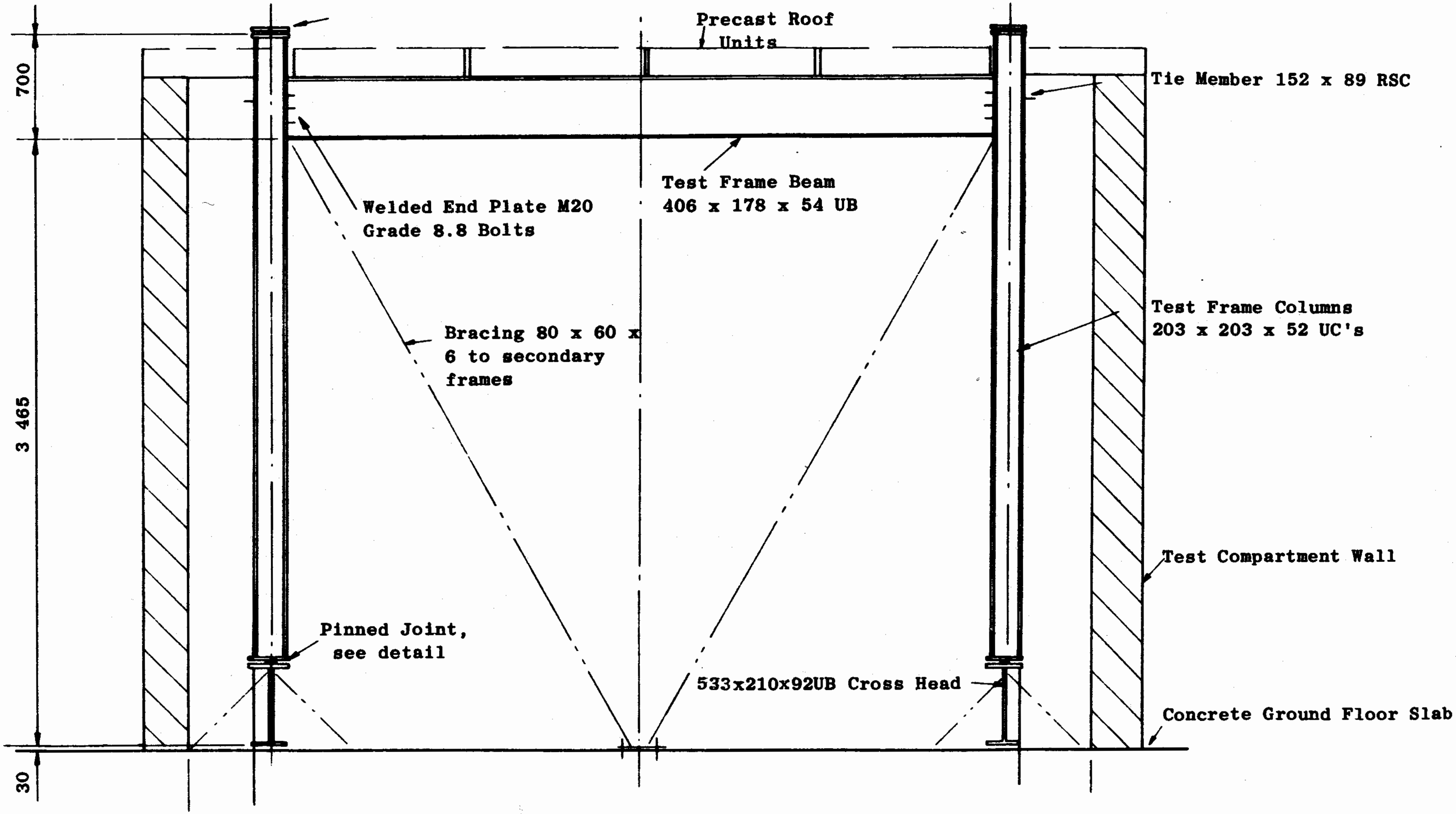
TABLE 9 TEMPERATURES IN EXTERNAL COLUMN

TRIAL NUMBER : 22
TRIAL DATE : 24th OCTOBER 1985
SITE : FRS CARDINGTON

SECTION : 203 mm x 203 mm x 52 kg/m
NOMINAL Hp/A : 180 /m
COMPONENT IDENTITY : EXTCOL
FIRE LOAD : 20 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

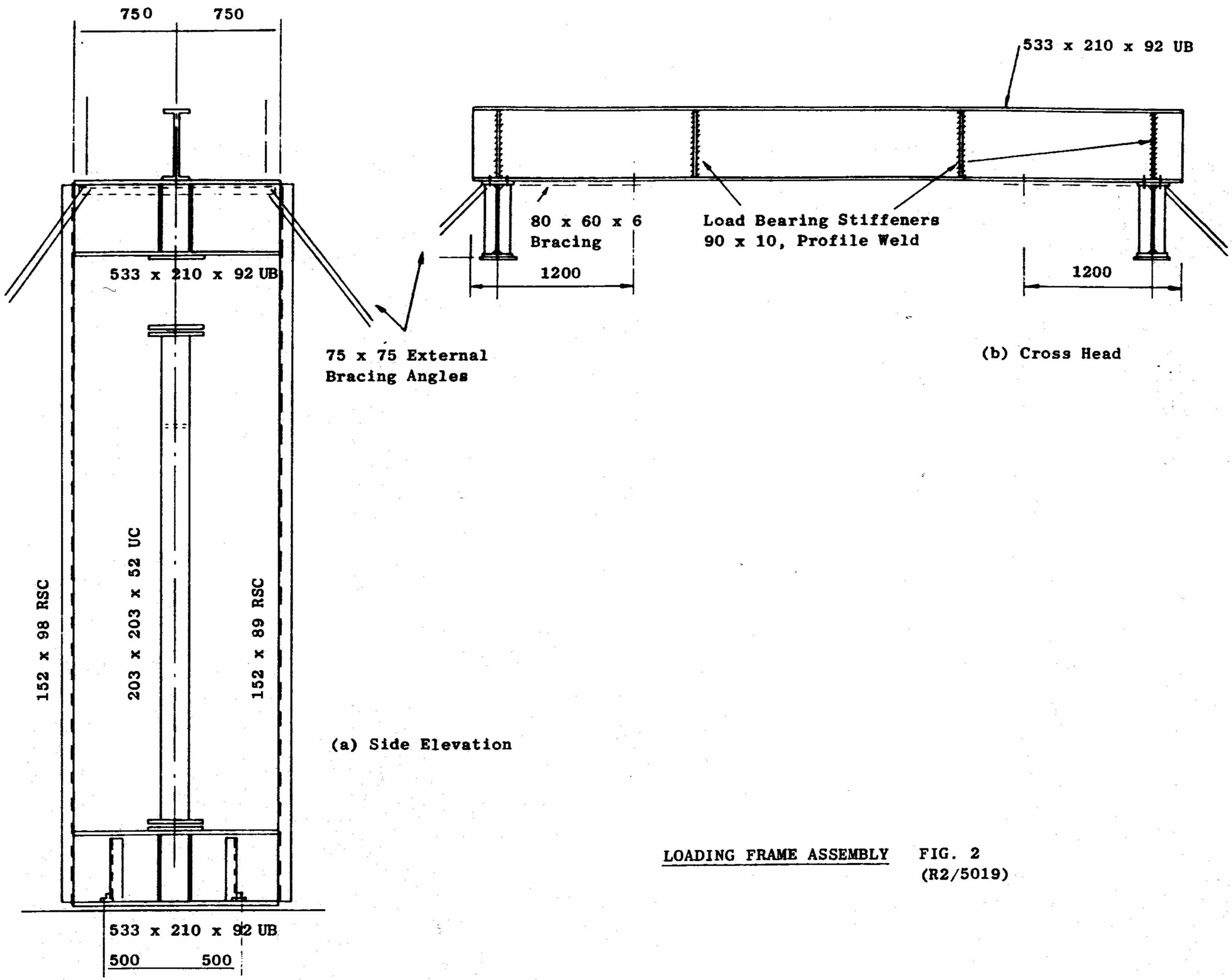
```
U  *             *
N  1             *  E
E  *             *  X
X  *             *  P
P  2 * * 3 * *   4  O
O  *             *  S
S  *             *  E
E  *             5  D
D  *             *
```

TIME (mins)	STEEL AND ATMOSPHERE TEMPERATURES (deg C)					
	3300mm LEVEL			1900mm LEVEL		
	1	3	5	3	5	ATM
0	13	12	12	12	12	13.0
1	12	13	12	12	12	14.0
2	13	20	17	12	14	27.0
3	18	32	22	13	20	48.0
4	24	45	28	14	26	70.0
5	31	60	35	17	35	80.0
6	36	75	41	20	43	83.0
7	40	88	47	22	51	83.0
8	47	100	55	26	59	97.0
9	50	111	60	28	66	97.0
10	55	122	66	33	75	104.0
11	59	130	72	36	82	107.0
12	62	140	76	40	89	110.0
13	66	149	83	44	97	110.0
14	69	157	88	47	104	114.0
15	74	166	94	52	113	111.0
16	78	173	98	56	121	115.0
17	82	182	103	60	129	118.0
18	85	187	108	64	136	122.0
19	88	191	110	68	142	115.0
20	91	194	114	72	147	100.0
21	93	194	116	75	150	99.0
22	95	192	117	77	152	90.0
23	96	190	118	80	154	97.0
24	96	187	117	82	154	87.0
25	96	184	117	84	155	80.0
26	94	181	116	85	154	74.0
27	94	178	115	87	153	67.0
28	93	175	114	88	152	67.0
29	92	171	113	88	150	57.0
30	91	168	112	88	148	53.0
31	90	164	110	88	146	55.0
32	89	161	109	88	144	55.0
33	87	157	107	88	141	55.0
34	86	153	105	88	139	50.0
35	86	150	104	88	137	48.0
36	85	147	103	87	135	51.0
37	83	143	100	86	132	48.0
38	82	140	99	85	130	44.0
39	81	136	97	84	127	43.0
40	80	133	96	83	125	43.0
41	79	130	94	83	122	39.0
42	79	128	93	83	121	37.0
43	77	125	91	81	117	35.0
44	76	122	90	79	115	38.0
45	75	120	89	80	114	37.0
46	74	117	87	79	111	35.0
47	73	114	85	77	109	35.0
48	72	111	84	76	106	33.0
49	71	109	82	75	104	30.0

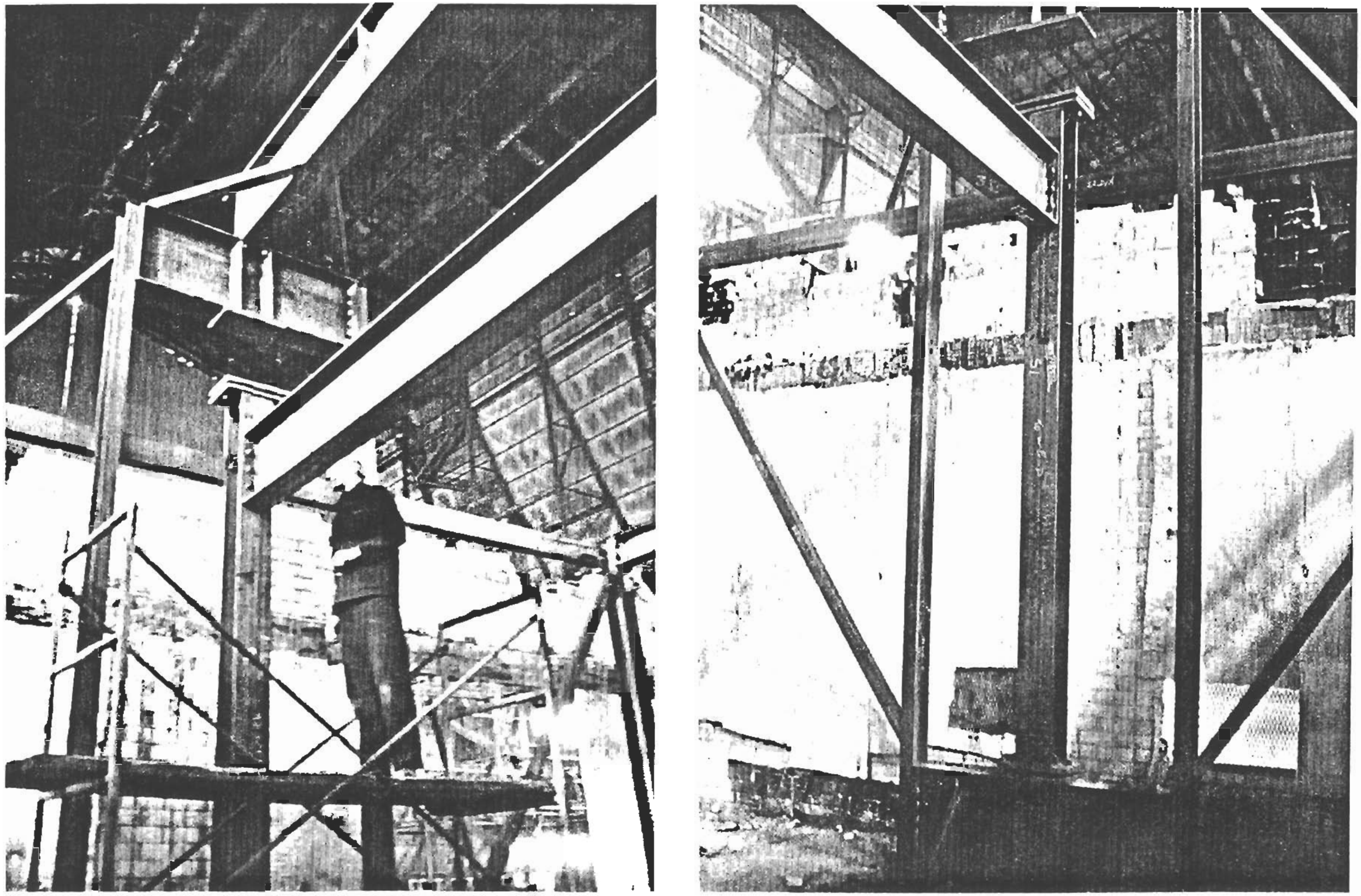


TEST FRAME - FRONT ELEVATION

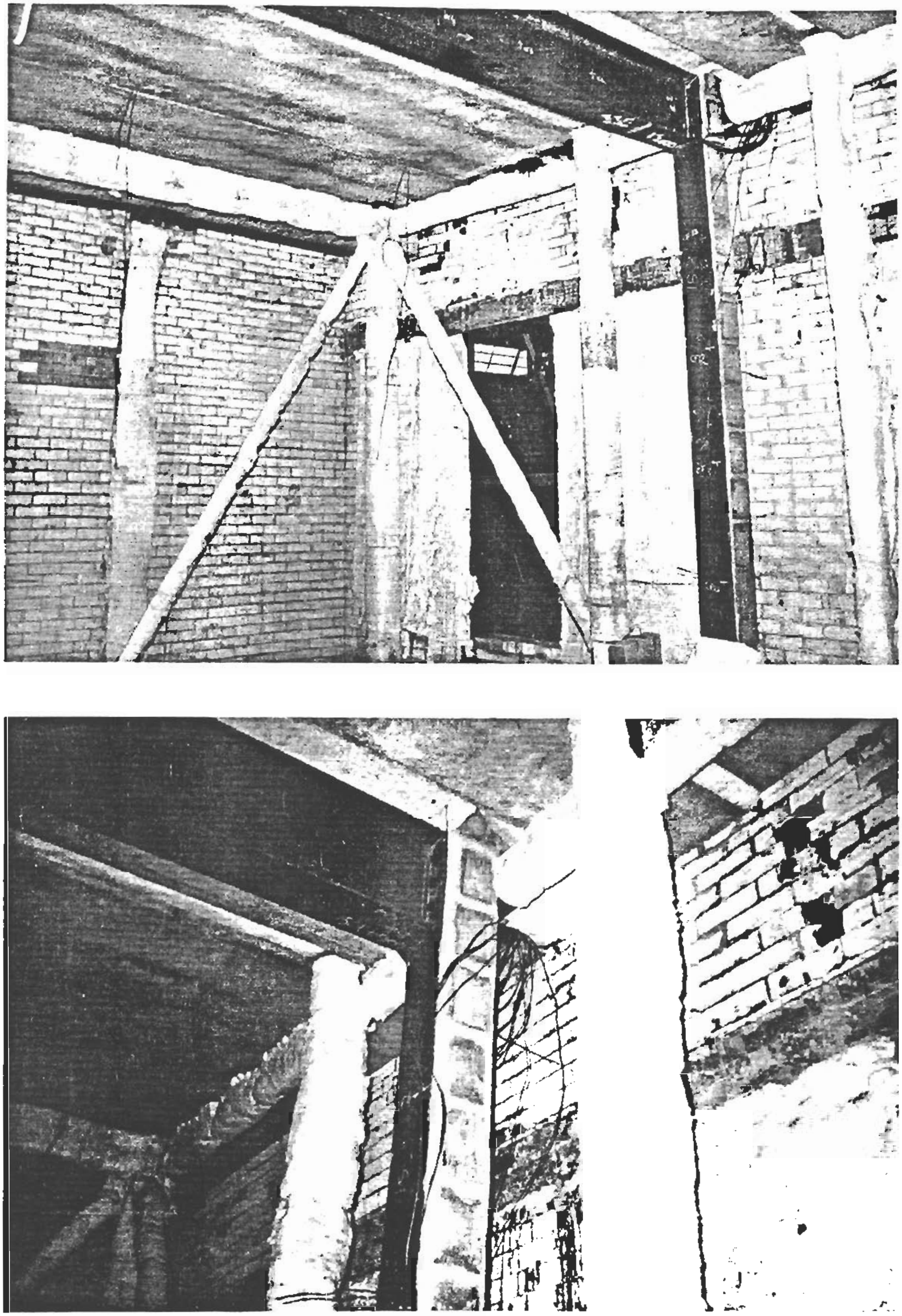
FIG. 1
(R2/5018)



LOADING FRAME ASSEMBLY FIG. 2
(R2/5019)

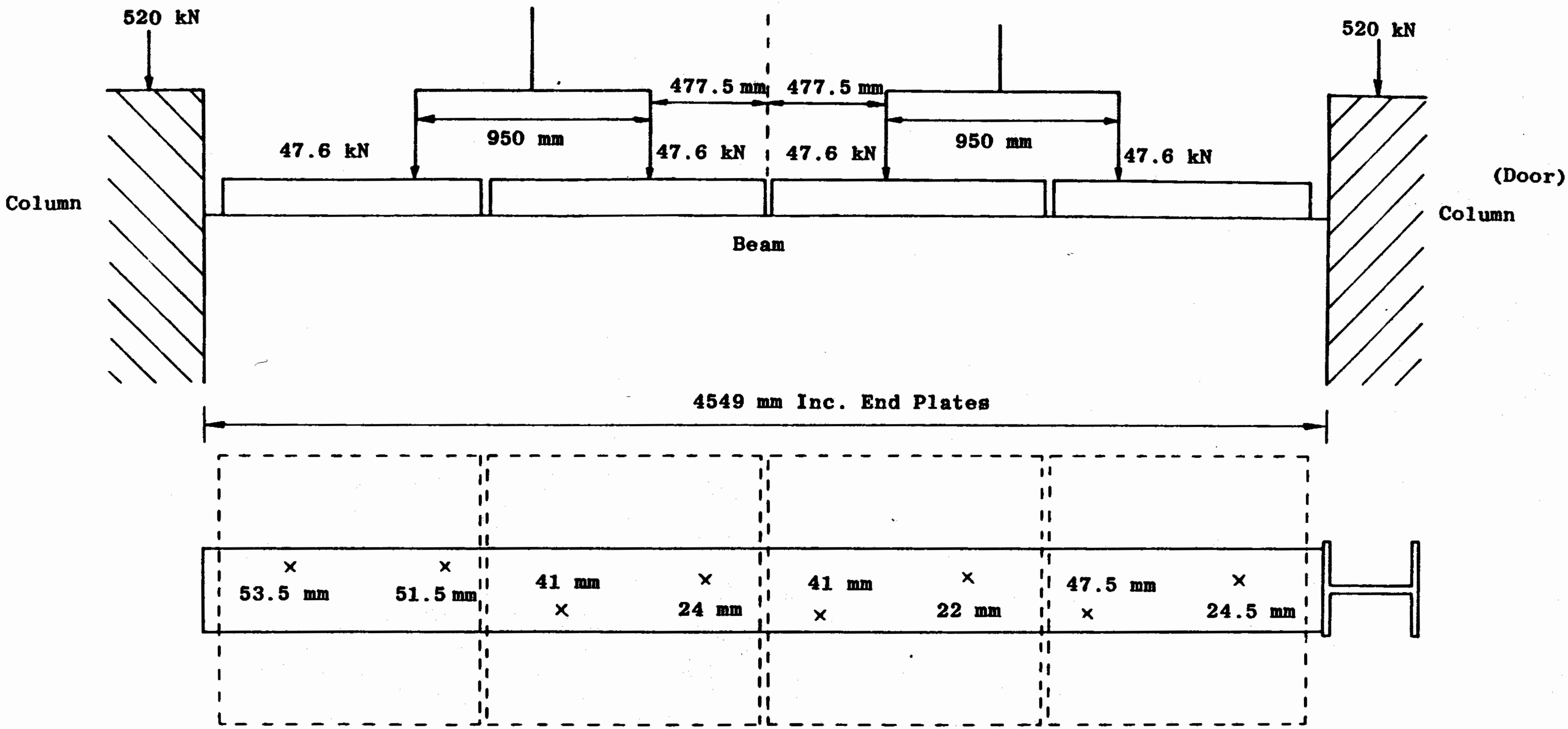


ERECTION OF TEST FRAME AND LOADING ASSEMBLY FIG. 3

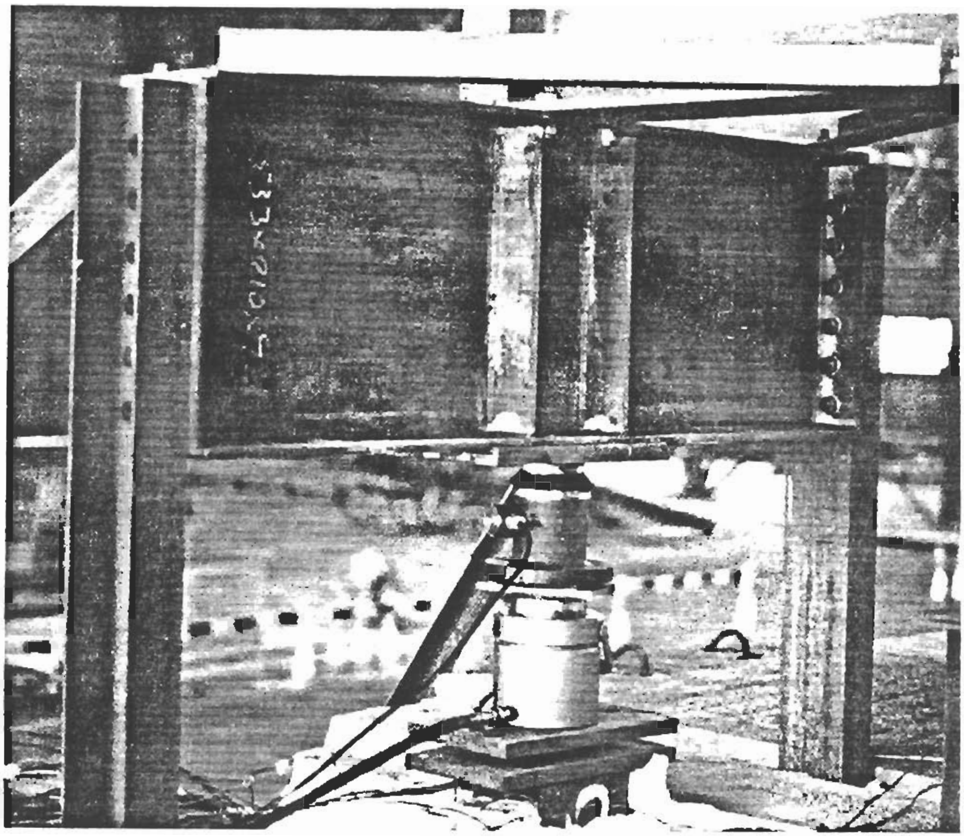


LOADING AND SECONDARY STEEL FRAME LAGGED WITH CERAMIC FIBRE BLANKET

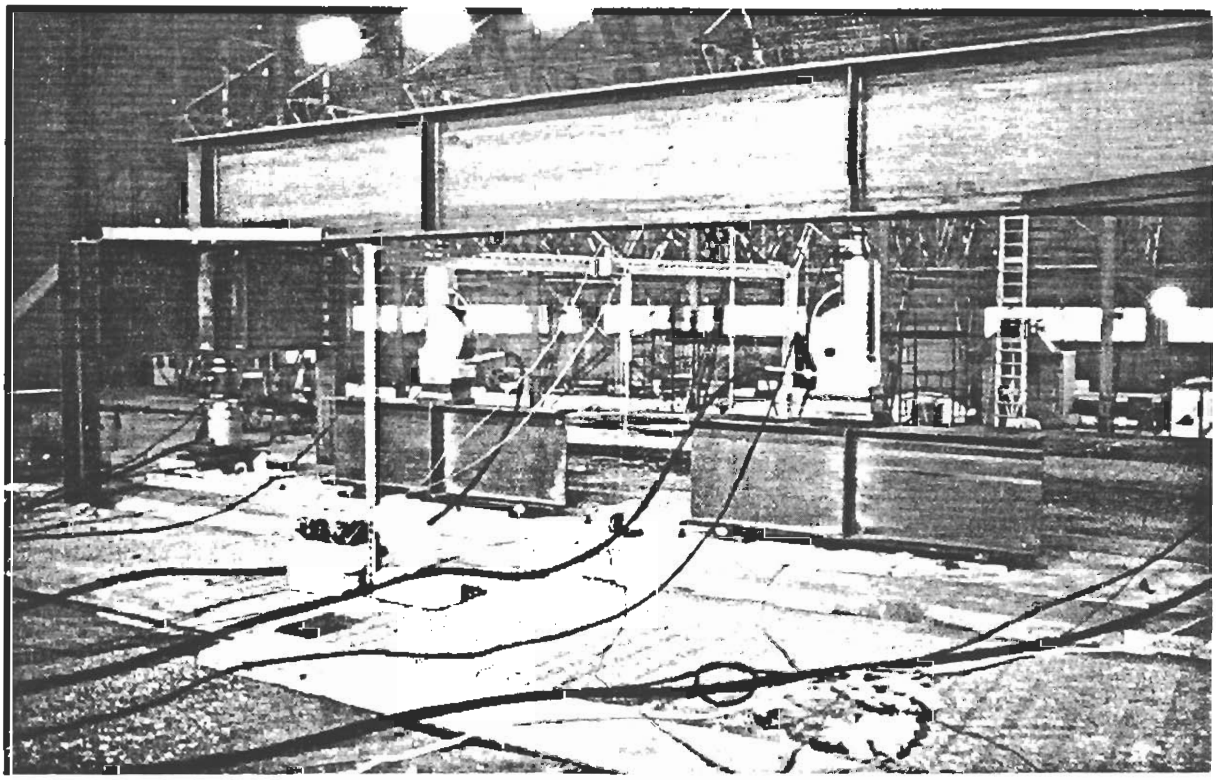
FIG. 4



<u>SCHEMATIC REPRESENTATION OF LOADING POINTS</u> FIG. 5
(R2/5020)

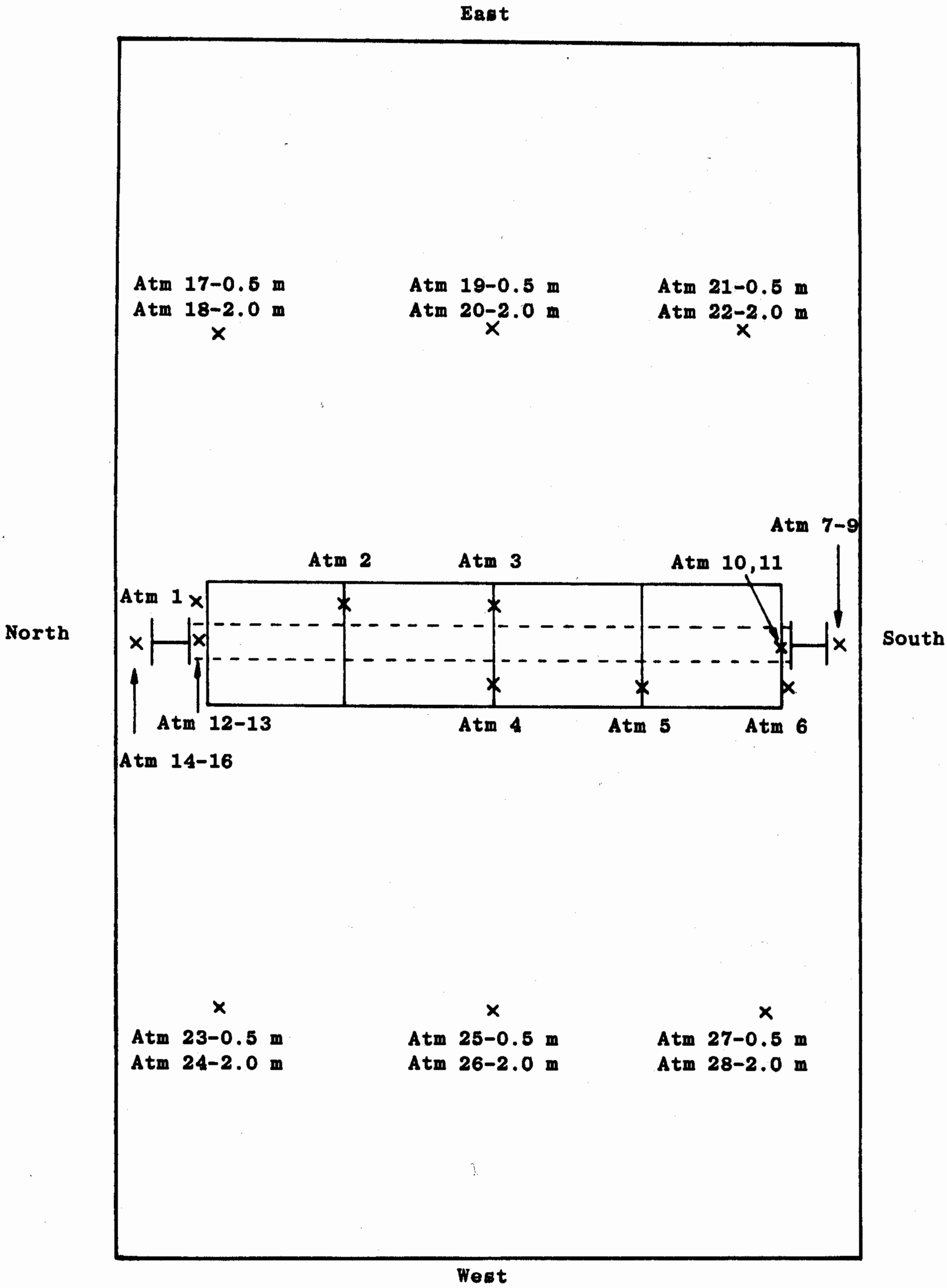


Column



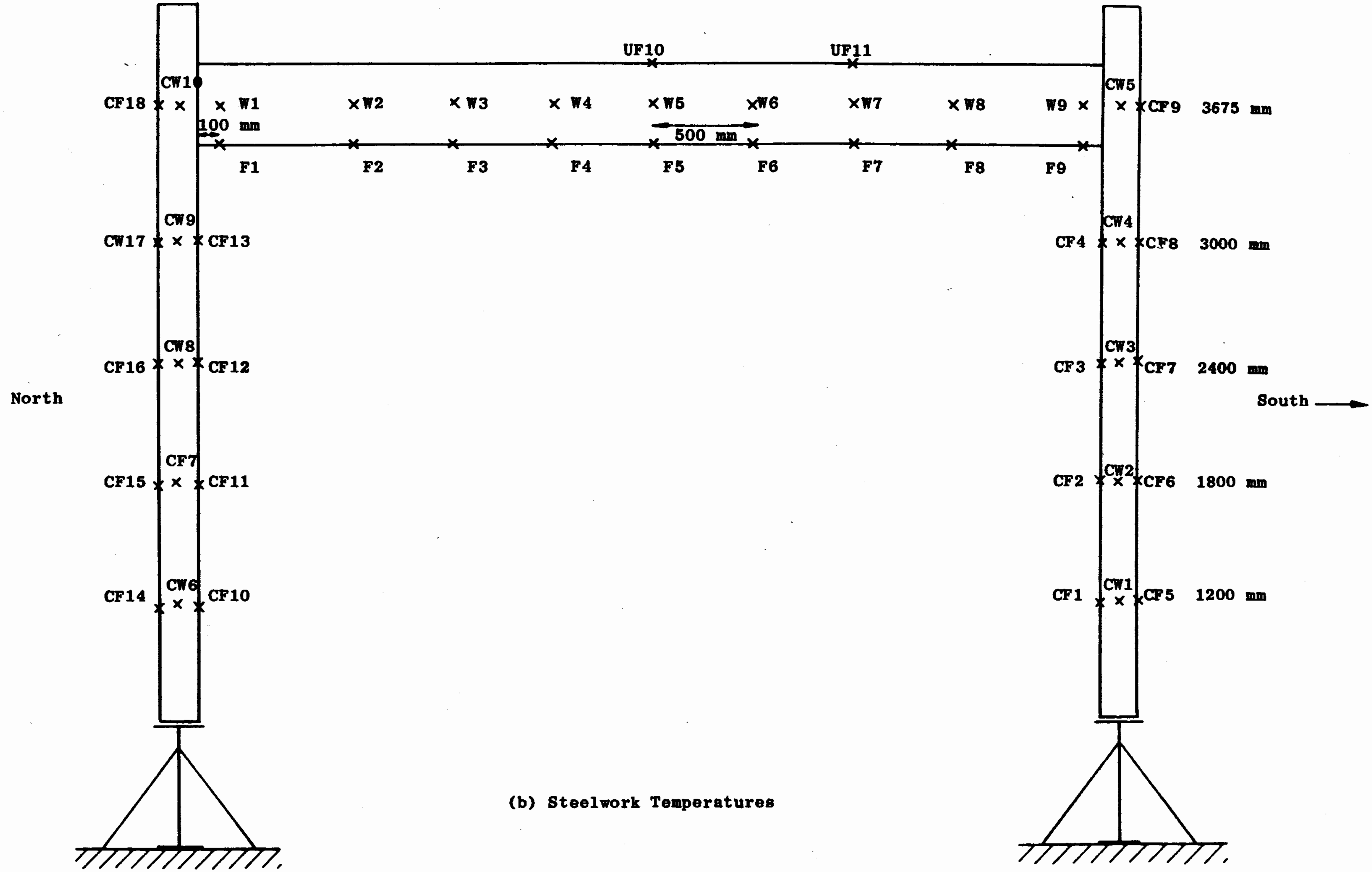
Beam

LOADING ARRANGEMENT USED IN FIRE TEST FIG. 6



(a) Combustion Gas Temperatures

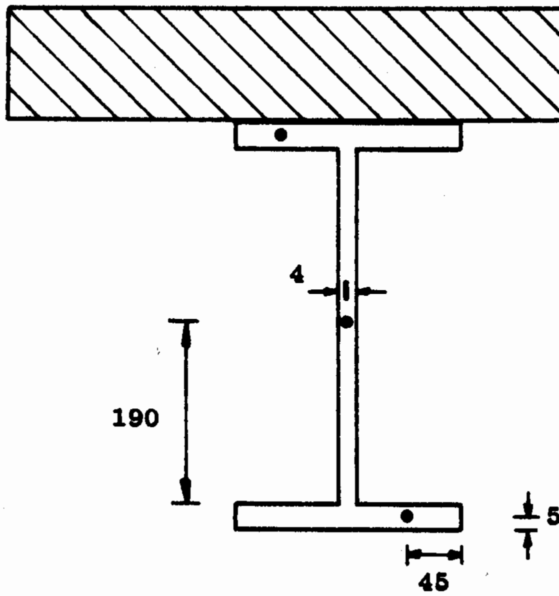
<u>POSITION OF THERMOCOUPLES IN COMPARTMENT</u> FIG. 7
(R2/5021)



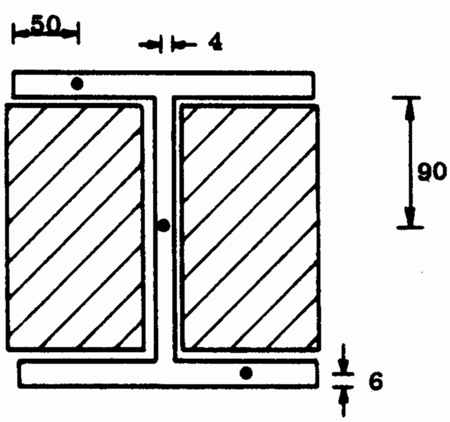
(b) Steelwork Temperatures

POSITION OF THERMOCOUPLES IN COMPARTMENT FIG. 7 (Continued)
(R2/5022)

Dimensions in mm



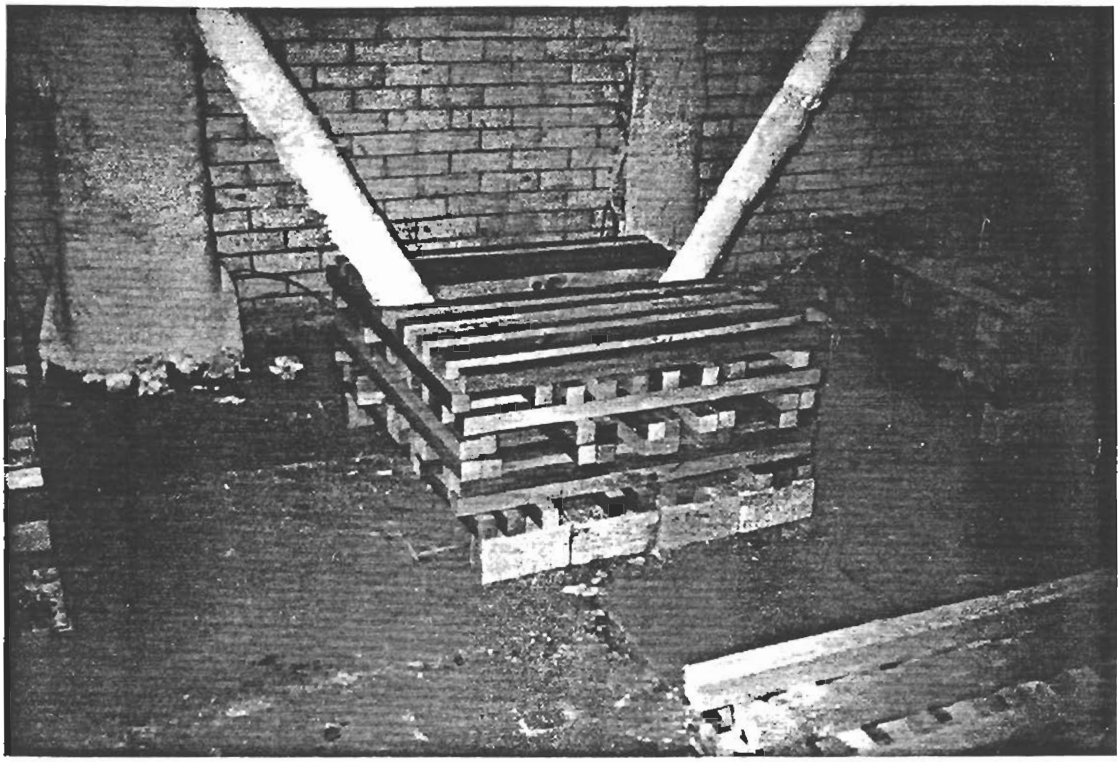
406 x 178 mm x 54 kg/m Universal Beam

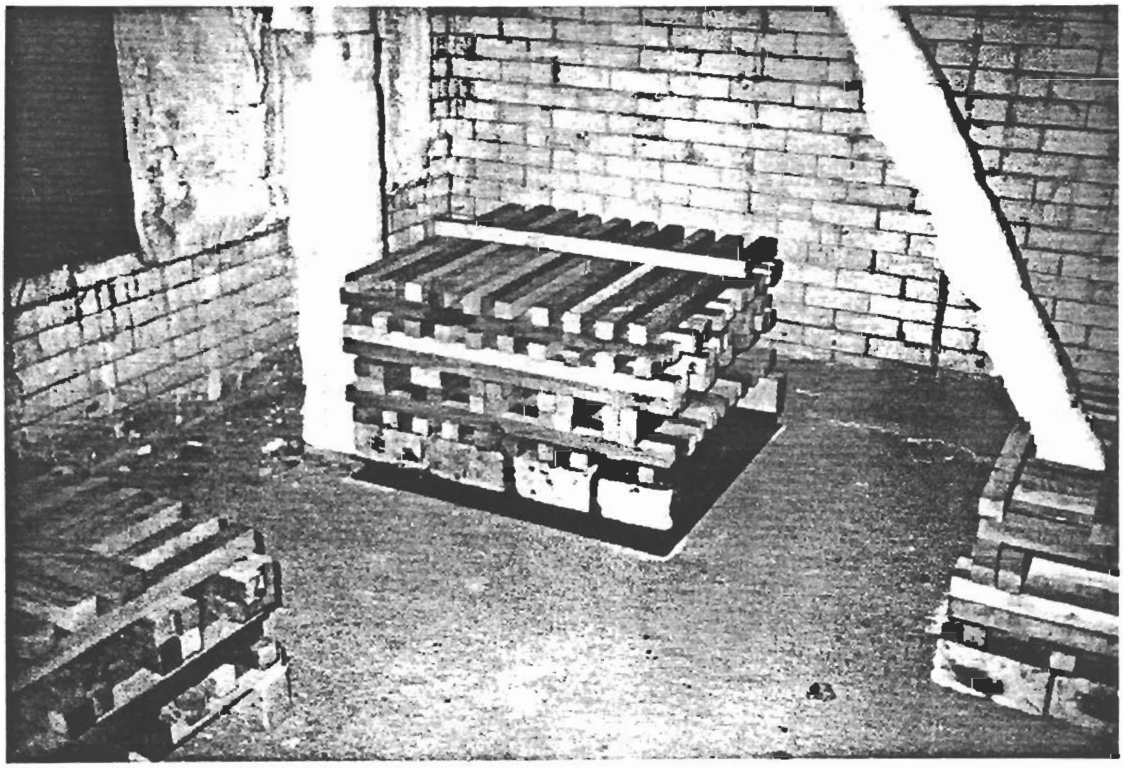


203 x 203 mm x 52 kg/m Universal Beam

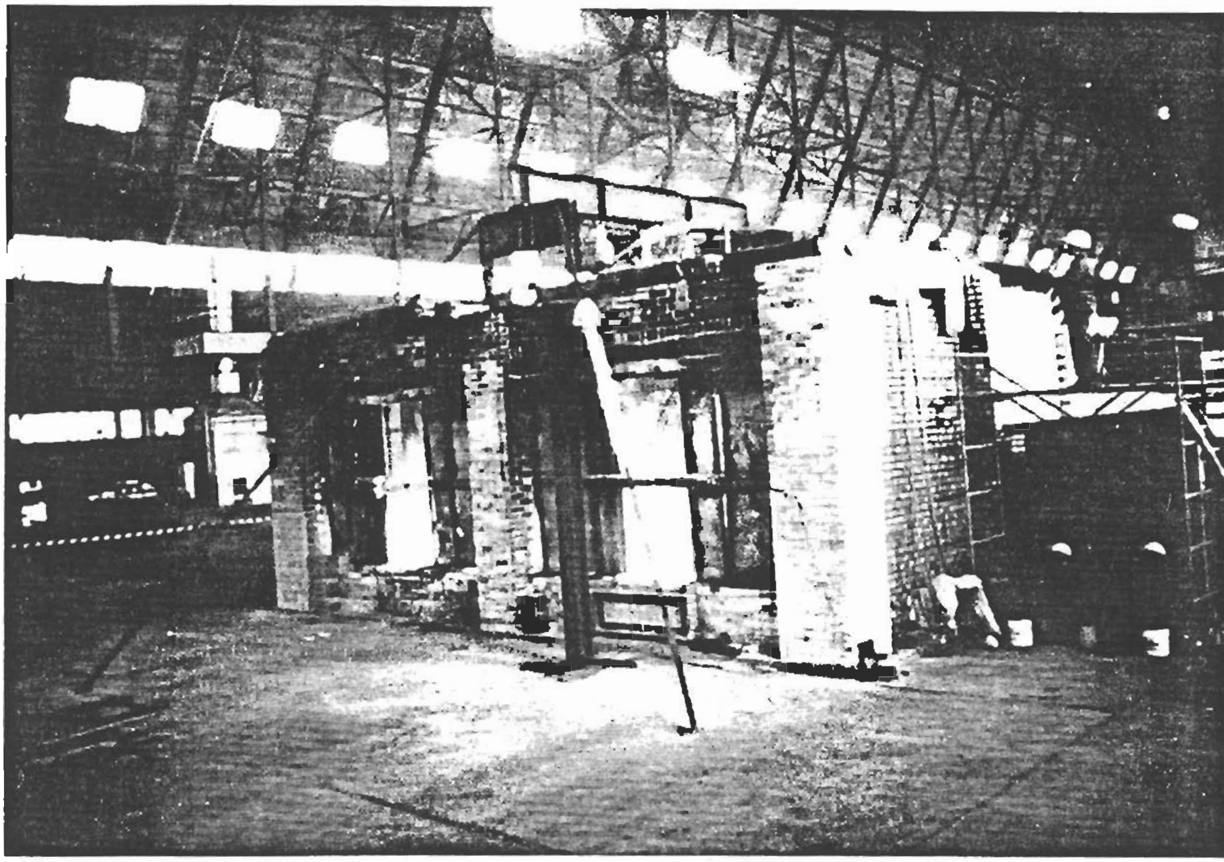
(c) Location of Thermocouples in Steelwork

POSITION OF THERMOCOUPLES IN COMPARTMENT FIG 7 (Continued)
(R2/5023)

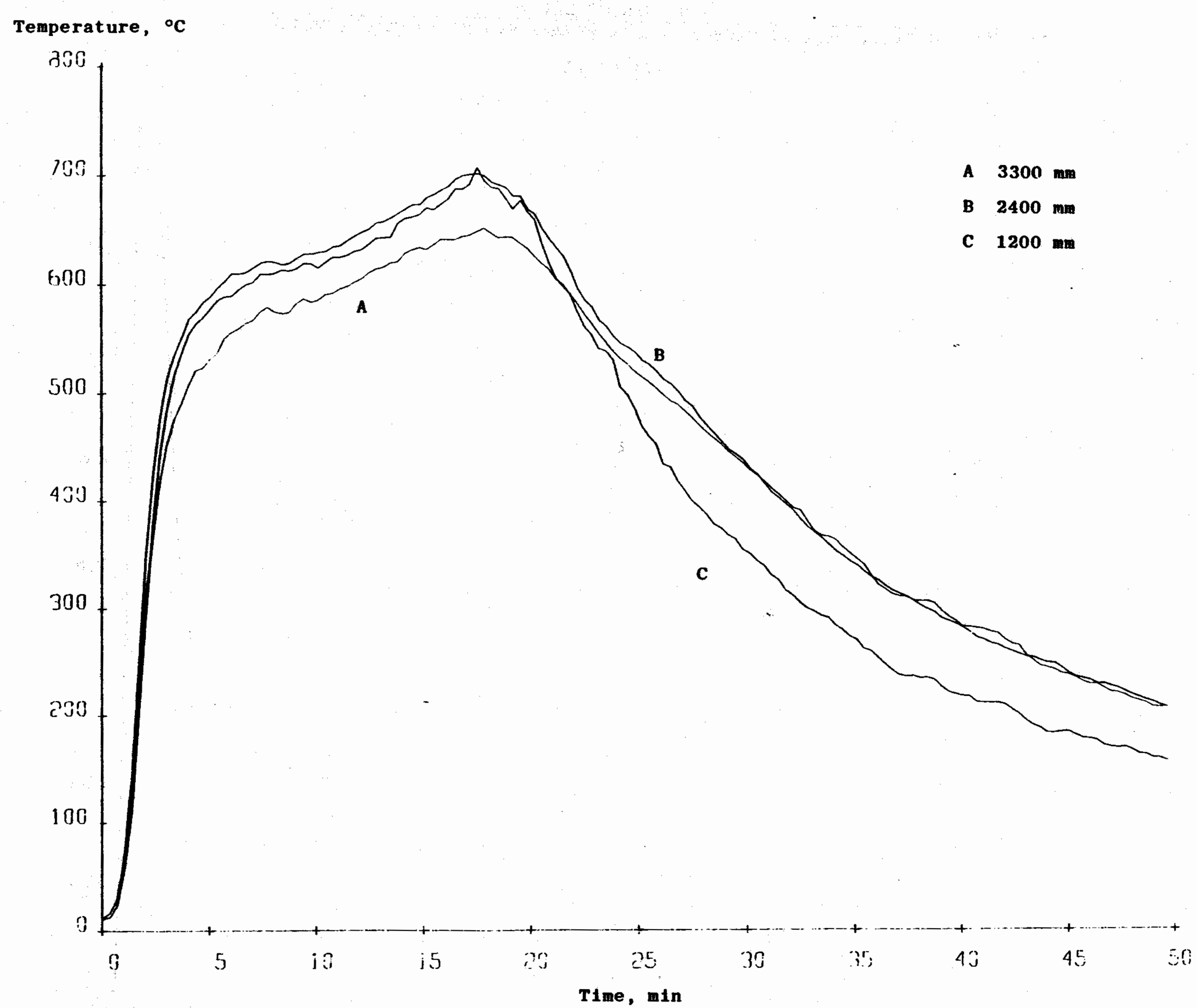




CRIB ASSEMBLY USED IN FIRE TEST   FIG. 8

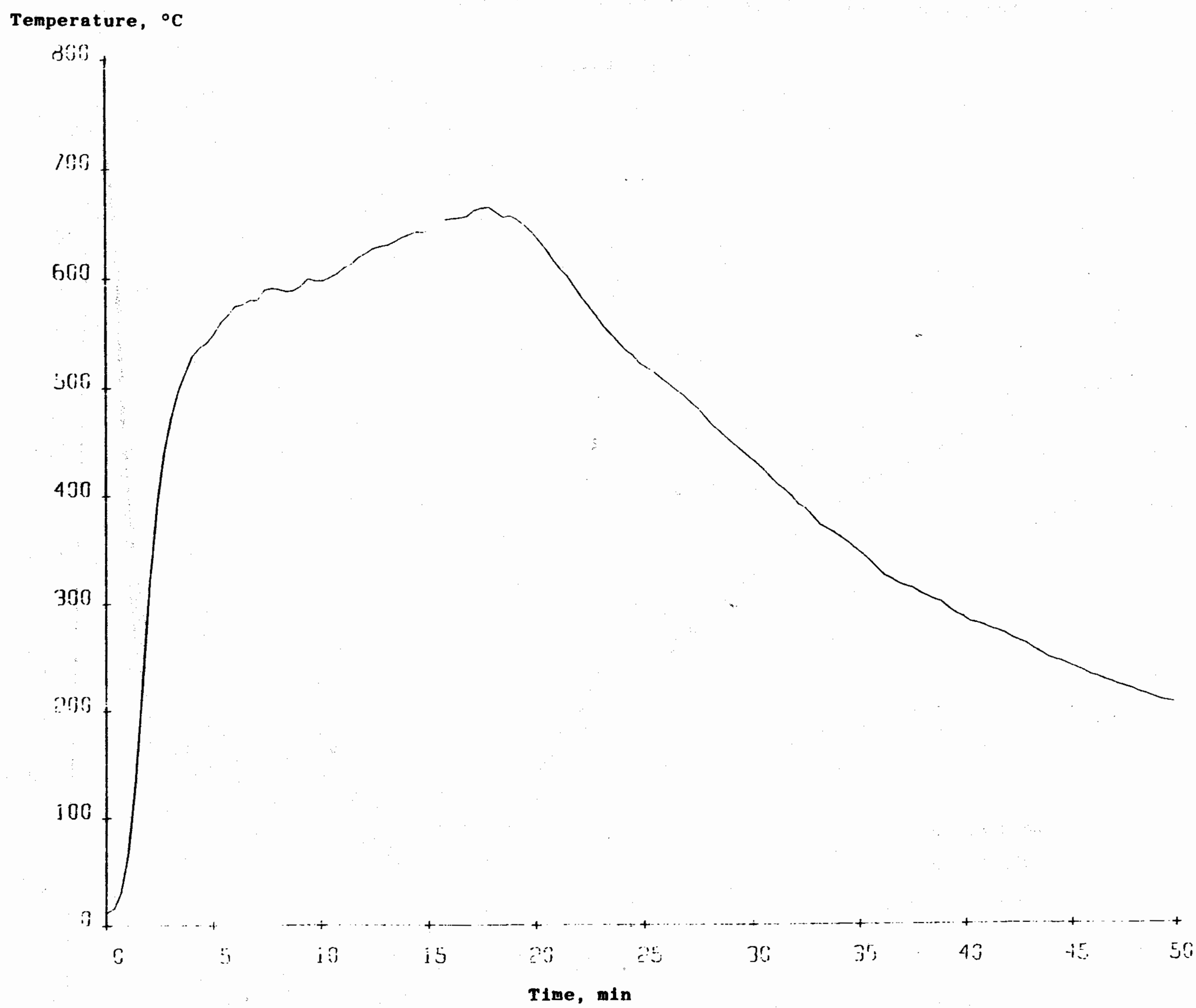


FIRE TEST IN PROGRESS FIG. 9



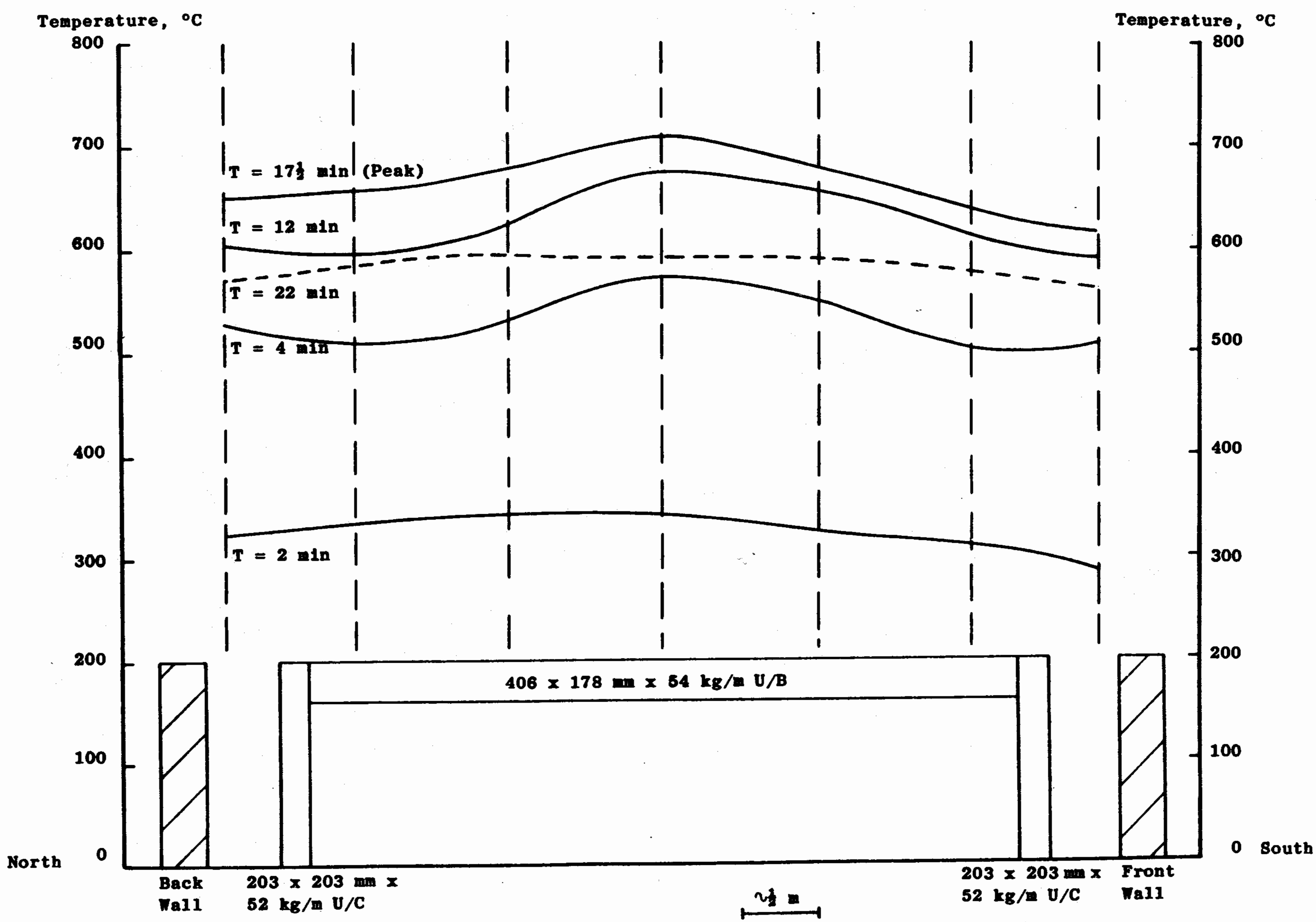
CHANGE IN COMBUSTION GAS TEMPERATURE WITH HEIGHT IN VICINITY OF COLUMNS

FIG. 10



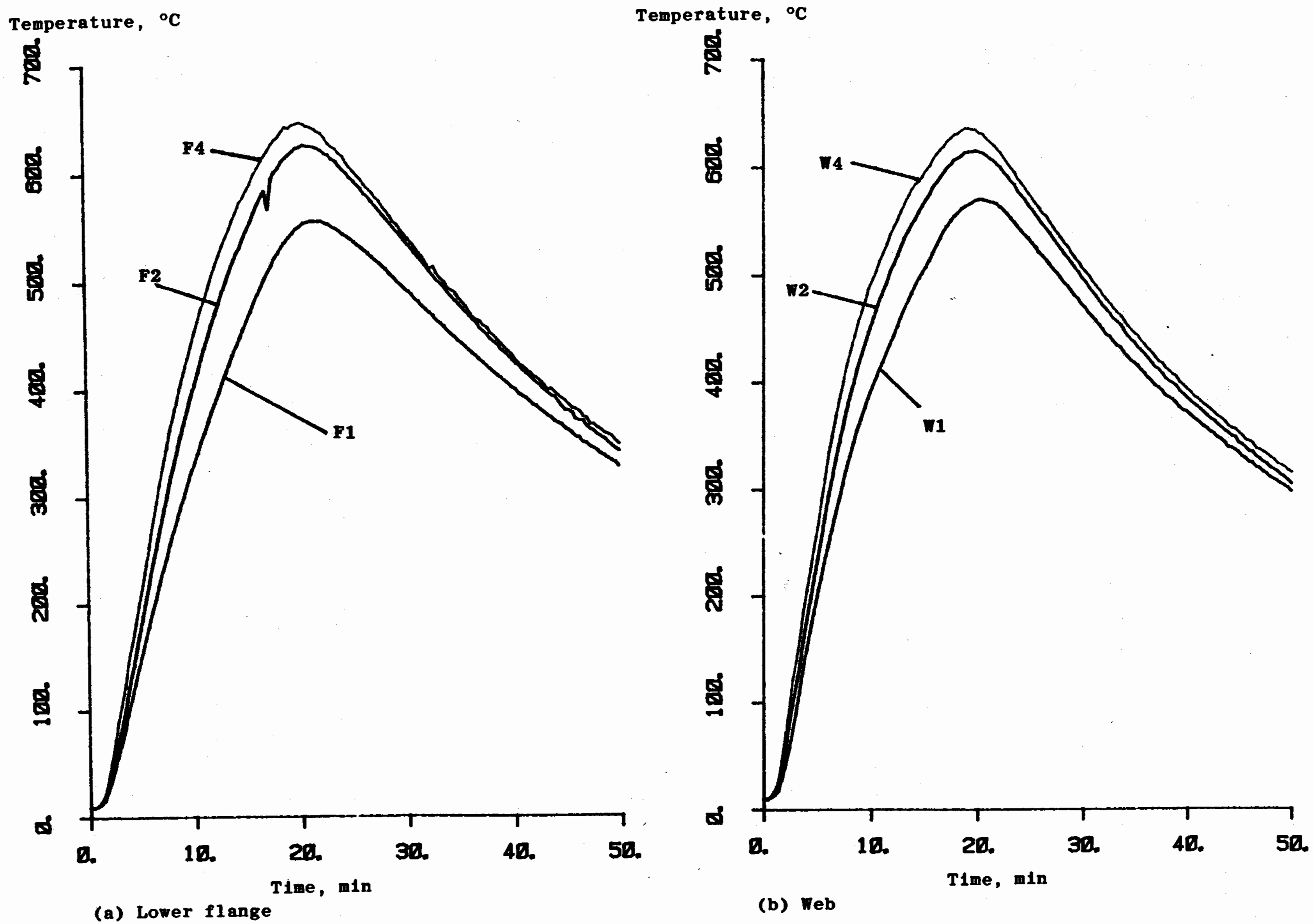
AVERAGE COMBUSTION GAS TEMPERATURE RECORDED IN THE VICINITY OF THE LOADED BEAM

FIG. 11



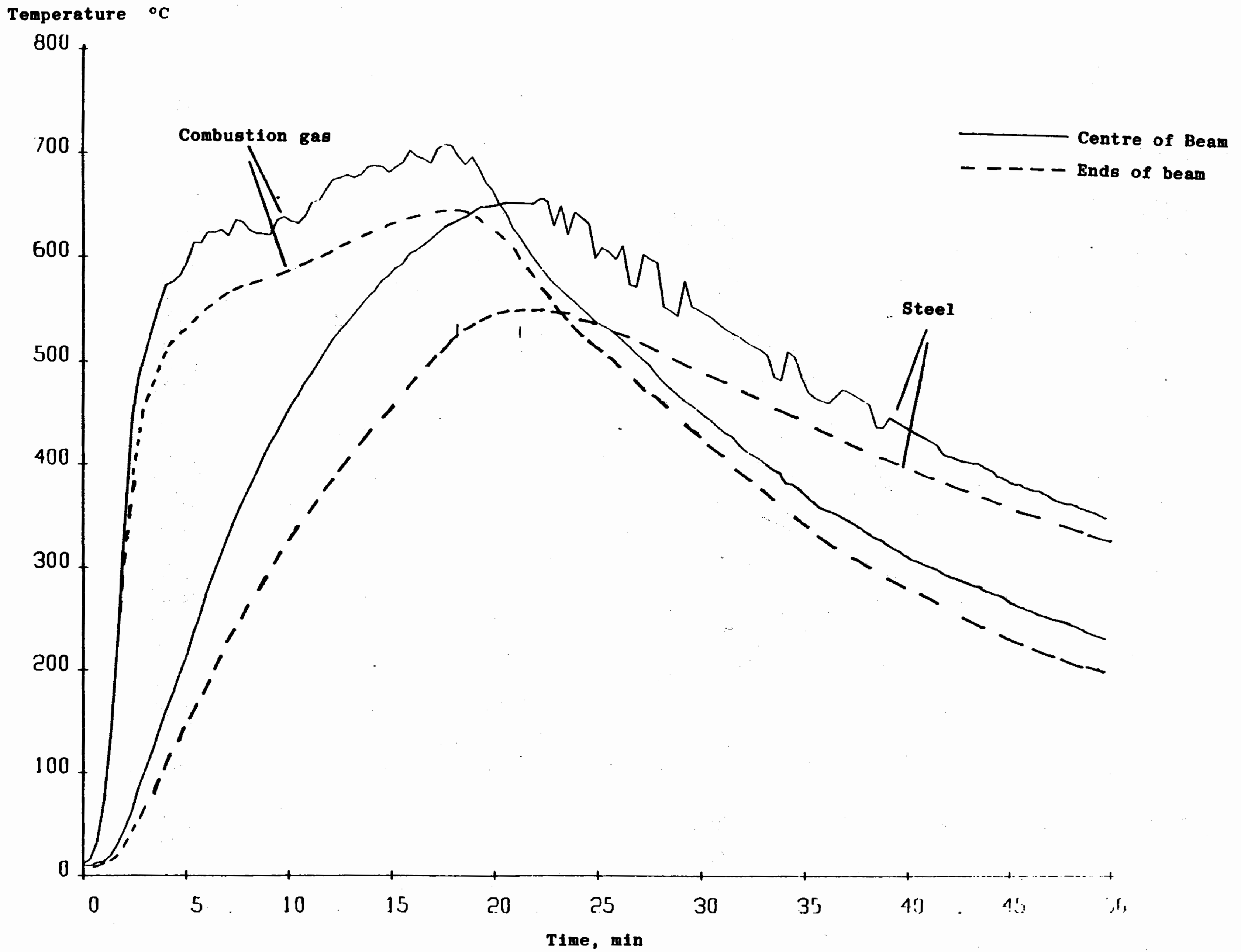
COMBUSTION GAS TEMPERATURE PATTERNS ESTABLISHED IN THE VICINITY OF THE LOADED STRUCTURE

FIG. 12
(R2/5024)

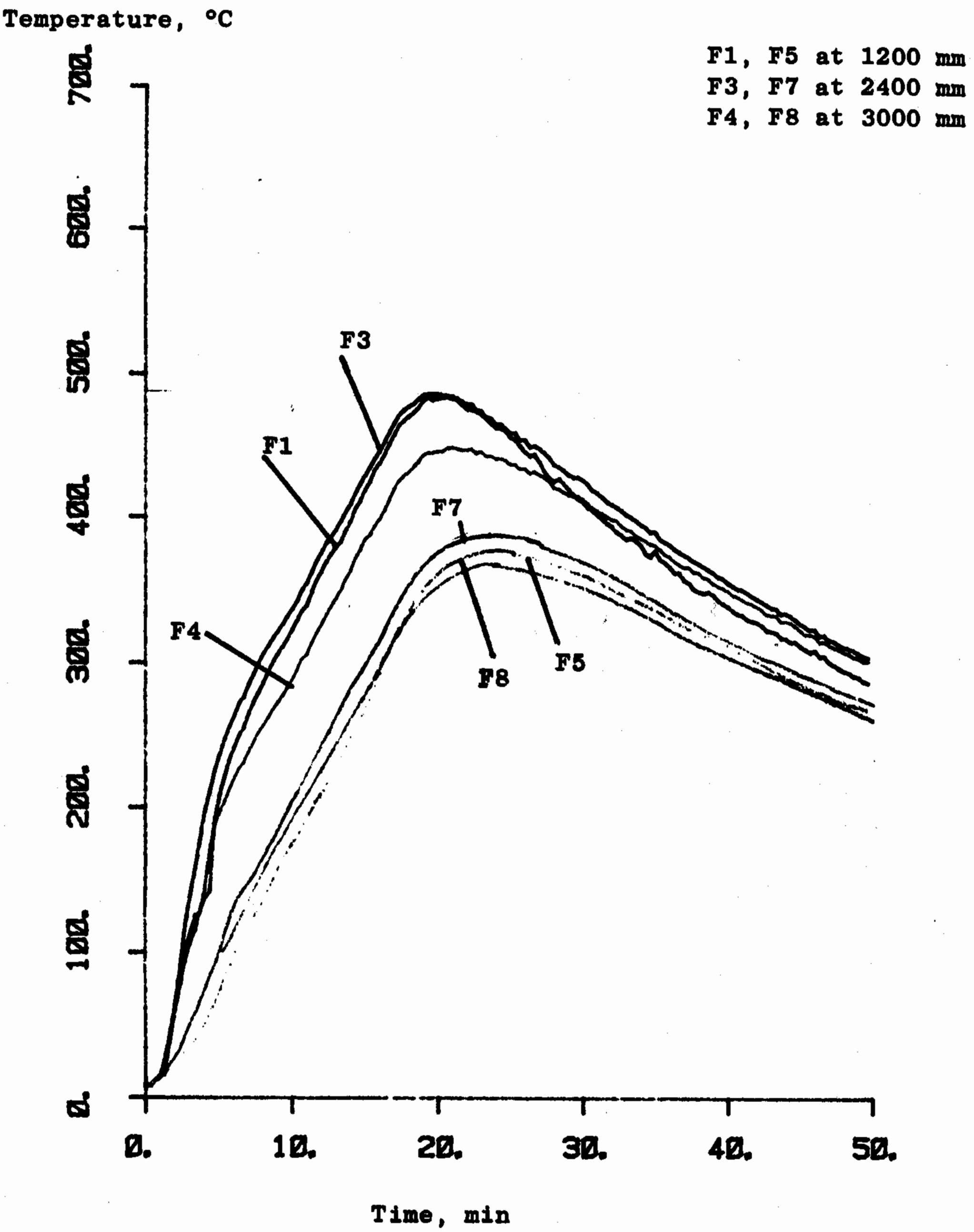


STEEL TEMPERATURES MEASURED AT SEPARATE POSITIONS ALONG THE 406 x 178 mm x 54 kg/m UNPROTECTED STEEL BEAM

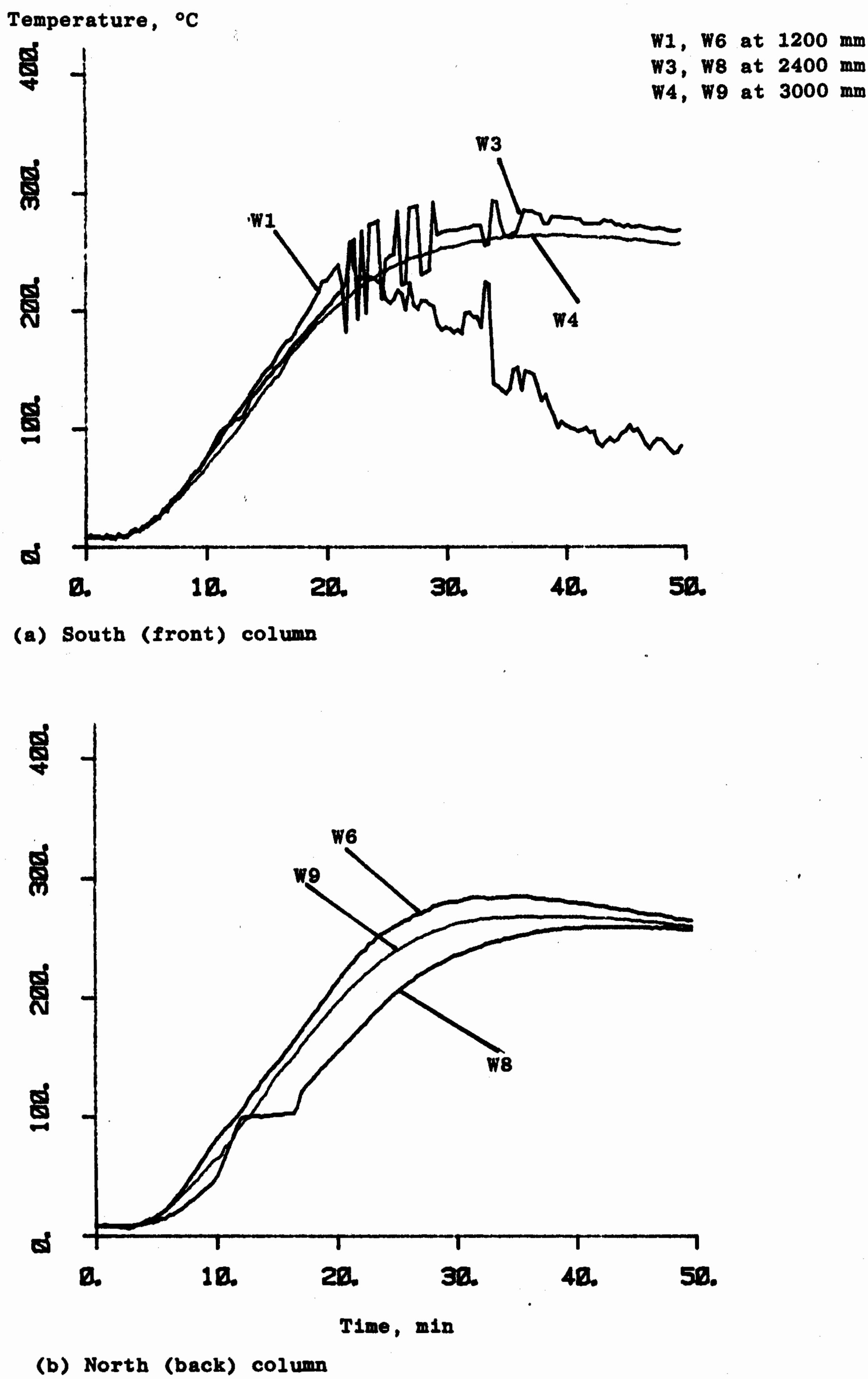
FIG. 13



AVERAGE COMBUSTION GAS AND STEEL TEMPERATURES RECORDED AT THE ENDS AND CENTRE OF THE BEAM FIG. 14

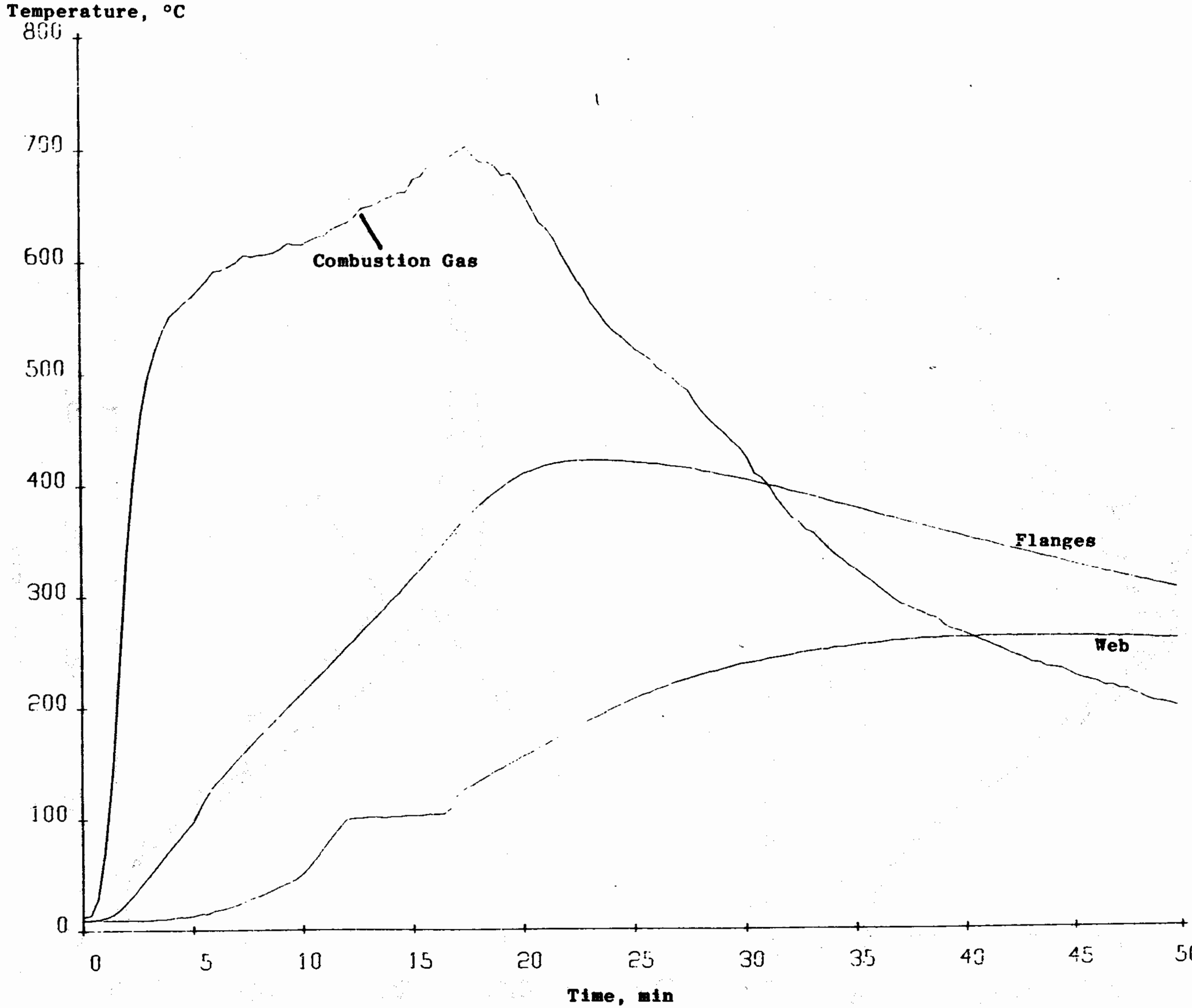


STEEL TEMPERATURES MEASURED ON THE EXPOSED FLANGES OF THE BLOCKED IN COLUMN AGAINST THE SOUTH WALL FIG. 15



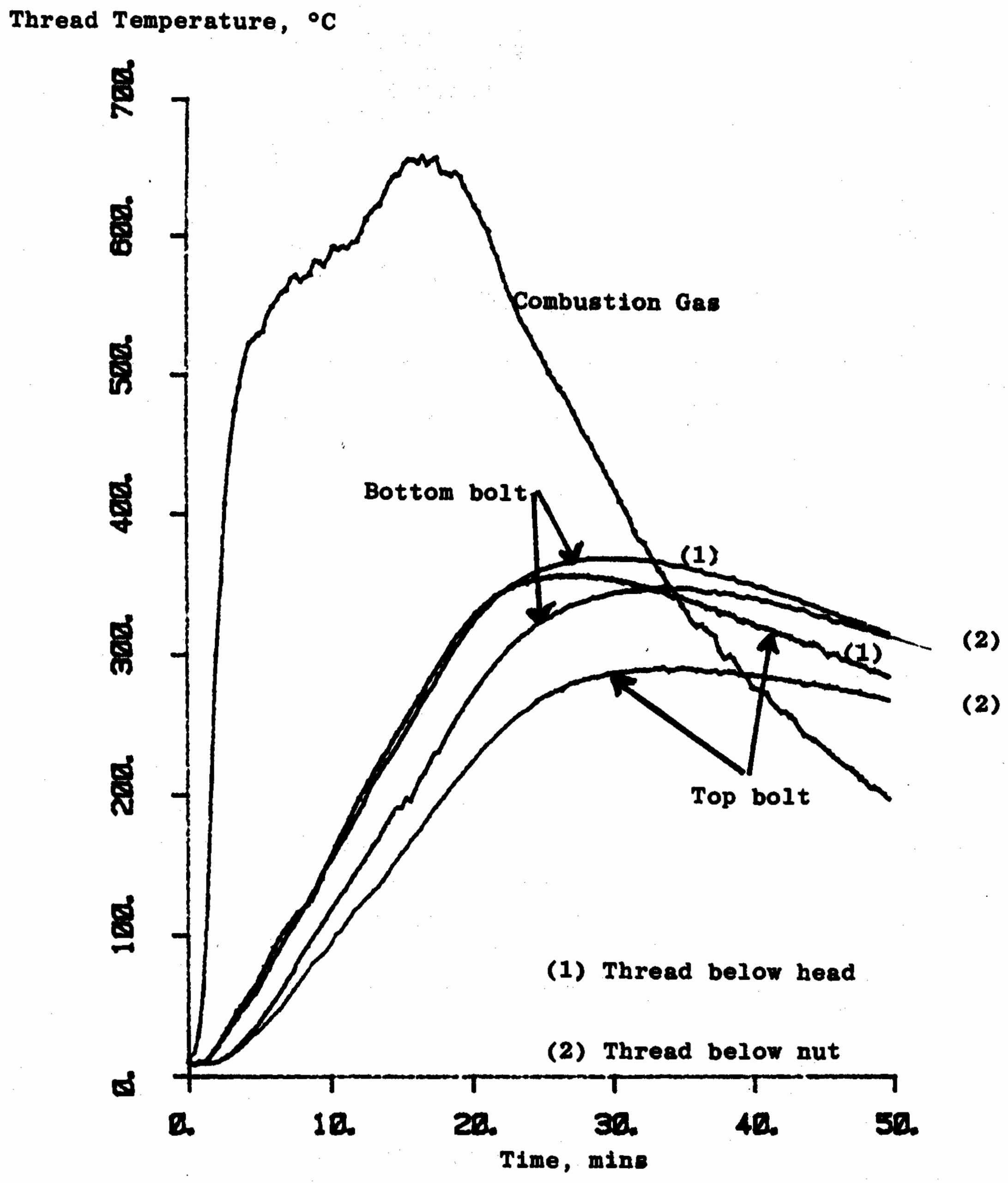
STEEL TEMPERATURES MEASURED IN THE WEBS OF THE BLOCKED IN COLUMNS

FIG. 16

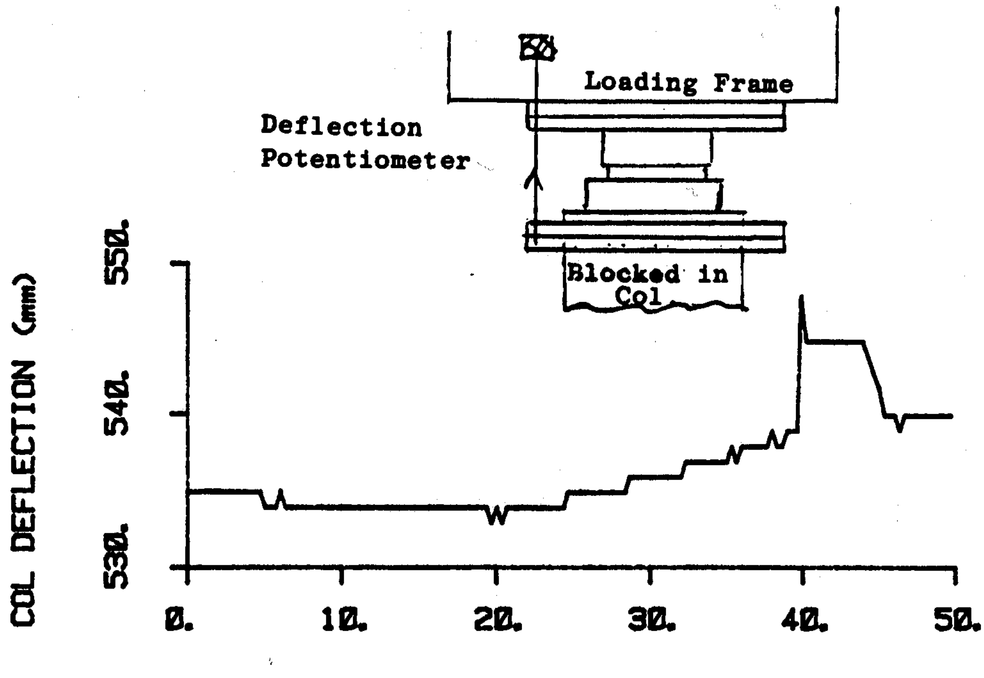


AVERAGE COMBUSTION GAS AND STEEL TEMPERATURES RECORDED AT THE CENTRE OF THE BLOCKED IN COLUMN ADJACENT TO THE NORTH WALL OF THE COMPARTMENT

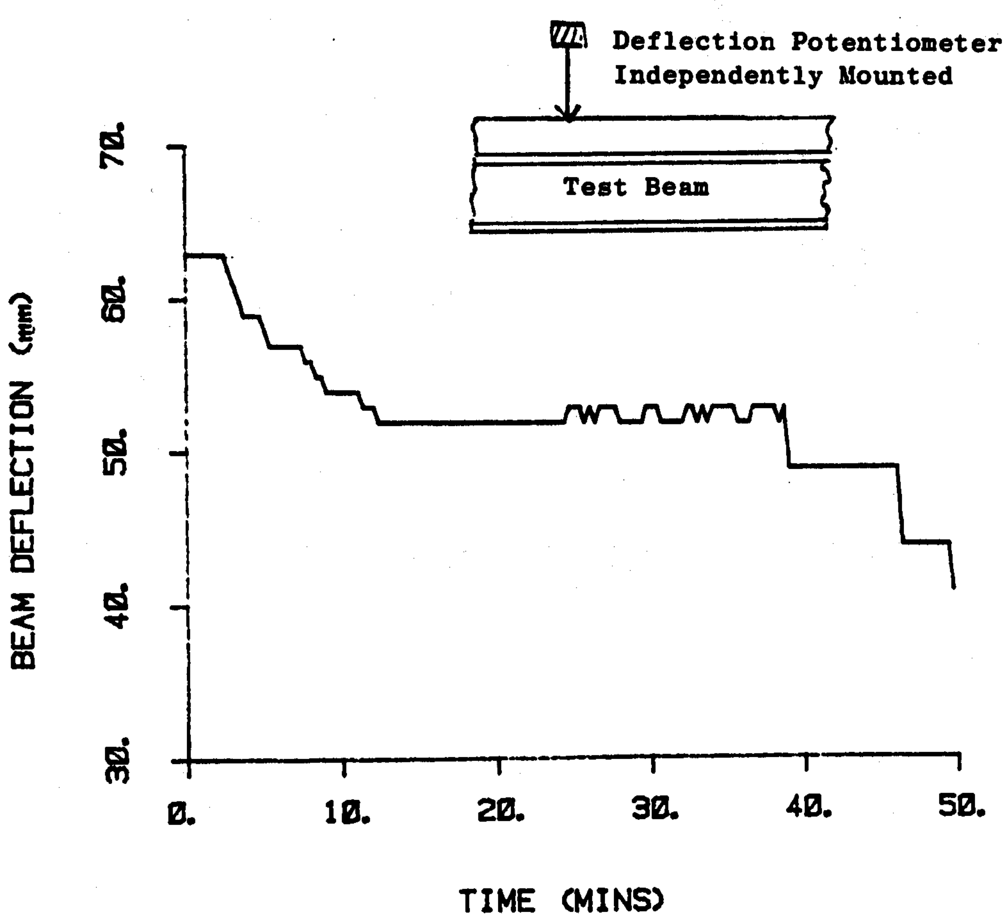
FIG. 17



<u>BOLT TEMPERATURES MEASURED IN A BEAM/COLUMN CONNECTION</u> FIG. 18



(a) Column



(b) Beam

DEFLECTION BEHAVIOUR OF TEST FRAME FIG. 19

SECOND NATURAL FIRE TEST ON A LOADED STEEL FRAME AT CARDINGTON

REPRINT OF BRITISH STEEL REPORT RS/RSC/7281/12/86/E

SECOND NATURAL FIRE TEST ON A LOADED STEEL FRAME AT CARDINGTON

D.J. Latham G. Thomson B.R. Kirby D.E. Wainman

SYNOPSIS

The second of two natural fire tests on a loaded, two dimensional steel framework is described. The structure comprised an unprotected 406 x 178 mm x 54 kg/m beam which spanned the compartment at ceiling height and was attached at each end by bolted connections to 'blocked in' columns. Maximum design loads as permitted by BS 449, were applied to both the beam and the columns in the structure. A fire load density of 25 kg/m² of wood and the 1/8 ventilation of two walls were selected to ensure that the stability of the test frame was exceeded.

The unprotected beam reached a maximum lower flange temperature at mid-span of 775°C after 20 minutes. The 'blocked in' columns reached maximum temperatures of 575°C and 600°C respectively. A time equivalent of 32.5 minutes was estimated to be appropriate for this fire.

During the test the beam initially hogged but then sagged at an increasing rate such that the loads had to be removed at a deflection of L/33. Extrapolation indicated that the limiting deflection of L/30 would have occurred ½ minute later. The 'blocked in' columns bowed towards the adjacent walls at the conclusion of the test.

These observations emphasised the fact that steel frameworks exhibit a significantly greater fire resistance than their individual steel elements.

This work completed the experimental programme of the joint BSC/DoE contract concerned with the structural stability of steel frames in natural fires.

KEY WORDS

3. Fire Resistance
4. Natural Fires
5. Structural Components
6. Construction Industry
6. Temperatures
7. Deflection
8. Testing

12th May 1986

CONTENTS

SECOND NATURAL FIRE TEST ON A LOADED STEEL FRAME AT CARDINGTON

1. INTRODUCTION

The prediction of the performance of steel frames in naturally occurring fires is an important aspect of fire resistant structural design. Currently, the analysis is being approached in two stages involving, initially, the simulation of the behaviour of loaded but restrained beams followed by a study of beam/column combinations. However, experimental data are required to assist in the verification of the mathematical model.

The Cardington compartment was modified to enable natural fire tests to be carried out on a loaded framework. The structure comprised a 406 x 178 mm x 54 kg/m bare steel beam which spanned the compartment at ceiling height and was attached at each end to a 203 x 203 mm x 52 kg/m 'blocked in' column. Maximum BS 449 design loads were applied both to the columns and the beam. In the first test a fire load density of 20 kg/m² of wood and the 1/8 ventilation of two opposite walls were selected to ensure that the limiting temperature for the load carrying capacity of the beam was attained[1]. Despite the fact that a maximum lower flange temperature of 657°C was measured there was no significant deflection, due principally to the degree of end restraint imposed at the connections.

The present report describes a second natural fire test on the loaded steel framework which formed the twenty-third experiment in the Cardington series sponsored jointly by the BSC and DoE. Both the blockwork in the test columns and the bolts in the connections had been replaced and additional fire protection had been given to the tie members of the loading frame to reduce thermal expansion. A more comprehensive coverage of the deflection characteristics of the assembly was provided. A fire load density of 25 kg/m² of wood and the 1/8 ventilation of two opposite walls in the compartment were used to ensure that the structural stability of the framework was exceeded.

2. EXPERIMENTAL PROCEDURE

The fire compartment, which measures 8.6 m x 5.5 m x 3.9 m high has been built within the No. 2 Hangar at RAF Cardington so that tests are almost independent of weather conditions. The constructional materials were selected on the basis that they would withstand repeated exposure to high temperatures without collapsing or changing their thermal characteristics and so some of them would not normally be found in modern buildings.

A total of twenty-one fire tests had already been carried out in the compartment to measure the heating rates of several unprotected beams and columns as well as a water filled hollow section. The steelwork was evenly distributed throughout the compartment to minimise its effect as a heat sink. Before the loaded framework was installed these sections were removed and this necessitated certain repairs to the structure and the removal of the precast concrete roof slabs. Once the new loaded framework had been installed a number of unused concrete planks were placed on the roof for the first loaded test. The inner exposed surfaces of the compartment comprised heat resistant brickwork.

2.1 Steel Framework

The steel framework selected for testing under load was typical of that used in a multi-storey building of 2 to 3 storeys in height. The design is detailed in Drawing No. C/01/AO/A but the salient features are given in Figs. 1 to 4.

The test sections comprised a 4.55 m length of 406 x 178 mm x 54 kg/m BS 4360 : Grade 43A universal beam and two 3.53 m lengths of a 203 x 203 mm x 52 kg/m universal column. These serial sizes were chosen because they had previously been included in earlier BS 476 : Pt. 8 fire tests on partially protected members.

The general arrangement of the test frame is shown in Fig. 1. The beam was connected to the columns by M20 Grade 8.8 bolts through welded end plates. The assembly was centrally positioned inside the compartment parallel to the short walls. Each column, which extended above the beam, was pin jointed at the base to 1.5 m lengths of 533 x 210 mm x 92 kg/m section which also formed the base of the loading frame. The webs of each column were protected by lightweight blocks built between the flanges using an ordinary mortar mix followed by a 28 day drying out period. Four 1200 x 550 x 150 mm concrete slabs which formed part of the compartment roof were attached to the top flange of the beam by welded 12 mm diameter threaded bars. The slabs were separated by a gap of 25 mm to prevent composite action with the beam and the gap was filled with ceramic fibre blanket.

A second frame shown in Fig. 2 provided a structure from which the appropriate design loads could be applied to the test assembly beneath. This comprised a 533 x 210 mm x 92 kg/m universal beam as a crosshead, each end of which was attached to two vertical 152 x 89 mm channel sections that straddled the blocked in columns and were fixed to the base sections of the loading frame. These sections were braced and bolted to the concrete floor.

Both frames were held in position by a combination of external bracing and a subsidiary steel framework contained within the compartment. General views of the assembly are shown in Fig. 3. With the exception of the test frame the remainder of the structure inside the compartment, Fig. 4, and lengths of the external braces in front of the ventilators were lagged with ceramic blanket. Despite these precautions the two vertical 152 x 89 mm channel sections attached to each end of the crosshead had expanded during the first fire test on the frame. Therefore, each tie member was given additional fire protection by coating the steel with wet plaster (50 mm thick) to a nominal diameter of 220 mm held in position by retaining mesh.

2.2 Loading the Frame

A hydraulic ram and load cell were superimposed between the top bearing plate of each 'blocked in' column and the crosshead member to provide the maximum permissible, compressive, design load of 552 kN (BS 449:1972). The beam was loaded at four positions (Fig. 5) along the span each with a load of 39.6 kN to generate a maximum design stress in bending of 165 N/mm² (BS 449:1972). The loads were maintained throughout the period of the fire test. A general view of the loading arrangement is shown in Fig. 6.

2.3 Instrumentation

The temperature distribution of the combustion gas in the compartment during the fire was monitored by 3 mm diameter chromel/alumel Type K thermocouples with Inconel sheaths and insulated hot junctions. In the vicinity of the test frame, the thermocouples were positioned 300 mm from each flange face of the blocked in columns and at heights of 1200, 2400 and 3330 mm above the floor. Thermocouples were also positioned 100 mm from the test beam and at 6 locations along the length of the lower flange. The combustion gas temperatures were also measured at locations half way between the main frame and each of the short walls of the compartment at heights of 2000 or 3300 mm above the floor. The disposition of the thermocouples is shown in Fig. 7(a).

Similar thermocouples were used to measure the steel temperature gradients in the flanges and webs of the test frame at the positions shown in Fig. 7(b). The tip of each thermocouple was inset into a 3 mm diameter hole drilled into the steel section at the positions shown in Fig. 7(c). Thermocouples were also attached at mid-height to the 152 x 89 mm channel sections of the loading frame.

In order to compare the steel temperatures recorded in the test with earlier measurements a 1.6 m length of 203 x 203 mm x 52 kg/m indicative column was placed in the compartment at the same position as that occupied by FSC1[2].

Thermocouples were attached to the flanges and web of this section at a height of 1500 mm above the floor. The 203 x 203 mm x 52 kg/m external column used in the earlier tests was also included in the comparison, the thermocouples were mounted at heights of 1.9 m and 3.3 m from the floor (corresponding to distances of 2.0 m and 0.5 m respectively from the ceiling of the compartment as referred to in earlier reports).

Deflection measurements were made at the centre of the loaded beam using two separate potentiometric transducers mounted to a fixture on the roof of the compartment. A similar device was located between the crosshead and the top of one blocked in column. Three linear displacement transducers were installed by FRS to follow the lateral bowing of each blocked in column. The transducers were positioned 850 mm, 2180 mm and 3550 mm respectively above the floor of the hangar outside the compartment, as shown in Fig. 8.

The temperatures of the top and bottom bolts of the connection were monitored with thermocouples inserted to a depth of 22 mm from the face of the exposed bolt head and to a depth of 12 mm from the end of the threads that were surrounded by mortar and blockwork. In addition, one top bolt was adapted to accept a temperature compensated strain gauge to measure the tensile stresses in the thread during the test. The strain gauge comprised a 6 x 2.6 mm Ni-Cr foil element with a gauge factor of 2.3 mounted on a polyimide carrier suitable for use up to 300°C.

The outputs from the separate measuring instruments were fed back to a Compulog 4 computer controlled data acquisition system. The output from the strain gauged bolt was also directed to a visual display unit.

2.3 Fire Load and Ventilation

Based on observations made during the first loaded frame test it was considered that the maximum lower flange temperature of the beam would have to increase by approximately 100°C to ensure structural collapse. The studies of the temperatures attained by unprotected steelwork in natural fires suggested that for similar ventilation conditions the wooden fire load density should be 25 kg/m², representing the highest fuel load examined at Cardington.

Previous work had also suggested that for a given total ventilation to the compartment the difference in the fire behaviour caused by openings in one wall, or the two opposite walls was small[2]. As it was important to obtain as symmetrical a heating pattern across the loaded frame as possible, openings were made in both long walls of the compartment using the appropriate shutters to maintain the 1/8 ventilation in the area of each wall that was used in Test No. 22.

It was considered advisable to reduce the rate of burning, as experienced in the earlier fires on unloaded members, to allow time for the loads on the beam to be effectively controlled and also to establish a more realistic temperature distribution over the cross section of the blocked in column. This had been achieved in the first test on the loaded frame by wiring together a number of the standard wooden sticks to form bundles 100 x 100 mm and placing these in two consecutive layers in the crib. Such a reduction in the total surface area of the fuel was too great. Therefore, the layout of each of the 12 cribs in the present test comprised 50 x 50 x 1000 mm sticks spaced 50 mm apart with alternate rows at right angles to each other but with the third layer from the bottom replaced by 100 x 100 bundles placed 100 mm apart.

3. EXPERIMENTAL RESULTS - CARDINGTON FIRE TEST NO. 23.

Date:	21st February, 1986.
Fire Load Density:	25 kg/m² in 12 cribs, total wood fire load = 1320 kg based on a 15% moisture content. (The wood comprised a mixture of kiln dried and sawn wood stored at Cardington).
Ventilation:	1/8 of North wall + 1/8 of South wall ≡ 0.06 $m^{\frac{1}{2}}$

3.1 General Observations

The cribs were ignited simultaneously on a still day when the air temperature inside the compartment was -5°C. General combustion of the fuel at the back of the compartment occurred later than elsewhere. Once the fire became established the intensity was greatest at the centre of the compartment. Representative photographs of the fire test are shown in Fig. 9.

The maximum load applied to both columns and the beam was maintained until the beam became **unstable**. At this time the rate of movement of the test frame became greater than the rate and extent of ram travel on the jacks. The load was removed after 22 minutes but by this time the maximum temperature in the beam had been passed.

The thermocouple outputs from the tie members supporting the crosshead were erratic due to the presence of moisture in the plaster but showed no rise in temperature. The test beam initially hogged but later sagged at an increasing rate. The blocked in columns bowed towards the sides of the compartment in the later stages of the test but the connections remained intact.

As in the first test,the output from the strain gauge bolt was erratic. A maximum tensile load of 145 kN was recorded after 4 minutes which then rapidly reduced to about 20 kN. Later a compressive load of -70 kN was indicated. In view of the nature of the deformation behaviour in the vicinity of the connection these observations were considered to be spurious.

An examination of the loaded frame at the conclusion of the test showed it to be distorted and probably incapable of supporting a significant load. A number of concrete slabs on the roof of the compartment exhibited considerable spalling.

3.2 Atmosphere Temperatures

The atmosphere temperatures in the vicinity of the loaded structure are given in Table 1 and at other positions inside the compartment in Table 2 as a function of time. Reference should be made to Fig. 7(a) for the thermocouple numbering system. Unfortunately, a fault in one data logger prevented the comprehensive monitoring of temperatures after 28 minutes.

A maximum average temperature of 837°C was recorded at the centre of the compartment after 17 minutes.

The change in combustion gas temperature with height is shown in Fig. 10, measured in the vicinity of the columns. After 17 minutes the average temperature at the 3.3 m level was 758°C, at the middle position 800°C but at the 1200 mm level the temperature ranged from 780°C ($\frac{A11 + A13}{2}$) to 713°C (A16); the lower value may be associated with the sluggish combustion of cribs in the vicinity.

The average change in combustion gas temperature across the top of the compartment is shown in Fig. 11. The development of the combustion gas temperature with time along the beam is represented in Fig. 12 for a number of time periods throughout the fire test. As a result of equal ventilation from both walls of the compartment the hottest region of the fire occurred at the centre of the beam. Once the peak temperature had been reached the heating became more uniform.

3.3 Steelwork Temperatures

The temperatures recorded during the test are given in Tables 3 to 9 and typical patterns of behaviour in Figs. 13 to 18. The numbered thermocouple positions used in the presentation of data are depicted at the head of each table.

3.1.1 Loaded Beam

The steel temperatures along the flanges of the beam are presented in Table 3 and the web temperatures in Table 4. The steel heating rate was faster at the centre of the beam as shown by the individual temperature profiles in the lower flange (Fig. 13(a)) and web (Fig. 13(b)). For example F4, close to the centre of the beam reached a maximum temperature of 775°C after 20 minutes whereas F1, close to the connection reached 671°C at the same time. The corresponding temperatures in the web were 777°C and 702°C and the upper flange (F10) reached 577°C at the same time.

The average changes in both atmosphere and steel temperatures at the ends and at the centre of the beam are summarised in Fig. 14. The maximum combustion gas temperature occurred approximately three minutes before the beam reached its highest temperature.

3.3.2 Loaded Columns

The steel temperatures for the blocked in column at the front of the compartment nearest to the hangar door are presented in Table 5 and for the blocked in column attached to the other end of the beam in Table 6. The steel heating rate was faster on the flange facing into the compartment. The temperatures measured in the front column are shown in Fig. 15. Based on both the atmosphere temperatures in the vicinity and the temperatures measured on the other column, Fig. 16, it is assumed that the thermocouple F3 was suspect. The maximum temperature on the exposed flange of the front column was therefore 606°C reached after 20 minutes by which time the maximum temperature in the unexposed flange was 514°C. The corresponding temperatures on the back column after 20 minutes were 575°C and 494°C.

The temperatures recorded by individual thermocouples in the webs of each column are shown in Fig. 17. The highest web temperature on the front column of 358°C was recorded after 35 minutes. The lowest temperature of 296°C occurred in the vicinity of the connection. In comparison with the first trial the steel temperatures were not influenced by the presence of moisture.

The average changes in both the atmosphere and steel temperatures at the centre of the blocked in column are typified by the curves of Fig. 18 recorded at the back of the compartment. The maximum average flange temperature of 545°C occurred 6 minutes after the fire had reached its peak.

3.3.3 Bolts

The temperatures measured in the thread of the bolts used for the connections are presented in Table 7 and Fig. 19 shows typical temperature profiles beneath the bolt head and nut for the front connection. The bolts in the lower part of this connection were the hottest during the fire test. The average maximum temperatures reached by the thread of the bolts beneath the head were 475°C for the lower and 435°C for the upper bolt, recorded after approximately 32 minutes. The drop in temperature along the thread was similar for both bolts.

In an earlier indicative BS 476 : Pt. 8 fire test on a similar connection the bottom bolts also exhibited a faster heating rate than the top bolts. After 25 minutes the bottom bolt threads reached a temperature of 336°C below the head and 238°C behind the brickwork. In the present test the corresponding temperatures were 470°C and 387°C for one connection and 464°C and 374°C for the other.

3.3.4 Indicative Column

The temperature measurements recorded at the 1500 mm position on the indicative column ($^{HP}/A$ = 180 m^{-1}) are presented in Table 8 and Fig. 20. A maximum average steel temperature of 768°C was reached after 21 minutes.

3.3.5 External Column

The external column with an $^{HP}/A$ = 180 m^{-1} reached a peak temperature of 255°C (1900 mm level) after 23 minutes. The peak temperature recorded on the exposed flange at a height of 3300 mm was 149°C. The results are presented in Table 9.

3.4 Deflection Behaviour

The central vertical displacement of the beam is shown in Fig. 21. As the equipment was mounted independent of the loading frame the results are considered to represent an accurate reflection of the behaviour. After approximately 5 minutes the beam began to hog; this trend continued to give a maximum apparent upward deflection of 45 mm. The beam started to sag after 14 minutes at an increasing rate rising to 30 mm/minute and the load was eventually removed after 22 minutes. At the point of inflexion the maximum lower flange temperature was 678°C. The total sagging deflection from a horizontal position was 138 mm (i.e. 120 + initial permanent deflection of the beam following the first test), equivalent to L/33. As the upper flange of the beam moved below the lateral support provided by the concrete roof planks the lower flange underwent torsional buckling. Subsequent examination revealed the presence of a plastic hinge approximately 600 mm from each end and a 5 mm separation at the top of the end plate of the connection from the column flange. The appearance of the beam on completion of the test is shown in Fig. 22. For safety reasons a check on the residual vertical deflection at the centre of the beam was not possible.

As the vertical tensile members linked to the crosshead showed no significant rise in temperature the measured extension of the front blocked in column, Fig. 23, is considered to be realistic. The column expanded to reach a maximum extension of 20 mm after 15 minutes. Beyond that time lateral movement of the column became more pronounced as the test beam sagged into the compartment. The lateral movement of each column as determined by FRS is presented in Table 10 and Fig. 24. These results showed that during the early stages of the test the inward facing flanges became convex the effect being more noticeable on the front member. This distortion accompanied the hogging of the test beam. After 20 minutes the centre of each column bowed towards the adjacent wall. The measured column displacements at the time when the load was removed are plotted in Fig. 25. The measurements on the column have been extrapolated to the corresponding positions of the top and bottom flanges of the beam. Thus, the total lateral movement of both columns towards the walls of the compartment was 65 mm from the upper flange of the beam and 68 mm from the lower flange. The residual displacement measured by the FRS transducers at a height of 2090 mm is also included in Fig. 25. Subsequent measurements at the same position on the columns when at ambient temperature recorded respective lateral displacement of 25 mm and 20 mm, consistent with the observations made during the test.

4. DISCUSSION

The behaviour of a natural fire can be related to an equivalent heating time in the BS476 : Pt. 8 fire resistance test. For the fire load and ventilation conditions used at Cardington the theoretical relationship established by FRS predicted a time equivalent of 30.75 minutes. The unprotected steel beam reached a maximum average lower flange temperature of 774°C in the fire (adjusted to an ambient temperature of 20°C) from which a time equivalent of 32 minutes was predicted by finite element mathematical analysis. A time equivalent of 33 minutes was also predicted from the maximum average temperatures recorded on the indicative column

The observations all emphasised that the particular framework under test exceeded the ½ h fire rating. In comparison with a fire resistance of 20 minutes established for the unprotected beam in the simply supported condition this was a considerable improvement. The increased fire resistance was due principally to the rotational restraint imposed at the ends of the beam. The maximum bolt thread temperatures ranged from 435°C to 475°C and apart from slight distortion of the end plate the connections were sufficiently fire resistant to avoid the need for any additional protection.

The deflection behaviour of the frame was complicated. The front 'blocked in' column recorded a maximum axial expansion of 20 mm after 15 minutes. Therefore after 14 minutes the measured upward displacement of the centre of the beam relative to its ends was no greater than 25 mm. As the stiffness of the beam was much greater than the universal column sections thermal bowing in a downward direction had been expected to override any tendency towards hogging from differential thermal expansion across the columns. Once the lower flange exceeded 678°C the beam failed to support the load and commenced to sag. The rate of vertical deflection then increased until the displacement could not be followed by the hydraulic jacks which were then endangered by the heat from the fire. The load was therefore removed after 22 minutes when the total deflection of the beam was L/33. Had it been possible to maintain the load, a deflection of L/30 would probably have occurred after a further 30 seconds.

Laboratory studies at FRS have developed theories for calculating the angular rotation and lateral deflection of a steel member in the absence of externally applied loads when the member has a temperature gradient across the section[3]. The same analysis has been used to calculate the influence of temperature gradients alone on the total lateral separation between the 'blocked in' columns and the change in length of the beam at a height corresponding to its lower flange from the data in Table 11. The calculated displacements are compared with those measured on the loaded columns in Fig. 26. During the first four minutes of the test no lateral thermal movement of the columns was detected. Apart from some realignment of the framework that might have occurred there was no obvious experimental reason for this discrepancy, although a similar occurrence occurred in the FRS study on thermal bowing. After 14 minutes into the test the calculated lateral extension of the beam was 41.4 mm which compared favourably with the measured displacement of both columns. As the bottom of the columns were pin jointed the high rotational forces at the connections due to thermal bowing would superimpose only a small axial tensile stress in the beam. Once the beam began to sag the increasing separation between the columns of the test frame would result in plastic deformation of the longitudinal member.

5. CONCLUSIONS

A test frame comprising an unprotected 406 x 178 mm x 54 kg/m beam bolted to two 'blocked in' 203 x 203 mm x 52 kg/m columns was installed in the Cardington compartment. The maximum design load (BS 449:1972) was applied axially to each column and over four points to the beam. The test frame was subjected to a natural fire based on a fire load density of 25 kg/m² and the 1/8 ventilation of two walls.

The FRS relationship predicted a time equivalent of 30.5 minutes for the fire load and ventilation conditions used. The finite element mathematical model predicted a time equivalent of 31 minutes for the beam in the test frame and 33 minutes for an indicative column placed inside the compartment.

The unprotected beam reached a maximum lower flange temperature at the centre of the span of 775°C after 20 minutes. The 'blocked in' columns reached respective maximum temperatures of 575°C and 606°C on the inner facing flanges; the outer facing flanges were about 100°C cooler and the temperatures in the web were not influenced by the presence of moisture. The bottom bolts in the connections were hotter than the upper bolts with an average maximum temperature in the thread beneath the head of 475°C.

The beam 'hogged' during the early stages of the test but started to sag after 14 minutes when the maximum lower flange temperature was 678°C. The maximum deflection achieved was L/33. The inward facing flanges of the blocked in columns became convex during the early stages of the test but bowed towards the adjacent walls at the end.

These observations emphasised the fact that steel frameworks can exhibit a greater fire resistance than their individual steel elements. The particular structure under test satisfied the ½ h fire rating without the need for additional protection.

6. REFERENCES

1. Contract Report RSC/7281/11/86.

2. Contract Report RSC/7281/10/86.

3. Cooke, G.M.E., 'Thermal Bowing of Steel Members at Elevated Temperatures', BRE Notc N81/83.

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TABLE 1 ATMOSPHERE TEMPERATURE DATA (ADJACENT TO LOADED STRUCTURE)

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

COMPONENT IDENTITY : ATMOSPHERE
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

TIME	ATMOSPHERE TEMPERATURES (deg C)															
	<---------------- COLUMNS ---------------->								<---------------- BEAM ---------------->							
	1200mm LEVEL				2400mm LEVEL				3300mm LEVEL							
	(s)	(s)	(n)	(n)	(s)	(s)	(n)	(n)	(n)	(n)	(n)	(s)	(s)	(s)	(s)	(n)
(mins)	A9	A11	A13	A16	A8	A10	A12	A15	A1	A2	A3	A4	A5	A6	A7	A14
0	0	0	0	0	-1	0	-1	0	1	-4	1	-2	0	-1	-1	0
1	24	24	28	27	37	39	40	45	54	42	45	44	39	28	37	59
2	151	151	164	151	270	255	282	263	305	281	309	333	305	233	251	305
3	350	336	361	327	438	465	488	468	475	482	509	532	527	456	400	453
4	473	491	525	486	506	563	574	541	543	586	590	614	587	524	470	510
5	541	573	593	556	556	627	626	590	594	642	664	706	665	589	518	557
6	560	602	612	565	576	643	639	600	612	622	647	674	668	602	558	565
7	582	621	626	581	604	657	642	614	605	638	656	680	665	609	573	576
8	598	638	637	591	619	668	659	625	629	647	668	690	675	620	596	598
9	619	656	663	616	646	688	684	653	652	672	692	715	699	639	608	630
10	641	678	681	631	658	710	695	670	658	688	708	734	719	664	631	652
11	671	701	716	659	688	739	733	699	686	716	737	767	752	698	666	677
12	688	726	730	673	701	757	737	712	702	734	760	780	759	711	682	689
13	705	737	708	688	715	770	759	730	725	750	777	805	775	726	701	700
14	*	723	709	677	736	777	767	750	738	768	796	832	798	739	713	709
15	*	741	805	677	752	789	781	762	755	795	811	831	801	747	723	721
16	*	704	811	676	770	792	791	777	774	811	831	840	803	746	739	735
17	*	731	830	713	780	803	800	785	775	805	826	832	811	767	748	746
18	*	743	765	693	776	804	800	781	773	799	813	824	805	763	748	751
19	*	747	747	672	801	798	791	768	763	795	820	842	807	760	768	747
20	*	718	768	677	762	783	769	772	750	784	790	807	780	753	752	754
21	*	680	*	632	731	764	742	725	732	753	754	772	740	729	725	723
22	*	637	*	630	691	713	706	690	700	724	725	735	718	701	690	687
23	*	*	*	602	658	678	668	660	676	695	697	705	703	671	659	656
24	*	*	*	568	633	652	632	630	653	671	674	688	686	649	638	635
25	*	*	*	546	595	614	634	615	637	656	659	668	668	620	606	623
26	*	*	*	532	569	600	623	592	634	656	653	646	656	613	596	622
27	*	*	*	527	550	577	617	603	633	657	657	628	643	594	579	620
28	*	*	*	496	522	551	594	572	616	639	637	607	630	575	558	599
29	*	*	*	*	503	526	*	*	*	*	*	584	616	551	536	*
30	*	*	*	*	487	513	*	*	*	*	*	565	606	534	521	*
31	*	*	*	*	471	494	*	*	*	*	*	540	596	513	499	*
32	*	*	*	*	451	473	*	*	*	*	*	526	582	497	479	*
33	*	*	*	*	434	452	*	*	*	*	*	510	571	482	464	*
34	*	*	*	*	419	433	*	*	*	*	*	492	552	464	446	*
35	*	*	*	*	399	420	*	*	*	*	*	476	534	443	426	*
36	*	*	*	*	389	405	*	*	*	*	*	460	524	439	413	*
37	*	*	*	*	370	390	*	*	*	*	*	449	508	424	399	*
38	*	*	*	*	350	378	*	*	*	*	*	433	493	410	380	*

(*) Thermocouples and/or data logger faulty : Data invalid.
(s) South side of compartment.
(n) North side of compartment.

TABLE 2 ATMOSPHERE TEMPERATURE DATA (REMAINDER OF COMPARTMENT)

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

COMPONENT IDENTITY : ATMOSPHERE
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

TIME	ATMOSPHERE TEMPERATURES (deg C)											
	3300mm LEVEL						1900mm LEVEL					
	(s)	(s)	(s)	(n)	(n)	(n)	(s)	(s)	(s)	(n)	(n)	(n)
(mins)	A17	A19	A21	A23	A25	A27	A18	A20	A22	A24	A26	A28
0	1	0	0	-1	-1	0	2	0	0	-1	*	*
1	58	82	57	35	34	42	97	28	46	43	*	*
2	340	354	337	277	225	270	350	250	294	214	*	*
3	554	537	523	449	445	449	572	497	530	493	*	*
4	634	620	599	617	589	560	724	604	669	649	*	*
5	691	679	657	668	681	643	747	663	743	712	*	*
6	709	707	670	679	681	681	707	681	721	703	*	*
7	708	704	695	696	694	700	732	691	737	730	*	*
8	724	723	711	700	701	712	737	708	752	728	*	*
9	755	767	741	736	714	717	774	747	772	780	*	*
10	760	772	757	774	751	742	778	749	766	824	*	*
11	788	800	770	789	775	780	803	783	796	864	*	*
12	801	810	790	818	784	793	843	796	818	909	*	*
13	820	824	804	816	789	806	847	808	827	847	*	*
14	837	844	809	818	793	797	859	818	805	*	*	*
15	848	838	821	802	798	817	838	832	813	*	*	*
16	851	841	825	815	799	803	858	832	802	*	*	*
17	851	857	830	817	813	812	869	849	833	*	*	*
18	849	830	815	858	812	807	873	839	828	*	*	*
19	827	811	796	847	803	794	859	823	814	*	*	*
20	827	788	786	830	*	797	851	805	800	*	*	*
21	769	755	760	*	*	783	797	763	754	*	*	*
22	733	722	722	*	*	759	766	729	724	*	*	*
23	692	686	689	*	*	714	715	700	691	*	*	*
24	663	660	667	*	*	682	677	674	658	*	*	*
25	640	645	644	*	*	652	654	646	628	*	*	*
26	632	640	617	*	*	625	630	614	590	*	*	*
27	624	635	595	*	*	597	625	585	561	*	*	*
28	612	625	574	*	*	573	595	559	534	*	*	*
29	*	*	549	*	*	550	*	538	512	*	*	*
30	*	*	530	*	*	529	*	517	494	*	*	*
31	*	*	511	*	*	494	*	494	473	*	*	*
32	*	*	492	*	*	473	*	475	454	*	*	*
33	*	*	477	*	*	458	*	454	436	*	*	*
34	*	*	460	*	*	440	*	441	421	*	*	*
35	*	*	445	*	*	432	*	427	398	*	*	*
36	*	*	433	*	*	424	*	412	383	*	*	*
37	*	*	421	*	*	407	*	398	370	*	*	*
38	*	*	407	*	*	396	*	387	358	*	*	*

(*) Thermocouples and/or data logger faulty : Data invalid.
(s) South side of compartment.
(n) North side of compartment.

TABLE 3 TEMPERATURES IN BEAM FLANGES

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

SECTION : 406 mm x 178 mm x 54 kg/m
NOMINAL Hp/A : 190 /m
COMPONENT IDENTITY : BEAM (FLANGES)
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

```
 **  A1         A2         A3                  **
 **  /          /          /                   **
 *******************10******11**********  (U/F)
 **                                            **
 ** 1    2    3    4    5    6    7    8    9 **  (Web)
 ***1***2***3***4***5***6***7***8***9***  (L/F)
 **                   /         /         /   **
 **                  A4        A5        A6
Back Column                            Front Column
 (North)                                 (South)
```

TIME	STEEL TEMPERATURES (deg C)										
	LOWER									UPPER	
(mins)	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
0	0	0	0	-1	0	-1	-1	0	0	0	0
1	2	2	3	2	2	2	1	3	2	3	2
2	18	22	28	29	24	24	20	28	18	12	13
3	50	60	74	80	76	72	64	67	51	36	38
4	90	119	141	158	153	141	123	124	88	69	70
5	140	187	220	241	238	218	192	184	134	120	112
6	188	243	284	309	310	289	258	240	180	149	152
7	232	301	347	372	378	356	322	298	226	183	190
8	272	356	400	427	434	412	379	350	269	221	227
9	313	407	453	481	489	466	433	401	312	271	264
10	354	457	500	527	547	516	485	453	355	231	299
11	396	506	546	570	589	560	531	498	397	287	336
12	438	551	589	612	632	603	575	544	438	286	372
13	477	588	625	647	669	639	614	583	477	*	407
14	513	622	657	678	*	671	648	618	512	*	438
15	548	657	689	709	*	700	678	649	544	*	470
16	579	685	715	732	*	723	703	677	573	*	497
17	609	711	734	740	*	737	725	700	600	*	522
18	630	725	737	749	*	741	737	715	622	*	543
19	649	733	743	760	*	751	739	728	640	*	561
20	671	745	762	775	*	758	743	734	653	*	577
21	667	730	745	764	*	758	746	733	661	*	587
22	670	730	742	761	*	752	743	730	663	*	591
23	668	725	733	751	*	742	736	723	660	*	589
24	668	724	735	747	*	730	726	714	654	*	585
25	655	706	708	726	*	718	716	704	648	*	581
26	666	713	716	733	*	712	709	699	640	*	582
27	681	732	738	748	*	700	697	690	631	*	575
28	665	722	712	727	*	686	690	681	620	*	567
29	*	*	*	*	*	676	683	664	607	*	557
30	*	*	*	*	*	674	676	652	599	*	552
31	*	*	*	*	*	661	660	636	588	*	546
32	*	*	*	*	*	644	644	623	578	*	538
33	*	*	*	*	*	627	627	608	566	*	531
34	*	*	*	*	*	610	611	594	555	*	522
35	*	*	*	*	*	592	593	578	544	*	510
36	*	*	*	*	*	577	579	565	533	*	502
37	*	*	*	*	*	563	565	553	522	*	493
38	*	*	*	*	*	549	552	540	511	*	485

(*) Thermocouples and/or data logger faulty : Data invalid.

TABLE 4 TEMPERATURES IN BEAM WEB

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

SECTION : 406 mm x 178 mm x 54 kg/m
NOMINAL Hp/A : 190 /m
COMPONENT IDENTITY : BEAM (WEB)
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

TIME	STEEL TEMPERATURES (deg C)								
	WEB								
(mins)	W1	W2	W3	W4	W5	W6	W7	W8	W9
0	0	0	0	0	-1	0	0	0	0
1	2	5	6	4	7	6	2	5	2
2	22	37	45	45	37	50	31	41	20
3	65	92	111	113	97	130	94	104	61
4	120	167	194	203	202	213	171	172	107
5	186	256	292	308	303	306	258	249	162
6	245	328	364	383	374	383	339	320	214
7	297	393	431	452	446	452	410	387	263
8	345	447	482	504	495	502	468	441	308
9	391	497	530	552	543	551	518	490	351
10	434	539	571	592	587	591	563	537	392
11	477	581	610	632	624	627	603	576	432
12	516	618	645	665	659	661	639	613	470
13	552	648	673	694	691	690	669	644	505
14	584	676	698	719	717	712	695	670	536
15	613	703	725	742	741	734	717	693	565
16	640	724	741	749	*	747	736	713	589
17	663	738	745	761	*	756	742	727	612
18	679	739	753	771	*	759	746	736	630
19	691	743	759	776	*	760	753	736	643
20	702	750	763	777	*	759	755	736	652
21	702	746	754	770	*	747	751	734	655
22	698	738	742	759	*	731	742	726	652
23	687	726	728	743	*	716	728	713	643
24	674	713	720	732	*	702	714	700	632
25	660	696	699	715	*	690	701	686	619
26	664	702	704	718	*	691	691	680	607
27	670	718	717	728	*	676	686	670	595
28	654	704	706	711	*	668	678	654	582
29	*	*	*	*	*	657	660	633	567
30	*	*	*	*	*	642	644	618	559
31	*	*	*	*	*	627	625	601	546
32	*	*	*	*	*	609	609	587	536
33	*	*	*	*	*	594	593	571	524
34	*	*	*	*	*	578	577	556	513
35	*	*	*	*	*	559	561	542	503
36	*	*	*	*	*	546	548	529	492
37	*	*	*	*	*	533	535	516	482
38	*	*	*	*	*	520	522	504	473

(*) Thermocouples and/or data logger faulty : Data invalid.

TABLE 5 FLANGE AND WEB TEMPERATURES IN BLOCKED-IN COLUMN AGAINST SOUTH WALL

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

SECTION : 203 mm x 203 mm x 52 kg/m
NOMINAL Hp/A : ------
COMPONENT IDENTITY : COLUMN (SOUTH)
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

```
                *       *
                *  W5   *  F9          --- 3675 mm
                *       *      A7      --- 3300 mm
          F4    *  W4   *  F8          --- 3000 mm
                *       *
     A10  F3    *  W3   *  F7  A8      --- 2400 mm
                *       *
          F2    *  W2   *  F6          --- 1800 mm
                *       *
     A11  F1    *  W1   *  F5  A9      --- 1200 mm
                *       *
          Exposed      Unexposed
          Flange        Flange
```

TIME	STEEL AND ATMOSPHERE TEMPERATURES (deg C)																		
	EXPOSED FLANGE						UNEXPOSED FLANGE								WEB				
(mins)	F1	F2	F3	F4	A11	A10	F5	F6	F7	F8	F9	A9	A8	A7	W1	W2	W3	W4	W5
0	0	-1	-1	-1	0	0	-1	-1	-1	-1	-1	0	-1	-1	-1	-2	-1	-1	0
1	3	4	13	11	24	39	0	0	0	0	2	24	37	37	0	1	0	-1	0
2	25	25	101	61	151	255	3	7	9	7	15	151	270	251	-1	-2	-1	-1	0
3	63	65	196	84	336	465	13	22	25	21	35	350	438	400	0	-2	0	0	0
4	97	103	232	98	491	563	33	42	45	39	52	473	506	470	5	6	3	3	1
5	125	162	253	178	573	627	56	65	68	60	70	541	556	518	12	10	9	7	3
6	205	210	392	236	602	643	77	88	98	78	90	560	576	558	27	14	17	14	7
7	240	244	429	264	621	657	105	121	139	114	105	582	604	573	49	26	28	24	12
8	273	274	447	289	638	668	131	148	167	141	117	598	619	596	74	32	41	34	19
9	307	308	471	318	656	688	156	175	193	167	159	619	646	608	84	48	56	45	28
10	346	341	499	347	678	710	184	202	222	193	181	641	658	631	98	72	72	58	37
11	388	378	528	380	701	739	214	233	253	222	203	671	688	666	116	81	88	73	47
12	425	416	557	414	726	757	243	263	284	252	227	688	701	682	204	101	107	89	58
13	459	451	582	445	737	770	274	295	315	281	250	705	715	701	*	119	127	108	71
14	486	480	599	473	723	777	303	328	347	314	269	*	736	713	*	136	144	127	84
15	518	510	619	500	741	789	339	362	380	344	290	*	752	723	*	158	164	145	95
16	546	537	637	525	704	792	375	396	412	373	313	*	770	739	*	176	184	161	105
17	579	565	659	551	731	803	412	432	445	403	334	*	780	748	*	193	203	178	114
18	600	582	667	569	743	804	436	460	470	428	348	*	776	748	*	211	220	195	128
19	*	596	672	584	747	798	449	487	495	453	369	*	801	768	*	228	235	212	144
20	*	606	675	595	718	783	466	507	514	473	388	*	762	752	*	244	251	230	159
21	*	603	667	599	680	764	495	518	524	487	399	*	731	725	*	258	265	246	171
22	*	596	648	594	637	713	501	522	527	494	405	*	691	690	*	269	278	260	182
23	*	590	631	589	*	678	*	524	527	498	406	*	658	659	*	282	290	272	193
24	*	583	617	584	*	652	520	523	526	500	406	*	633	638	*	294	300	284	204
25	*	574	601	577	*	614	541	520	522	499	404	*	595	606	*	303	308	294	214
26	*	568	595	572	*	600	522	518	520	498	415	*	569	596	*	318	317	304	224
27	*	558	583	565	*	577	522	512	515	495	415	*	550	579	*	326	323	313	233
28	*	550	570	557	*	551	515	506	509	491	415	*	522	558	*	332	329	320	241
29	*	537	555	545	*	526	514	496	500	483	407	*	503	536	*	335	331	323	245
30	*	531	545	541	*	513	504	493	496	483	410	*	487	521	*	344	338	332	255
31	*	521	533	533	*	494	504	486	488	478	405	*	471	499	*	347	341	336	261
32	*	514	523	527	*	473	491	481	483	474	403	*	451	479	*	353	346	342	269
33	*	505	512	517	*	452	486	473	475	467	397	*	434	464	*	355	348	344	274
34	*	498	501	509	*	433	477	466	467	461	391	*	419	446	*	356	349	346	278
35	*	486	490	501	*	420	457	457	459	454	386	*	399	426	*	357	351	348	282
36	*	478	481	493	*	405	447	449	452	447	380	*	389	413	*	358	351	349	285
37	*	470	471	485	*	390	439	442	444	441	374	*	370	399	*	358	352	350	288
38	*	461	461	477	*	378	429	434	436	434	368	*	350	380	*	358	352	350	290
39	*	453	452	469	*	366	421	427	428	427	361	*	330	358	*	357	351	350	291
40	*	448	444	461	*	352	419	422	421	420	356	*	316	346	*	358	351	350	293
41	*	437	434	453	*	339	406	413	413	413	350	*	305	333	*	355	350	349	294
42	*	429	425	445	*	329	399	407	404	405	344	*	291	316	*	353	349	349	295
43	*	428	421	440	*	324	399	404	401	400	340	*	283	306	*	356	349	349	296

(*) Thermocouples faulty.

TABLE 6 FLANGE AND WEB TEMPERATÚRES IN BLOCKED-IN COLUMN AGAINST NORTH WALL

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

SECTION : 203 mm x 203 mm x 52 kg/m
NOMINAL Hp/A : ------
COMPONENT IDENTITY : COLUMN (NORTH)
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

	F18	* W10	*			--- 3675 mm
A14		*	*			--- 3300 mm
	F17	* W9	*	F13		--- 3000 mm
A15	F16	* W8	*	F12	A12	--- 2400 mm
	F15	* W7	*	F11		--- 1800 mm
A16	F14	* W6	*	F10	A13	--- 1200 mm
	Unexposed Flange		Exposed Flange			

TIME	STEEL AND ATMOSPHERE TEMPERATURES (deg C)																		
	EXPOSED FLANGE						UNEXPOSED FLANGE								WEB				
(mins)	F10	F11	F12	F13	A13	A12	F14	F15	F16	F17	F18	A16	A15	A14	W6	W7	W8	W9	W10
0	0	-1	0	1	0	-1	0	-1	0	-1	0	0	0	0	*	0	0	0	1
1	1	1	0	2	28	40	1	-1	1	1	8	27	45	59	*	-1	-1	-1	0
2	10	10	12	14	164	282	8	3	8	8	38	151	263	305	*	-1	-1	-2	-1
3	29	30	34	38	361	488	26	17	25	21	49	327	468	453	*	-1	0	-2	0
4	55	59	64	66	525	574	41	38	46	42	66	486	541	510	*	2	2	2	1
5	86	92	104	107	593	626	64	64	69	66	88	556	590	557	*	7	7	6	2
6	137	137	148	145	612	639	90	89	99	89	103	565	600	565	*	16	16	12	5
7	172	170	180	176	626	642	146	119	133	117	147	581	614	576	*	26	28	20	11
8	228	199	210	205	637	659	154	145	157	140	174	591	625	598	*	38	41	30	18
9	240	226	240	235	663	684	188	170	183	162	193	616	653	630	*	52	53	42	24
10	273	259	272	266	681	695	210	197	209	189	222	631	670	652	*	65	66	53	33
11	311	306	313	303	716	733	252	231	241	221	249	659	699	677	*	80	78	67	41
12	348	330	344	335	730	737	269	258	268	248	270	673	712	689	*	97	97	84	52
13	*	362	378	368	708	759	295	287	298	276	286	688	730	700	*	115	112	96	60
14	*	395	412	403	709	767	307	319	328	301	306	677	750	709	*	133	129	115	71
15	*	447	452	440	805	781	385	357	362	333	327	677	762	721	*	150	144	130	82
16	*	481	485	472	811	791	410	390	393	365	348	676	777	735	*	166	159	145	94
17	*	511	514	500	830	800	448	423	423	396	366	713	785	746	*	184	173	161	102
18	*	509	529	520	765	800	444	445	445	414	384	693	781	751	*	199	189	176	101
19	*	531	549	540	747	791	462	468	466	436	398	672	768	747	*	214	209	191	110
20	*	575	575	561	768	769	504	494	487	462	413	677	772	754	*	230	228	208	120
21	*	560	576	567	*	742	489	499	495	467	417	632	725	723	*	243	244	221	145
22	*	568	581	573	*	706	492	507	503	475	421	630	690	687	*	257	258	237	161
23	*	570	581	574	*	668	*	512	505	479	419	602	660	656	*	270	271	250	173
24	*	576	582	574	*	632	*	516	506	495	418	568	630	635	*	279	281	262	183
25	*	565	575	570	*	634	*	511	504	483	418	546	615	623	*	288	291	273	195
26	*	578	606	586	*	623	*	527	519	500	437	532	592	622	*	315	316	301	223
27	*	595	637	601	*	617	*	545	537	530	453	527	603	620	*	343	343	329	252
28	*	586	625	594	*	594	*	537	530	520	451	496	572	599	*	347	347	335	260

(*) Thermocouples faulty : Data invalid.
No data recorded after 28 minutes.

TABLE 7 TEMPERATURES MEASURED IN BOLTS OF EACH CONNECTION

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

COMPONENT IDENTITY : BOLTS
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

```
    **                      **
TH  B1                      B1  TH
TT  B2                      B2  TT
    ************************
BH  B3                      B3  BH
BT  B4                      B4  BT
    **                      **
Back Column          Front Column
 (North)               (South)
```

TIME (mins)	STEEL TEMPERATURES (deg C)							
	NORTH				SOUTH			
	B1	B2	B3	B4	B1	B2	B3	B4
0	*	1	0	0	0	0	0	0
1	*	-1	-1	-1	0	0	0	0
2	*	-1	8	0	8	1	10	0
3	*	3	25	4	22	6	28	4
4	*	10	45	11	38	16	47	12
5	*	19	66	23	55	27	67	22
6	*	32	85	38	74	40	89	34
7	*	46	106	55	93	54	109	48
8	*	61	124	72	111	69	128	64
9	*	76	145	89	125	86	149	80
10	*	90	167	106	148	99	172	97
11	*	104	192	123	170	114	194	116
12	*	124	215	144	191	127	218	134
13	*	142	239	161	213	142	243	153
14	*	161	266	182	236	159	267	173
15	*	179	294	202	259	177	293	194
16	*	197	322	224	283	196	319	214
17	*	215	349	246	307	215	345	235
18	*	233	373	267	329	234	369	256
19	*	252	397	287	350	252	391	271
20	*	270	421	308	368	270	410	291
21	*	288	438	327	384	278	427	314
22	*	304	452	345	397	298	441	333
23	*	317	460	362	407	313	451	349
24	*	327	465	375	415	325	458	363
25	*	339	470	387	422	336	464	374
26	*	366	492	416	427	345	469	383
27	*	392	515	443	430	353	472	391
28	*	398	513	449	432	359	473	398
29	*	*	*	*	431	361	472	402
30	*	*	*	*	435	369	475	409
31	*	*	*	*	434	372	474	413
32	*	*	*	*	435	377	475	418
33	*	*	*	*	433	378	473	420
34	*	*	*	*	431	379	471	421
35	*	*	*	*	428	380	469	421
36	*	*	*	*	425	380	466	422
37	*	*	*	*	422	380	463	421
38	*	*	*	*	418	379	459	420

(*) Thermocouples and/or data logger faulty : Data invalid.

TABLE 8 TEMPERATURES IN INDICATIVE COLUMN

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

SECTION : 203 mm x 203 mm x 52 kg/m
NOMINAL Hp/A : 180 /m
COMPONENT IDENTITY : COLUMN (INDICATIVE)
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

```
* 1 * * * * * * *
        *
        *
        *
        3
        *
        *
        *
* * * * * * * 2 *
```

TIME	STEEL TEMPERATURES (deg C)		
	1500mm LEVEL		
(mins)	1	2	3
0	0	0	0
1	1	3	8
2	20	31	25
3	58	80	82
4	111	146	140
5	174	216	205
6	236	280	269
7	297	344	329
8	355	404	386
9	411	462	439
10	463	513	490
11	515	562	539
12	562	607	584
13	603	645	623
14	639	678	657
15	673	707	687
16	692	728	708
17	717	749	730
18	743	760	750
19	753	770	755
20	760	776	759
21	766	778	761
22	764	773	755
23	758	766	746
24	744	753	733
25	724	734	716
26	710	717	704
27	700	700	695
28	692	684	678
29	672	675	657
30	657	665	642
31	639	646	624
32	623	629	609
33	606	611	592
34	589	594	575
35	575	579	562
36	561	564	548
37	547	550	534
38	533	536	521
39	520	522	508
40	507	509	494
41	496	497	485
42	484	486	473
43	477	478	464

TABLE 9 TEMPERATURES IN EXTERNAL COLUMN

TRIAL NUMBER : 23
TRIAL DATE : 21st FEBRUARY 1986
SITE : FRS CARDINGTON

SECTION : 203 mm x 203 mm x 52 kg/m
NOMINAL Hp/A : 180 /m
COMPONENT IDENTITY : EXTCOL
FIRE LOAD : 25 kg/m2 WOOD
TOTAL VENTILATION : 1/8 OF EACH OF 2 WALLS

```
U  *             *
N  1             *  E
E  *             *  X
X  *             *  P
P  2 * * 3 * * 4    O
O  *             *  S
S  *             *  E
E  *             5  D
D  *             *
```

TIME	STEEL AND ATMOSPHERE TEMPERATURES (deg C)					
	3300mm LEVEL			1900mm LEVEL		
(mins)	1	3	5	3	5	ATM
0	-1	-1	-1	-1	-1	-1.0
1	-1	-1	-1	-1	-1	0.0
2	2	6	5	-1	1	9.0
3	8	17	13	0	5	30.0
4	15	32	22	0	12	54.0
5	23	49	32	3	21	76.0
6	31	65	40	5	32	88.0
7	37	81	48	8	43	100.0
8	43	96	56	12	54	107.0
9	48	111	63	16	67	113.0
10	55	126	72	21	79	118.0
11	61	140	81	27	93	122.0
12	67	155	90	33	107	135.0
13	74	168	99	38	120	143.0
14	79	182	106	45	135	149.0
15	84	194	113	52	149	159.0
16	88	205	120	58	162	165.0
17	92	219	127	66	175	168.0
18	97	230	133	73	188	179.0
19	103	237	141	81	200	188.0
20	109	242	146	89	210	187.0
21	111	243	148	96	218	173.0
22	113	241	149	102	222	152.0
23	113	238	149	106	225	137.0
24	114	235	149	110	225	127.0
25	114	232	149	112	224	122.0
26	114	227	147	114	221	113.0
27	113	222	145	116	218	97.0
28	111	216	143	117	214	84.0
29	107	209	138	115	208	77.0
30	108	206	138	117	206	75.0
31	106	200	135	116	202	71.0
32	106	196	135	118	200	67.0
33	103	190	132	116	195	66.0
34	101	185	129	115	190	64.0
35	100	180	126	114	186	58.0
36	98	175	123	113	182	58.0
37	97	170	121	111	177	53.0
38	95	165	118	110	173	50.0
39	93	161	115	108	169	47.0
40	90	156	112	106	165	43.0
41	90	152	110	105	162	41.0
42	88	148	108	103	158	40.0
43	86	145	106	102	155	40.0

TABLE 10 FRS LATERAL DISPLACEMENT TRANSDUCER READINGS FOR BLOCKED-IN COLUMNS

Time, mm	South Facing Column Displacement, mm				North Facing Column Displacement, mm			
	H = 760	H = 2090	H = 3460	LF*	H = 760	H = 2090	H = 3460	LF*
0	0	0	0	0	0	0	0	0
4	0.15	0.20	0	0	0.10	0.10	-0.7	0
6	1.0	2.2	3.3	3.2	1.5	2.3	1.1	1.0
8	2.4	4.9	7.5	7.5	3.4	5.8	4.7	5.1
10	3.9	8.4	11.9	12.4	5.3	9.0	8.1	8.0
12	5.3	11.5	16.0	16.4	7.0	12.3	12.8	12.8
14	6.6	15.7	19.5	19.7	8.5	15.4	15.5	15.5
16	8.8	21.2	23.6	23.5	10.5	20.2	19.2	19.0
18	10.4	30.2	30.6	31.0	12.3	25.5	22.9	22.5
20	11.9	41.6	37.7	37.4	13.1	30.9	28.0	27.5
22	11.9	47.8	41.0	40.5	13.1	34.3	28.0	27.5

H = height from floor LF* = estimate adjacent to lower flange of beam

TABLE 11 UNRESTRAINED DISPLACEMENTS OF BLOCKED-IN COLUMNS AND BEAM IN NATURAL FIRE TEST ON LOADED STEEL FRAME

Time min	Average Steel Flange Temperatures, °C												Lateral Displacement, mm			
	Front Column				Back Column				Beam				Front Column	Back Column	Beam	
	T1	T2	T1-T2	T1+T2	T1	T2	T1-T2	T1+T2	T1	T2	T1-T2	T1+T2	ΔH	ΔH	ΔL	Δh
4	99	38	61	137	61	42	19	103	137	70	67	207	18.5	5.8	8.7	6.0
6	217	81	136	298	142	92	50	234	276	151	125	427	41.3	15.2	17.5	11.2
8	279	140	139	419	211	149	62	360	394	224	170	618	42.3	18.8	25.0	15.3
10	345	193	152	538	268	201	67	469	498	299	199	797	46.2	20.4	31.7	17.9
12	418	253	165	671	339	261	78	600	586	372	214	958	50.2	23.7	37.3	19.3
14	480	315	165	795	403	314	89	717	650	438	212	1088	50.2	27.1	41.4	19.1
16	536	381	155	917	479	390	89	869	708	497	209	1203	47.1	27.1	45.1	18.8
18	584	441	143	1025	519	437	82	956	734	543	191	1277	43.5	24.9	46.8	17.2
20	600	482	118	1082	570	487	83	1057	753	577	176	1330	35.9	25.2	48.0	15.8
22	595	505	90	1100	574	494	80	1068	743	591	152	1334	27.4	24.3	47.3	13.7

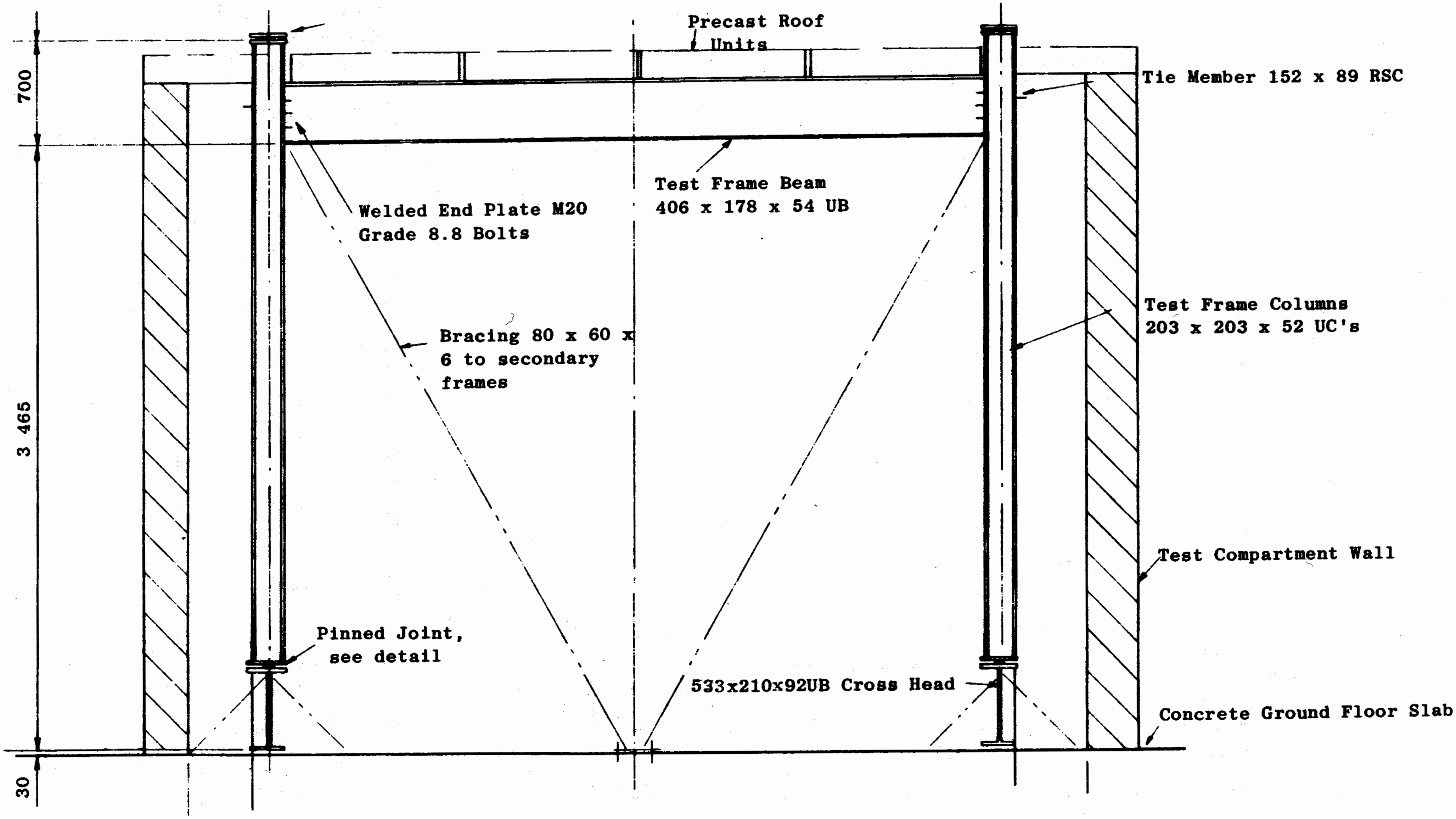
Note: T1 = Temperature rise of hotter flange
T2 = Temperature rise of cooler flange
H = Column height to lower flange of beam = 2992 mm
L = Beam span = 4553 mm
α = Average coefficient of expansion = 0.000014 mm/mm/°C
d_1 = Depth of column = 206.2 mm
d_2 = Depth of beam = 402.6 mm

FRS Equations:

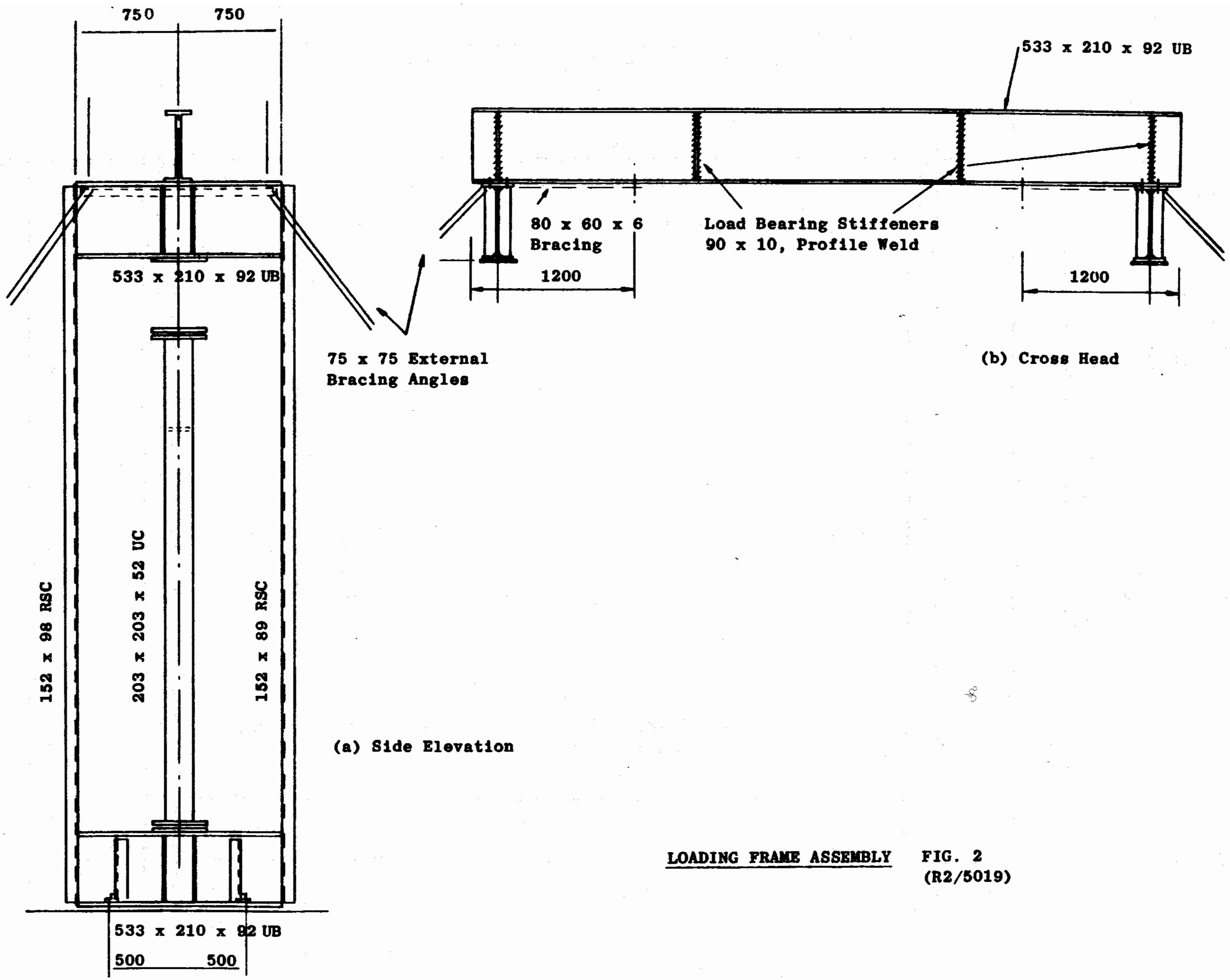
Lateral displacement of column $\Delta H = \frac{\alpha(T1-T2)H^2}{2d_1}$

Lateral displacement of beam $\Delta L = \frac{\alpha(T1+T2)L}{2} + \left[\frac{\alpha(T1-T2)L}{2}\right]$

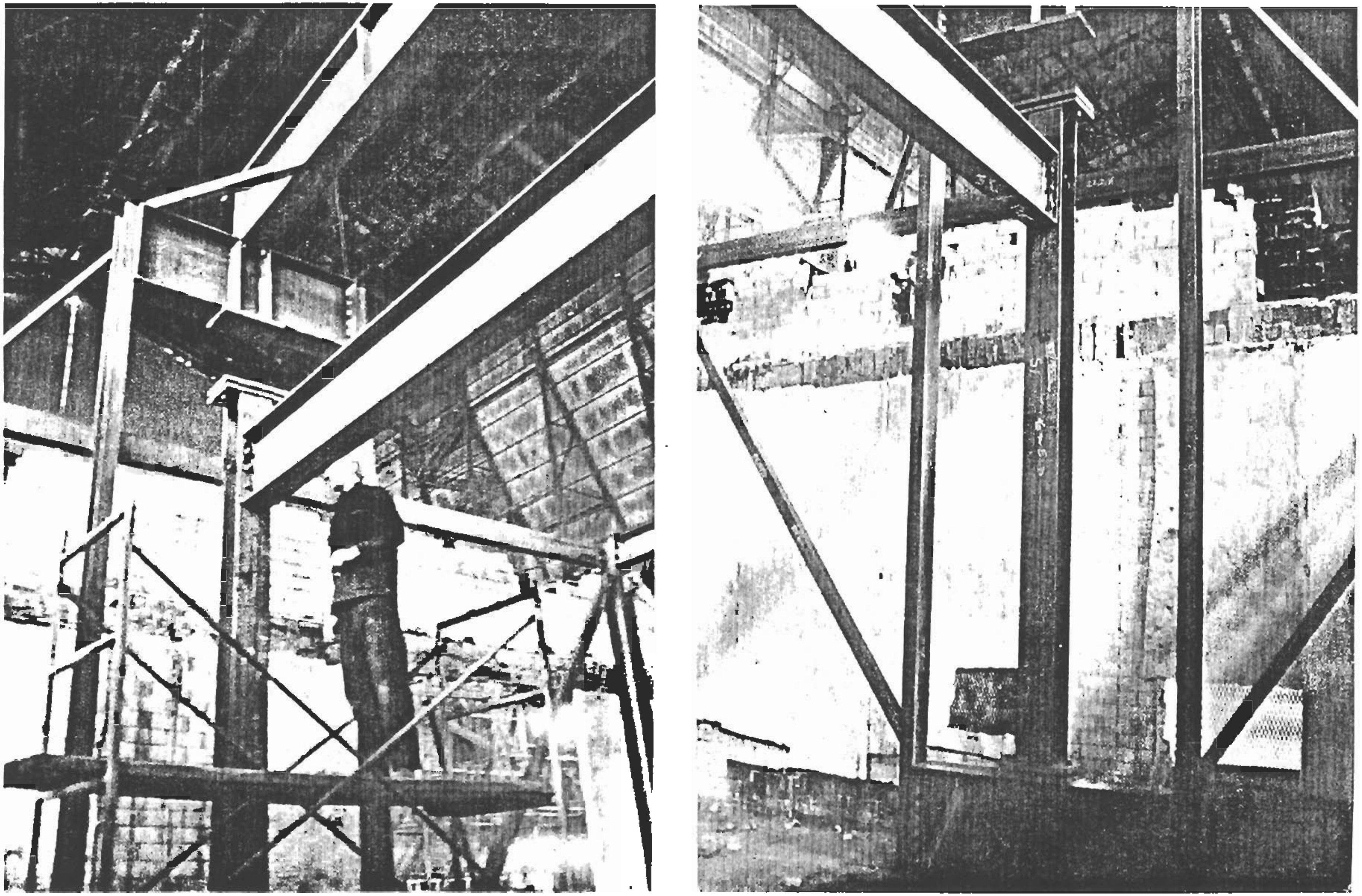
Thermal bowing of beam $\Delta h = \frac{\alpha(T1-T2)L^2}{8d_2}$



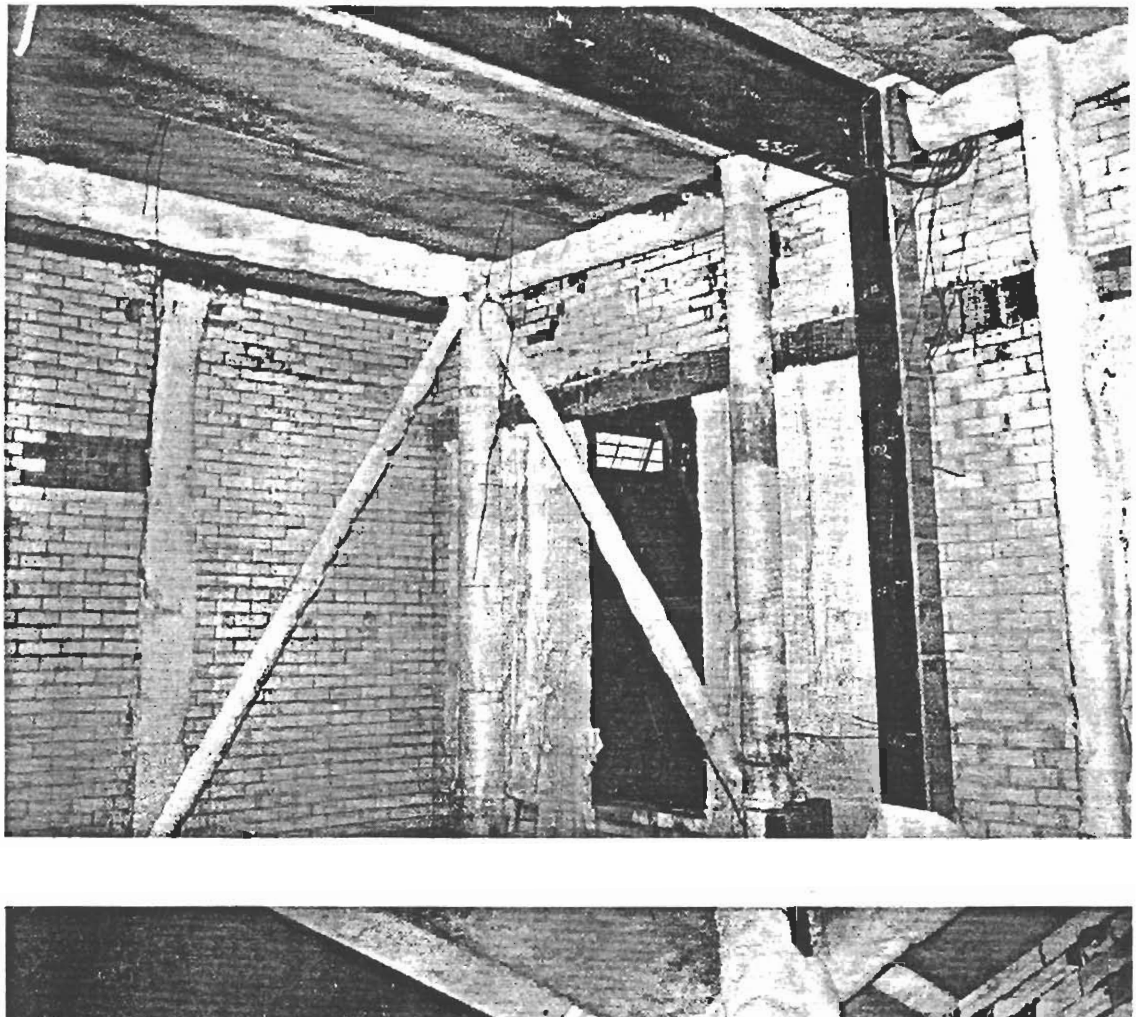
TEST FRAME - FRONT ELEVATION FIG. 1
(R2/5018)



LOADING FRAME ASSEMBLY FIG. 2
(R2/5019)

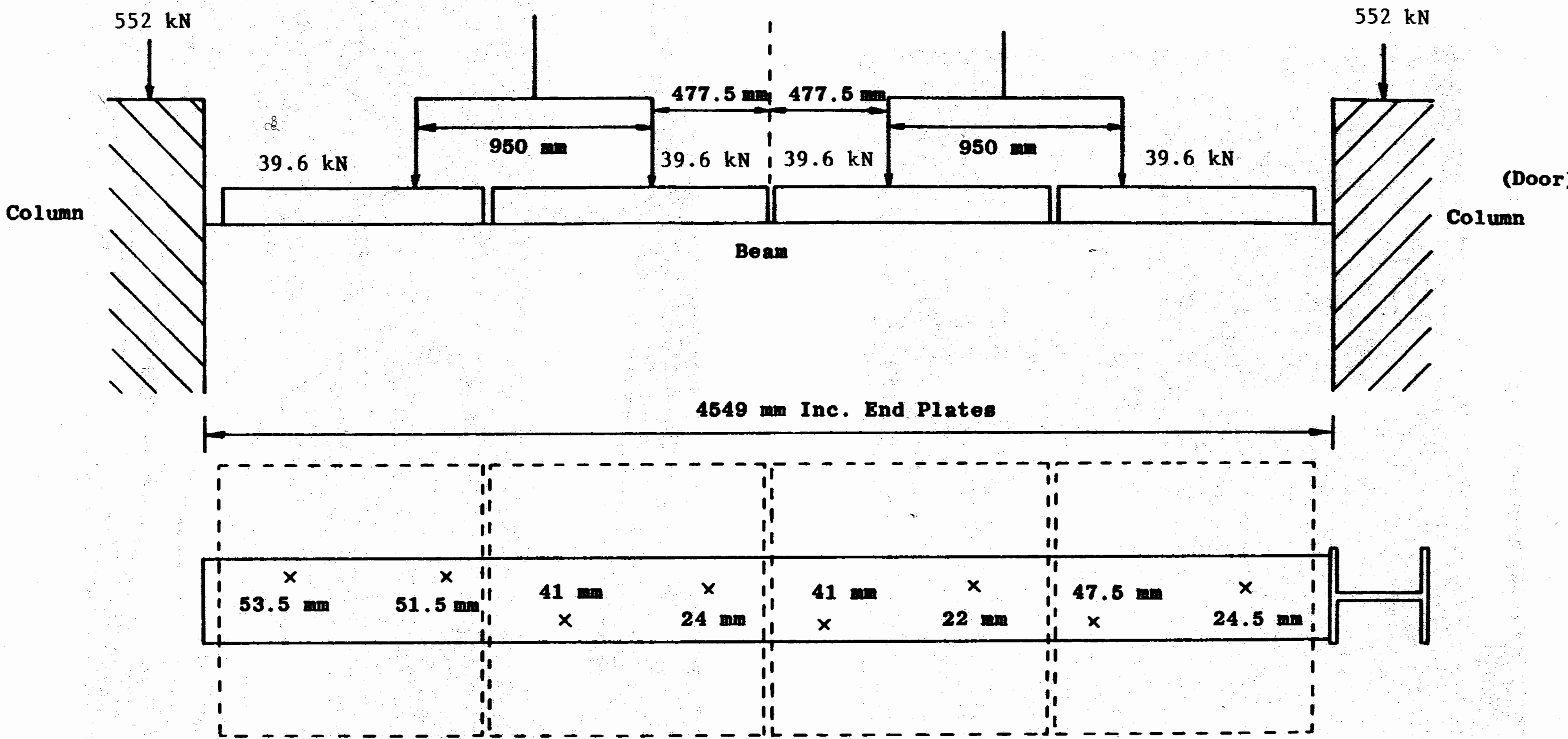


ERECTION OF TEST FRAME AND LOADING ASSEMBLY FIG. 3

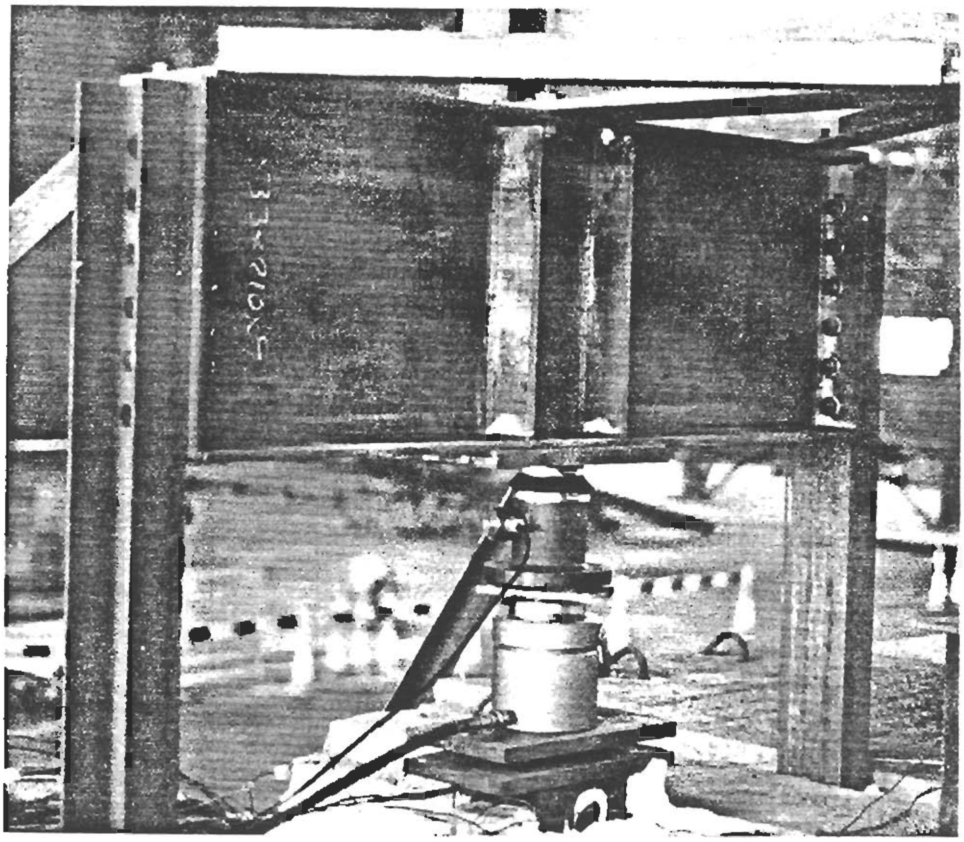


LOADING AND SECONDARY STEEL FRAME LAGGED WITH CERAMIC FIBRE BLANKET

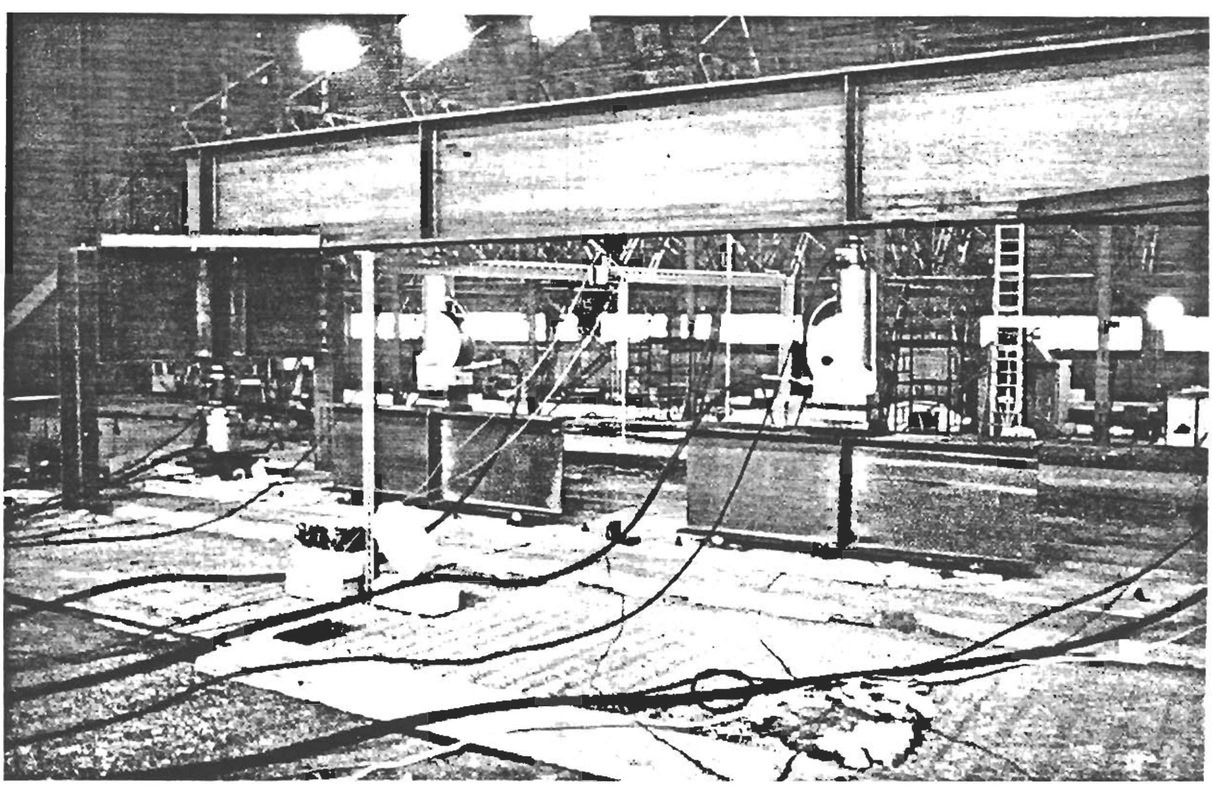
FIG. 4



SCHEMATIC REPRESENTATION OF LOADING POINTS FIG. 5
(R2/5020)

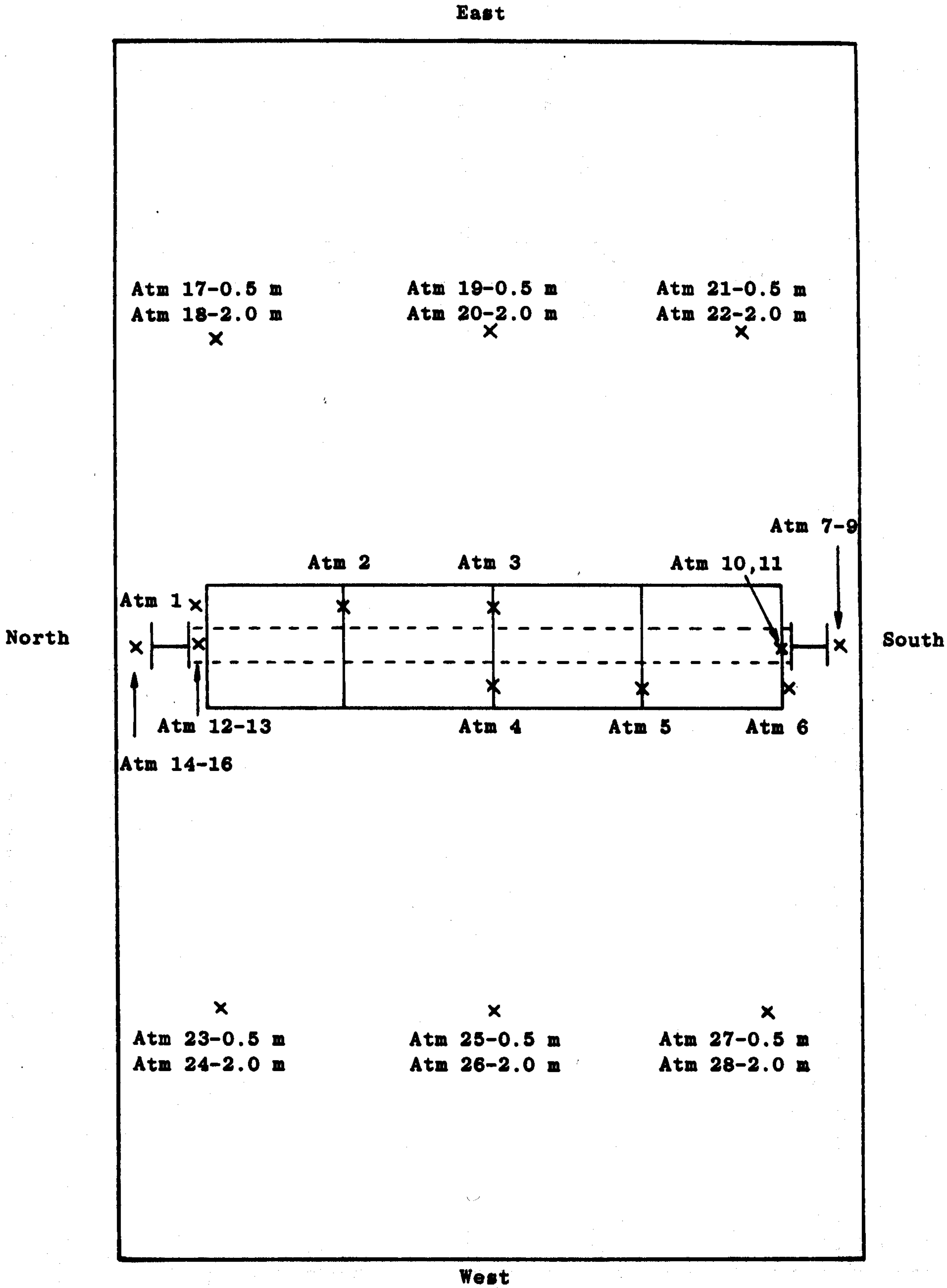


Column



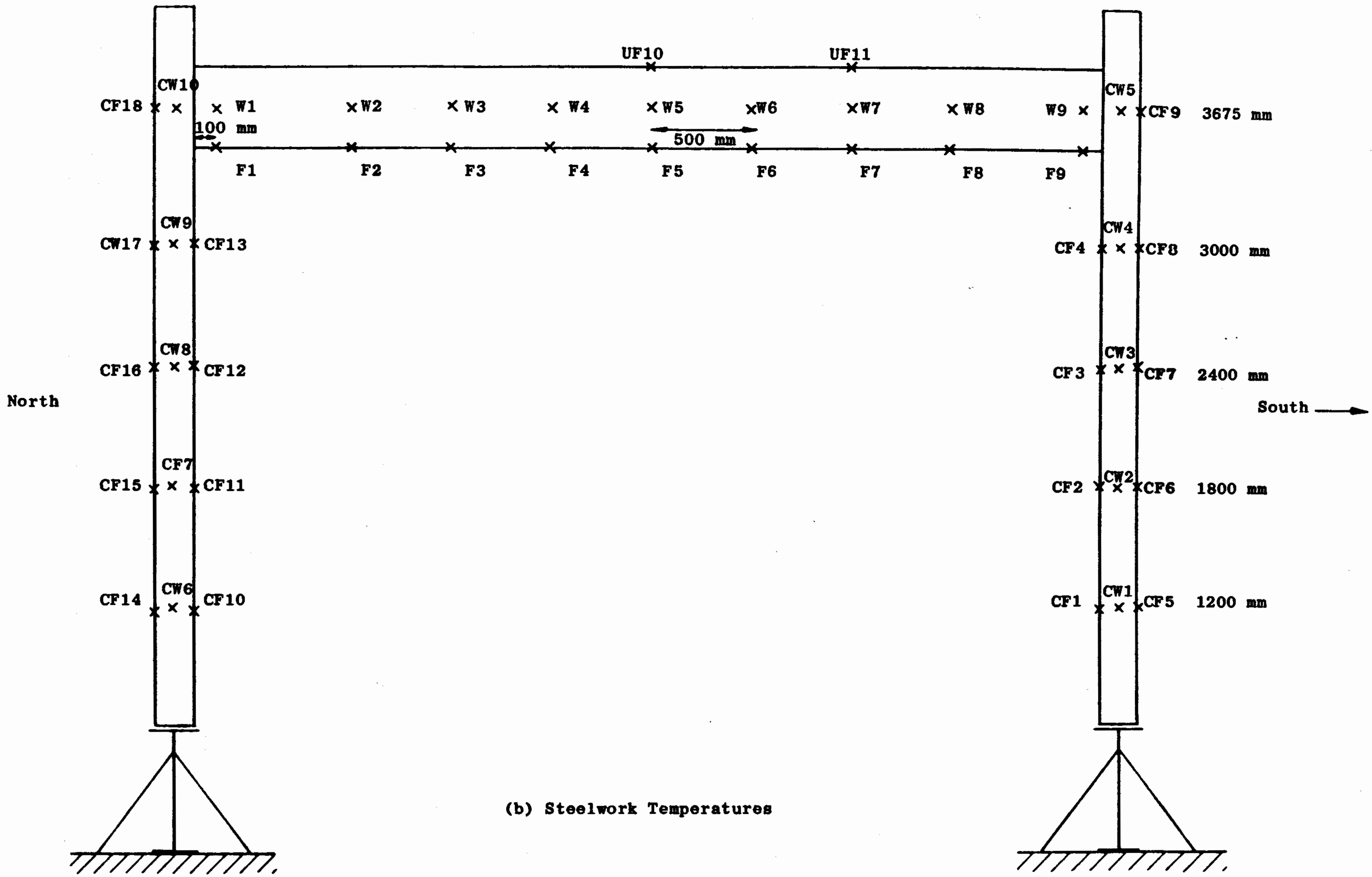
Beam

<u>LOADING ARRANGEMENT USED IN FIRE TEST</u> FIG. 6



(a) Combustion Gas Temperatures

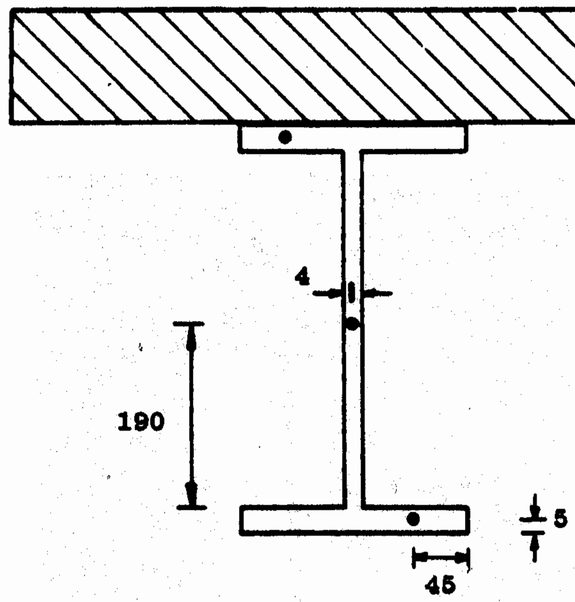
POSITION OF THERMOCOUPLES IN COMPARTMENT FIG. 7
(R2/5021)



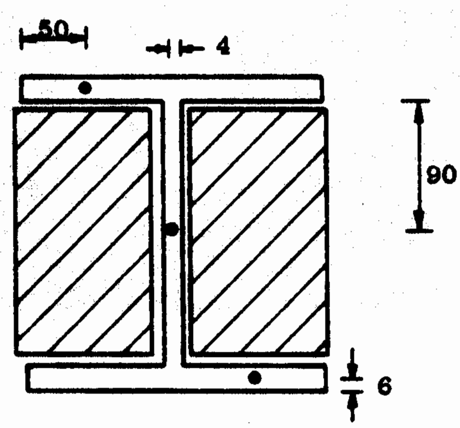
(b) Steelwork Temperatures

POSITION OF THERMOCOUPLES IN COMPARTMENT FIG. 7 (Continued)
(R2/5022)

Dimensions in mm



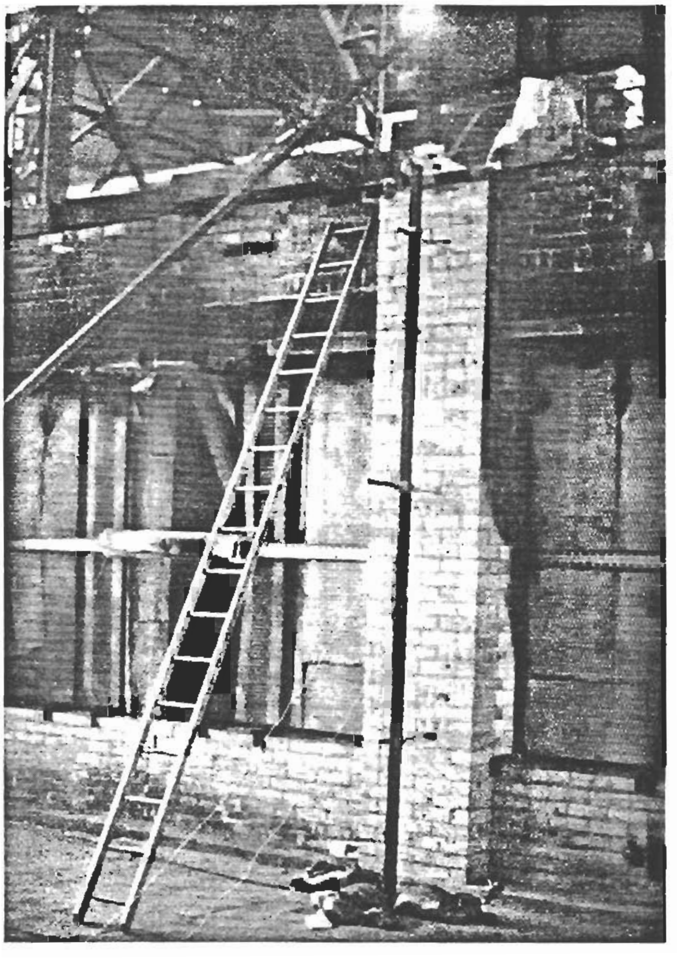
406 x 178 mm x 54 kg/m Universal Beam



203 x 203 mm x 52 kg/m Universal Beam

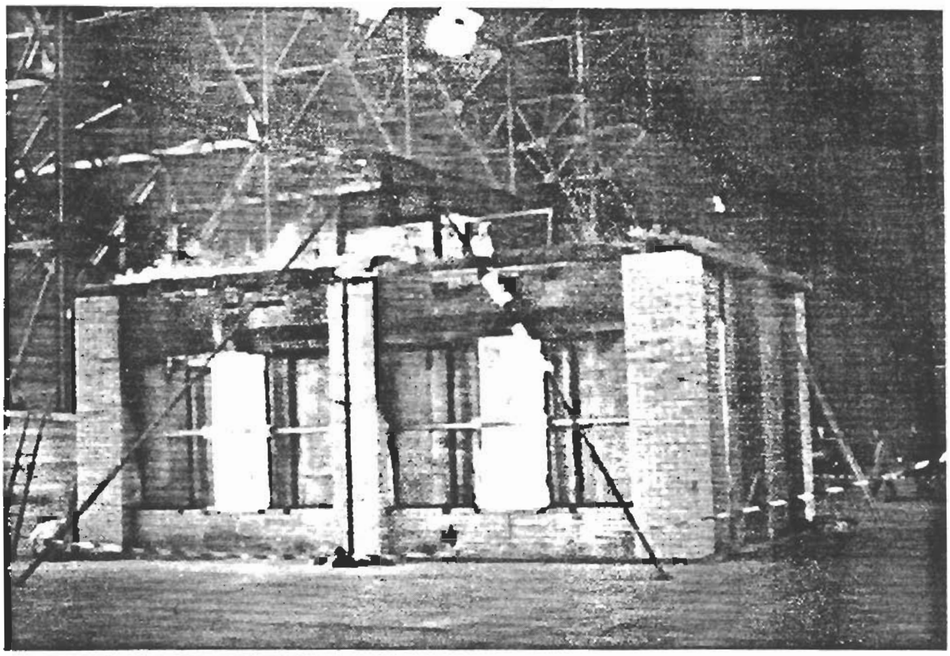
(c) Location of Thermocouples in Steelwork

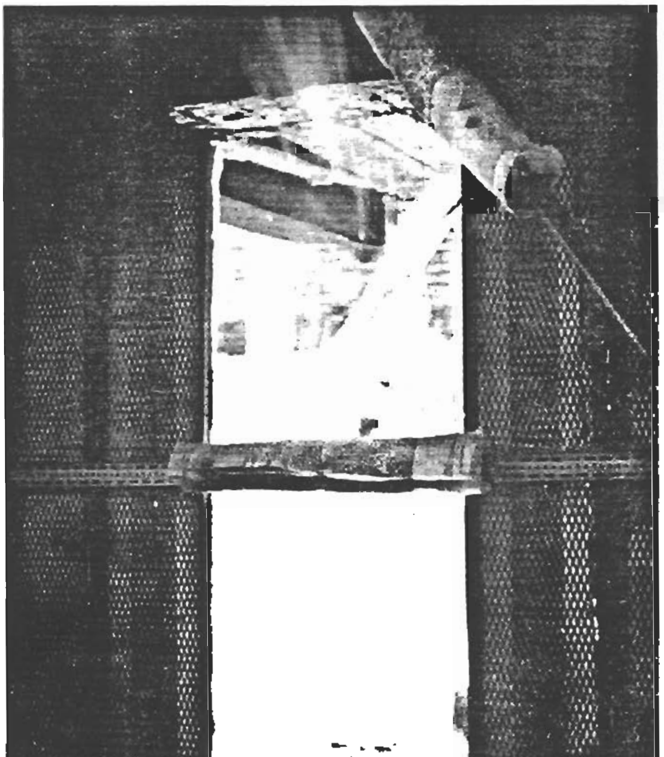
<u>POSITION OF THERMOCOUPLES IN COMPARTMENT</u> FIG 7 (Continued)
(R2/5023)



FRS DISPLACEMENT TRANSDUCER FIXTURE FOR MONITORING THE DEFLECTION OF THE BLOCKED-IN COLUMN

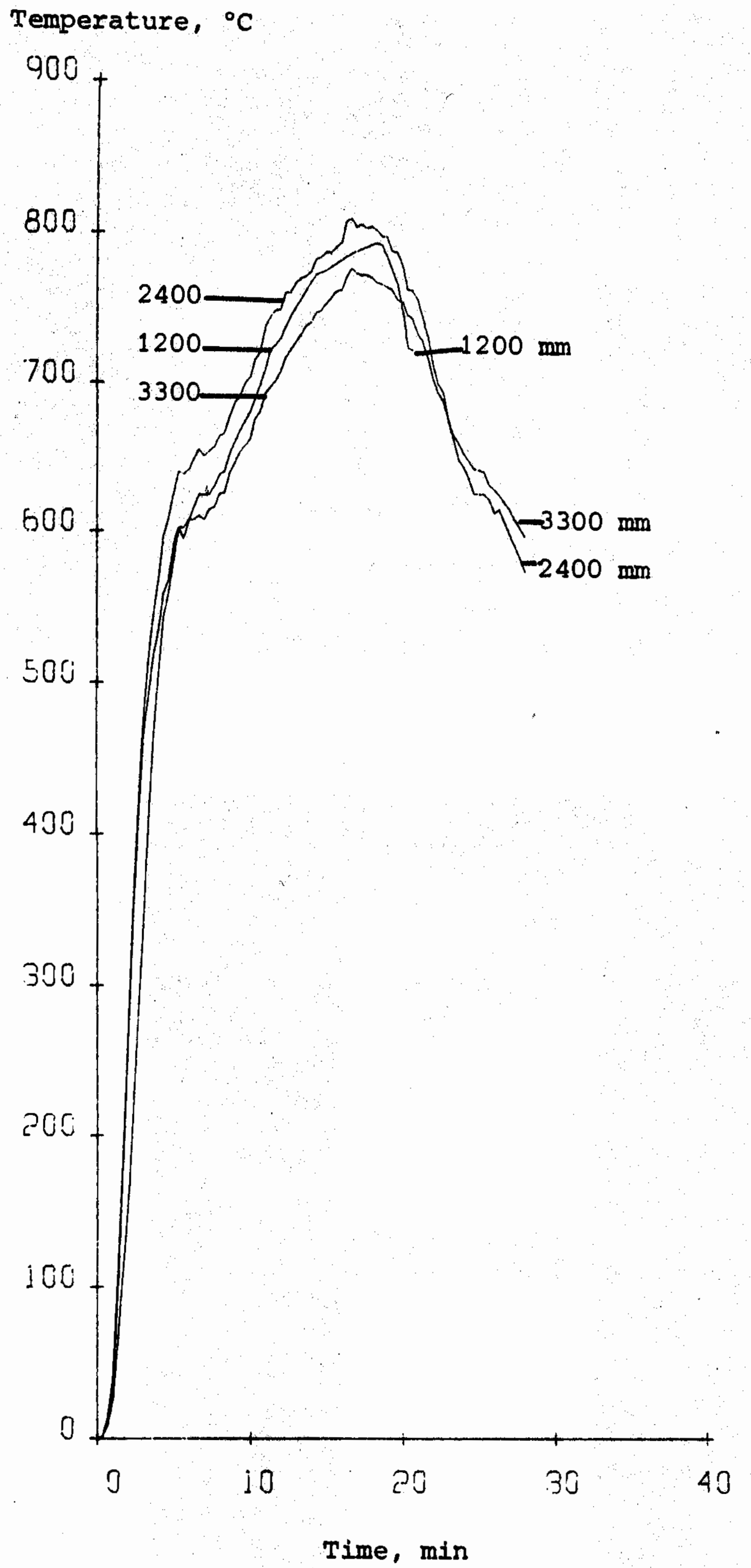
FIG. 8





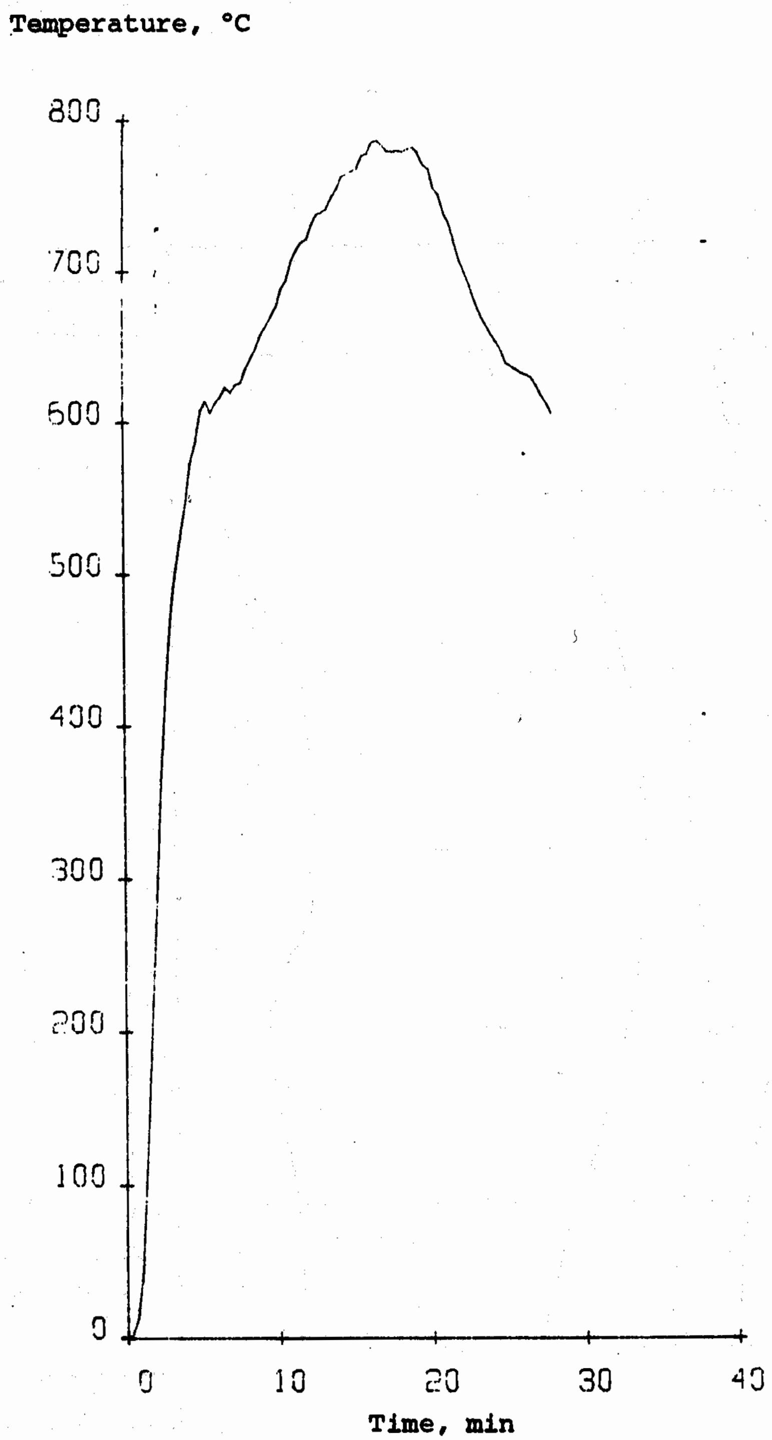
FIRE TEST IN PROGRESS

FIG. 9



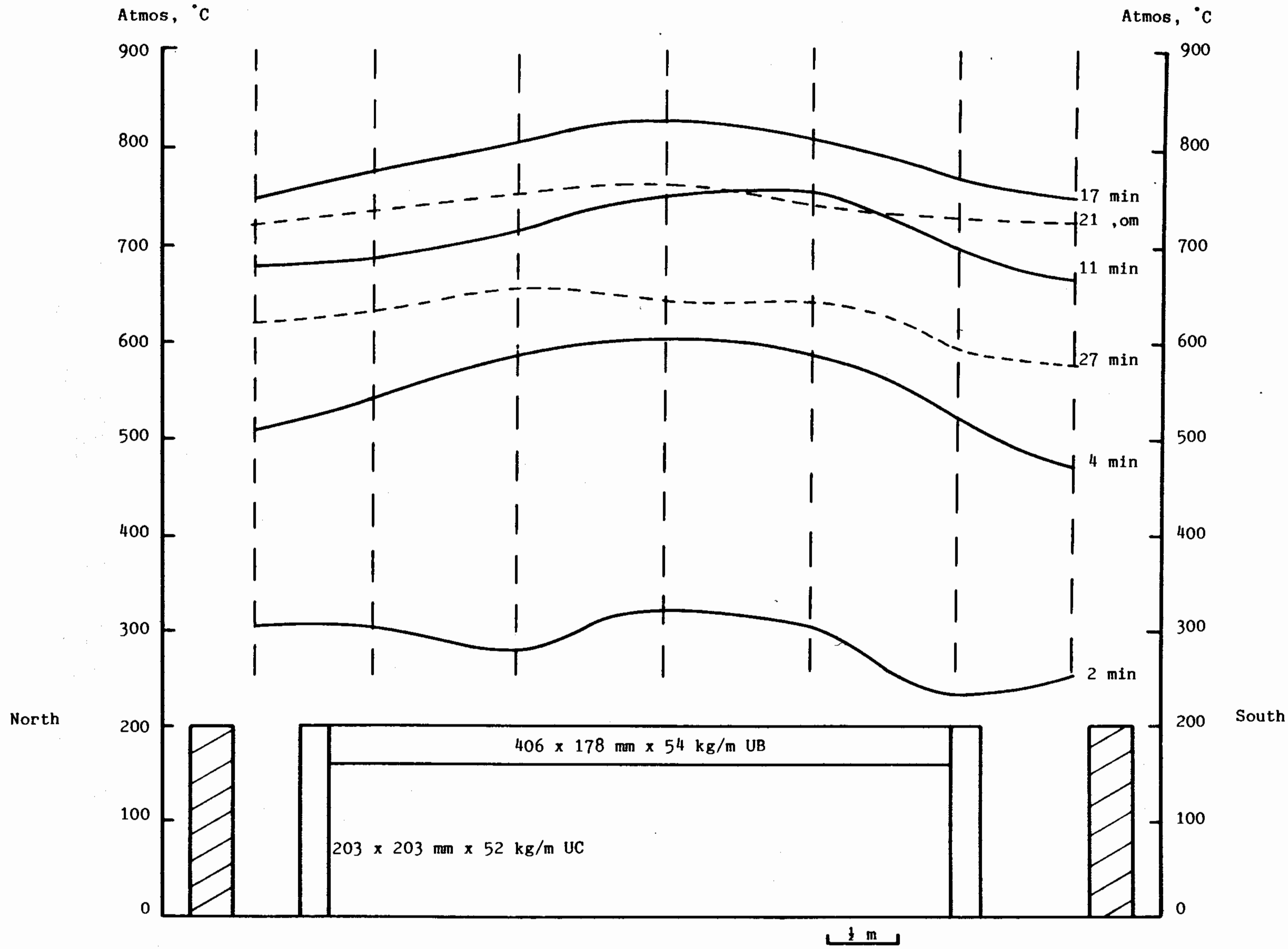
CHANGE IN COMBUSTION GAS TEMPERATURE WITH HEIGHT IN THE VICINITY OF THE COLUMNS

FIG. 10



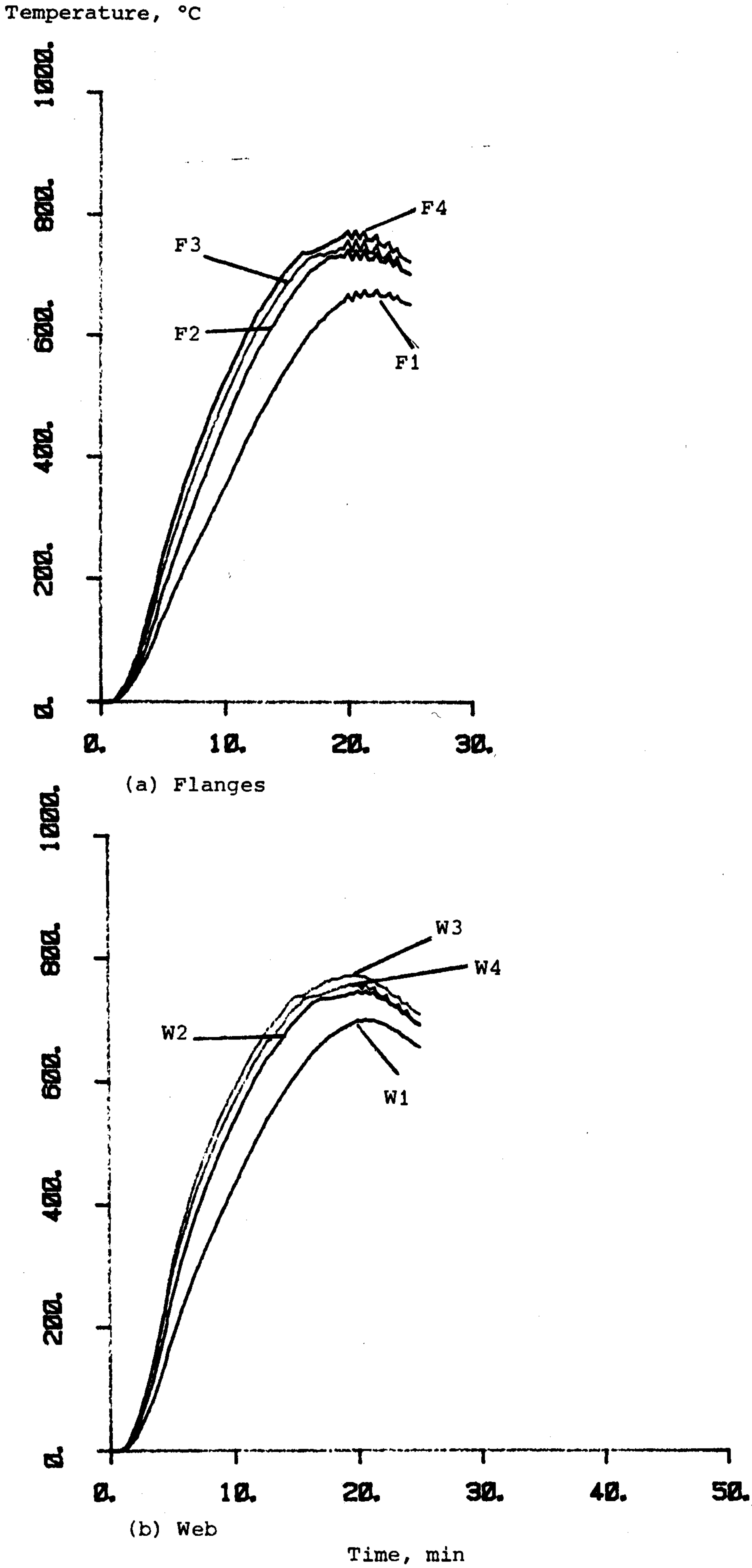
AVERAGE COMBUSTION GAS TEMPERATURE RECORDED IN THE VICINITY OF THE LOADED BEAM

FIG. 11

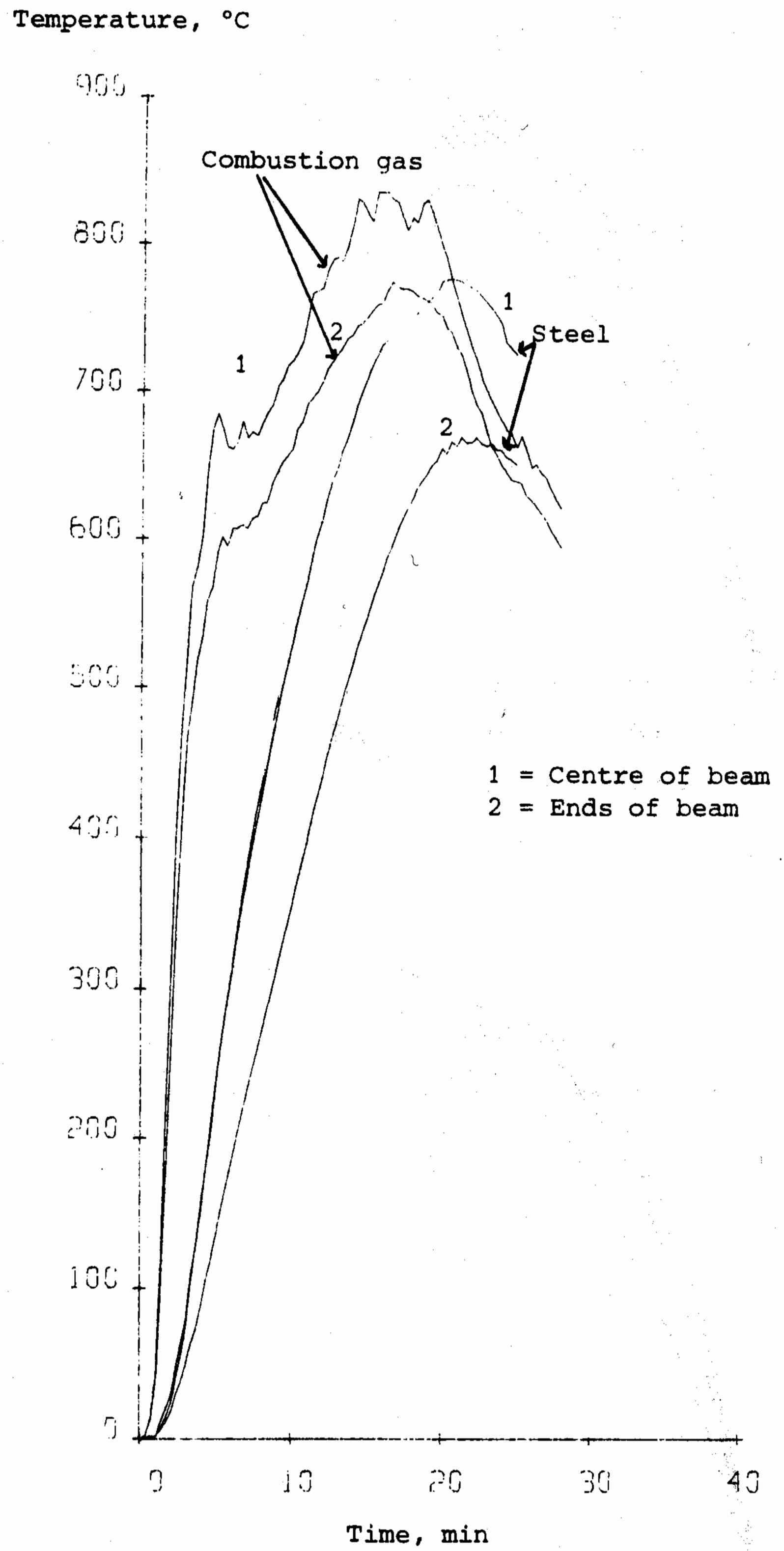


COMBUSTION GAS TEMPERATURE PATTERNS ESTABLISHED IN THE VICINITY OF THE LOADED STRUCTURE

FIG. 12
(R2/5312)

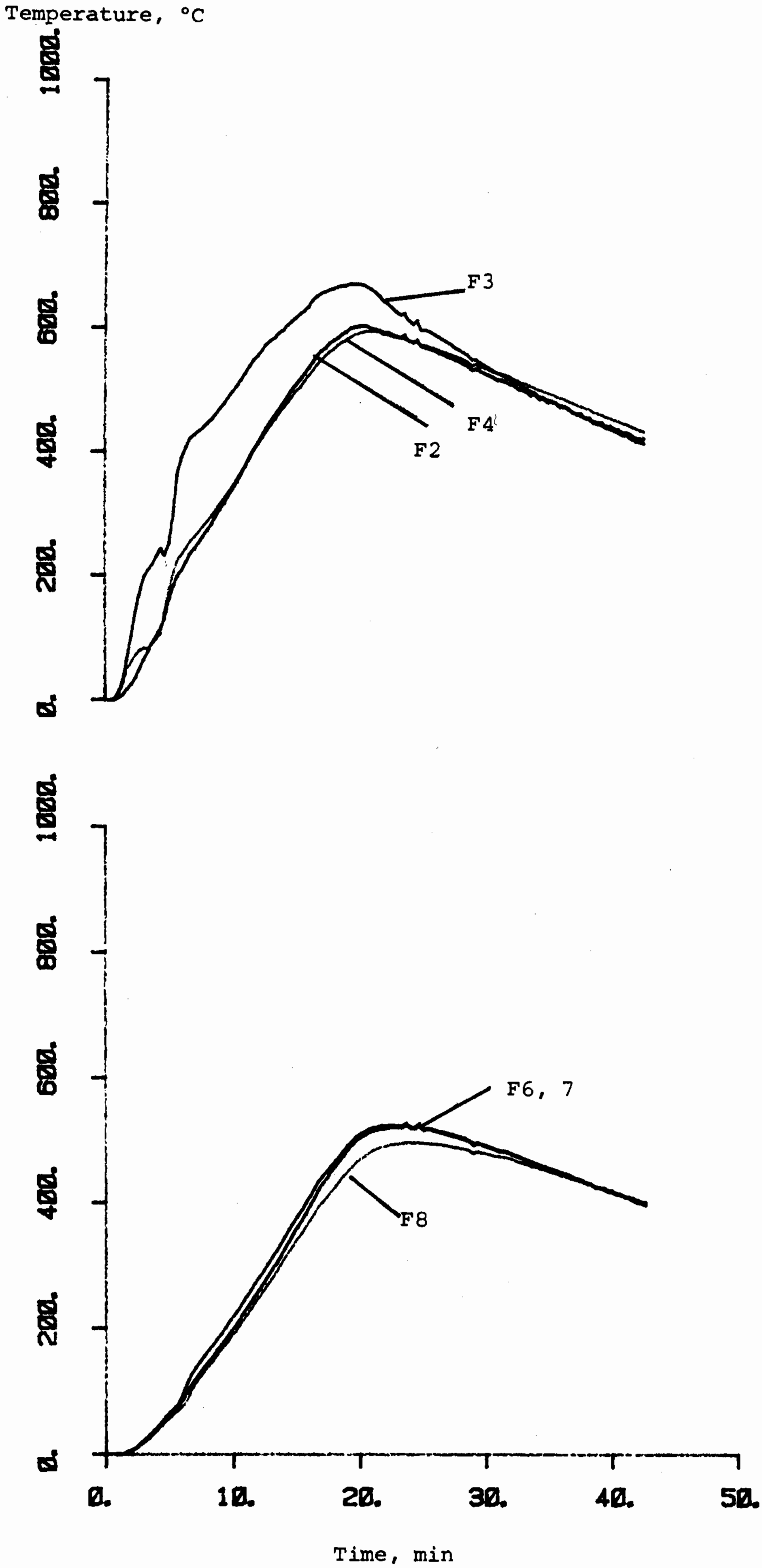


STEEL TEMPERATURES MEASURED IN BEAM FIG. 13



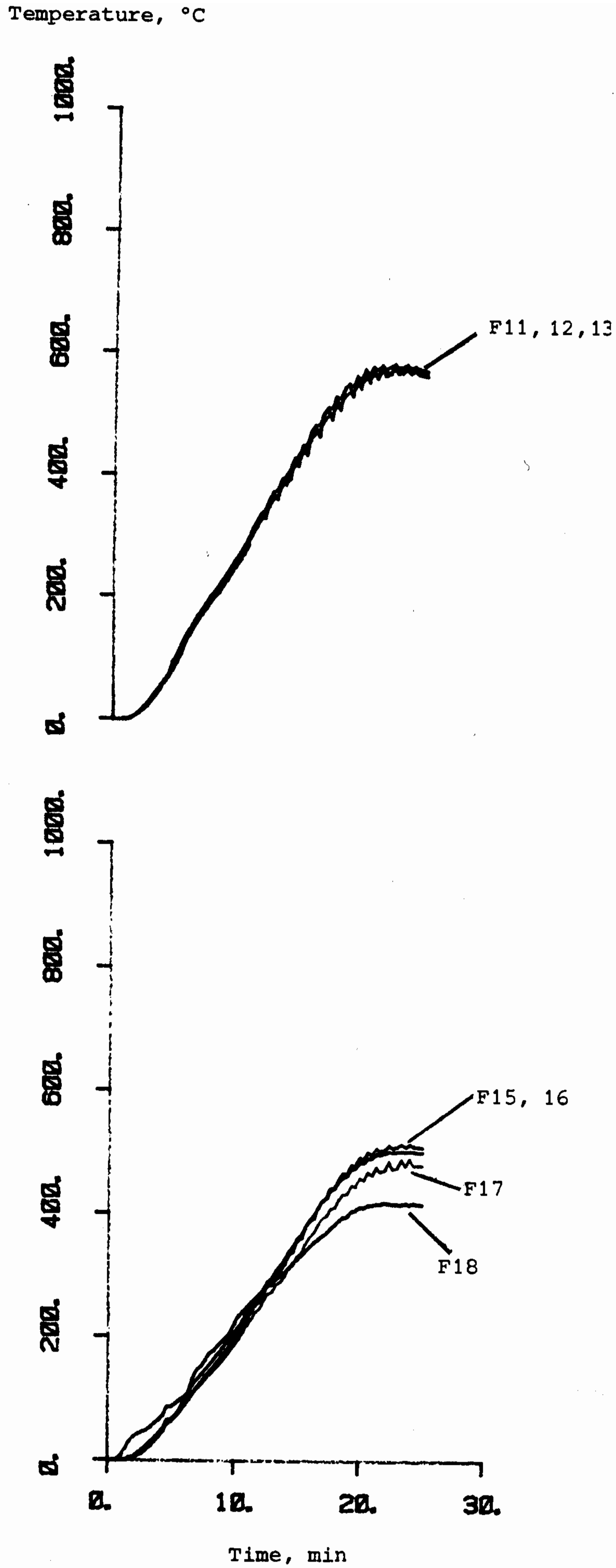
AVERAGE COMBUSTION GAS AND STEEL TEMPERATURES RECORDED AT THE ENDS AND CENTRE OF THE BEAM

FIG. 14



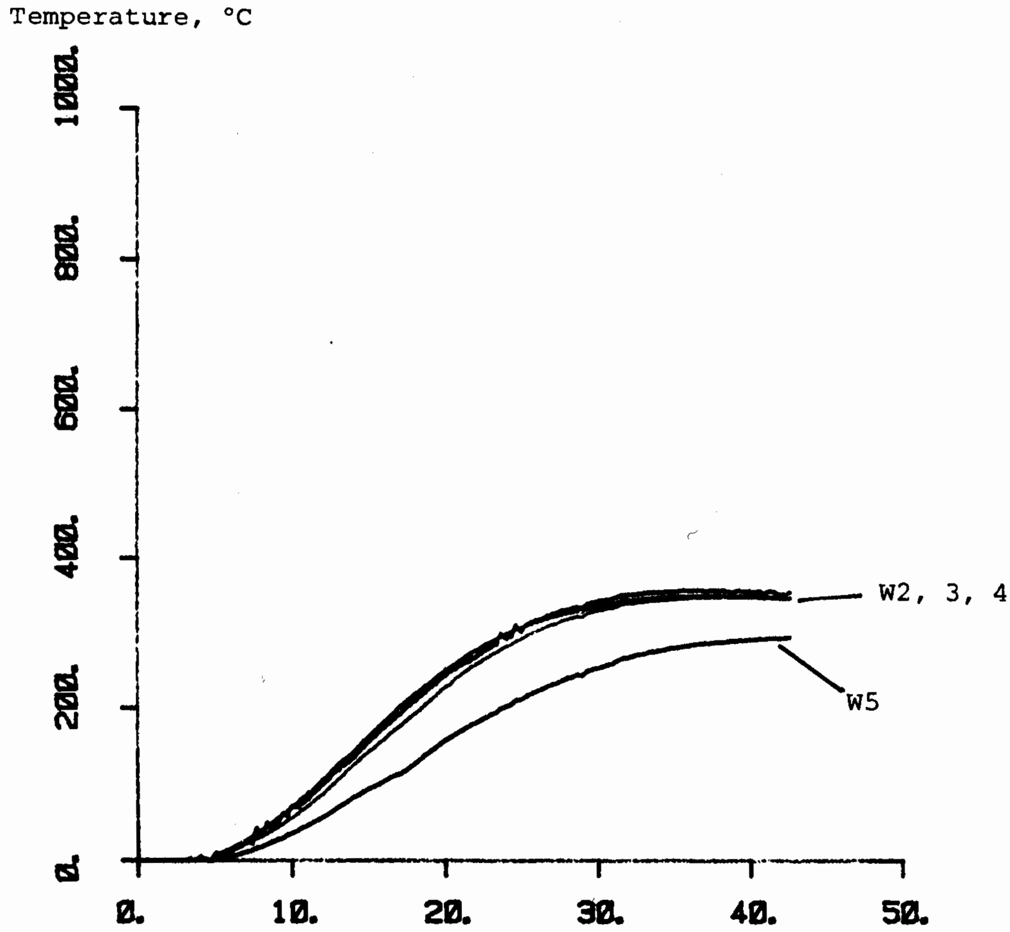
STEEL TEMPERATURES IN BLOCKED IN COLUMN ADJACENT TO THE SOUTH WALL OF THE COMPARTMENT

FIG. 15

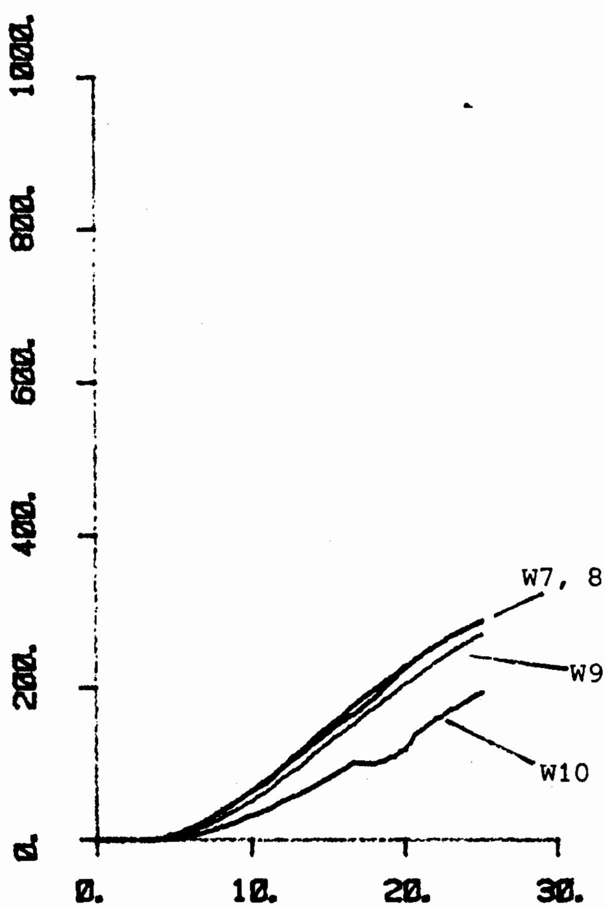


STEEL TEMPERATURES IN BLOCKED IN COLUMN ADJACENT TO THE NORTH WALL OF THE COMPARTMENT

FIG. 16

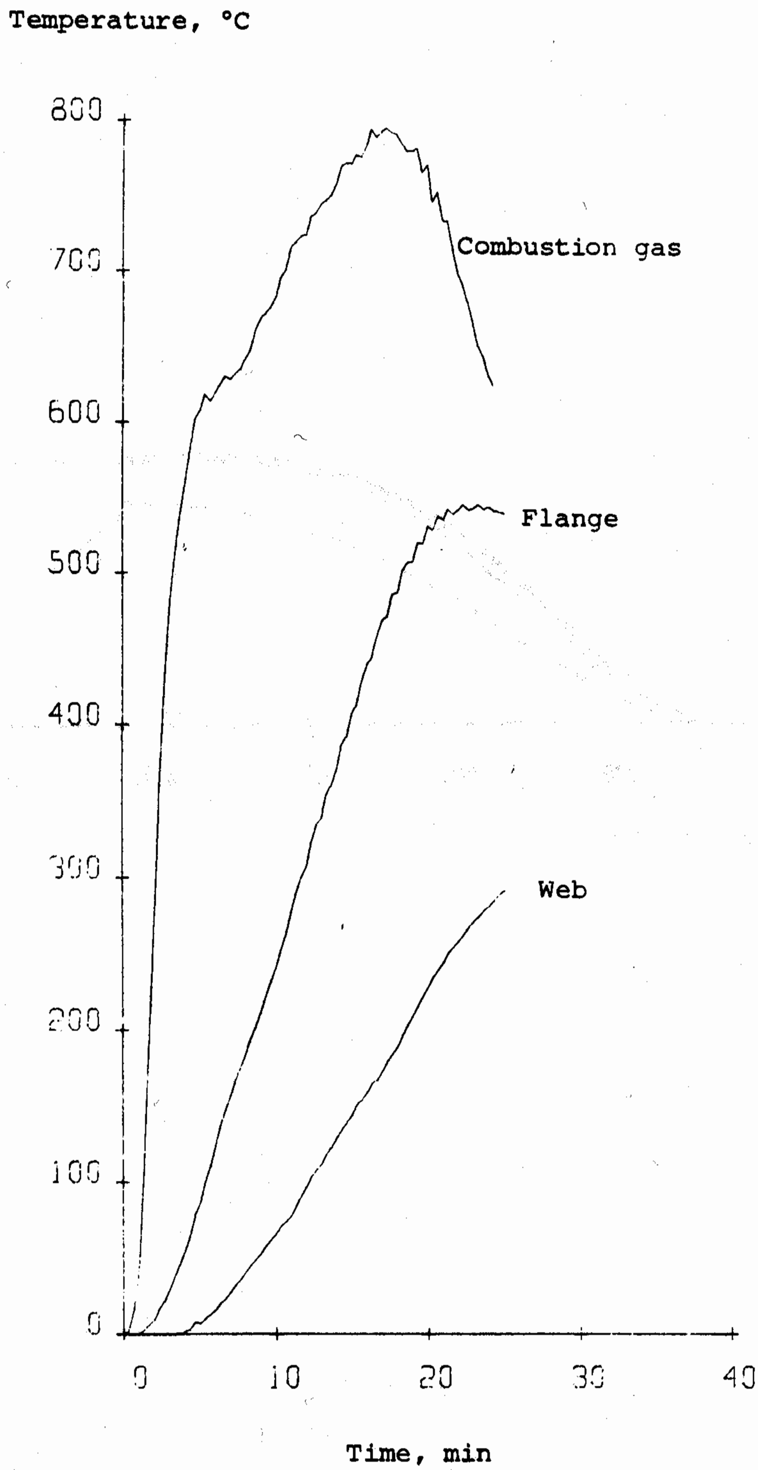


(a) South



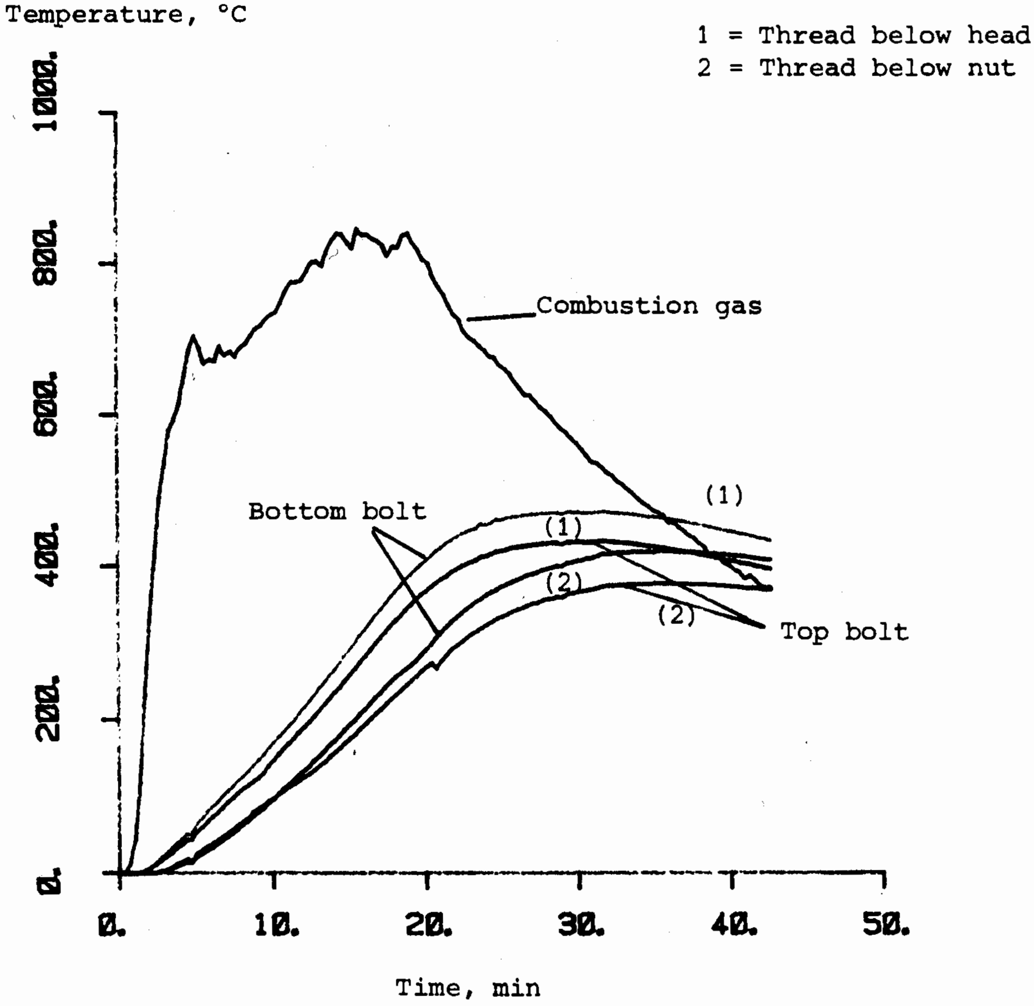
(b) North

STEEL WEB TEMPERATURES IN BLOCKED IN COLUMNS FIG. 17

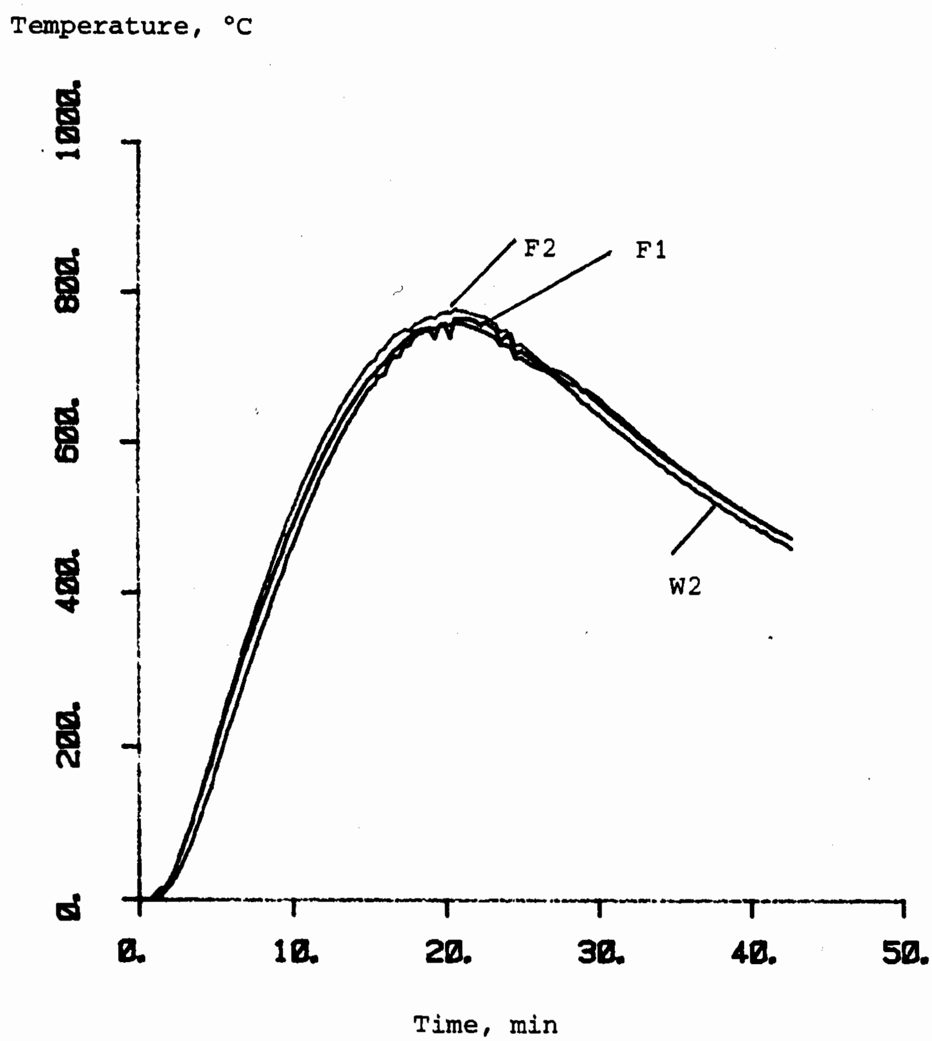


AVERAGE COMBUSTION GAS AND STEEL TEMPERATURES RECORDED AT THE CENTRE OF THE BLOCKED IN COLUMN ADJACENT TO THE NORTH WALL OF THE COMPARTMENT

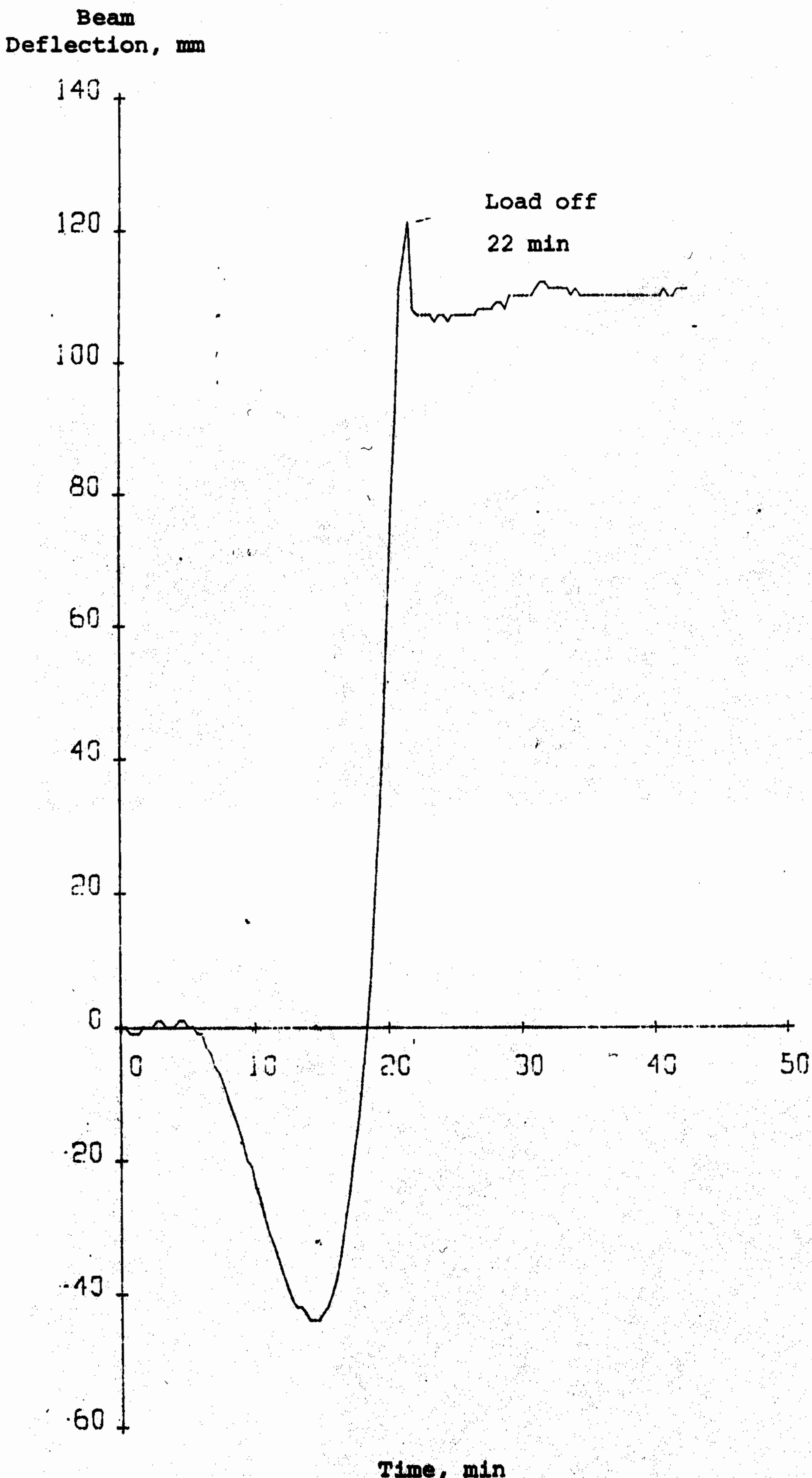
FIG. 18



TYPICAL TEMPERATURE PROFILES IN BOLTS FIG. 19

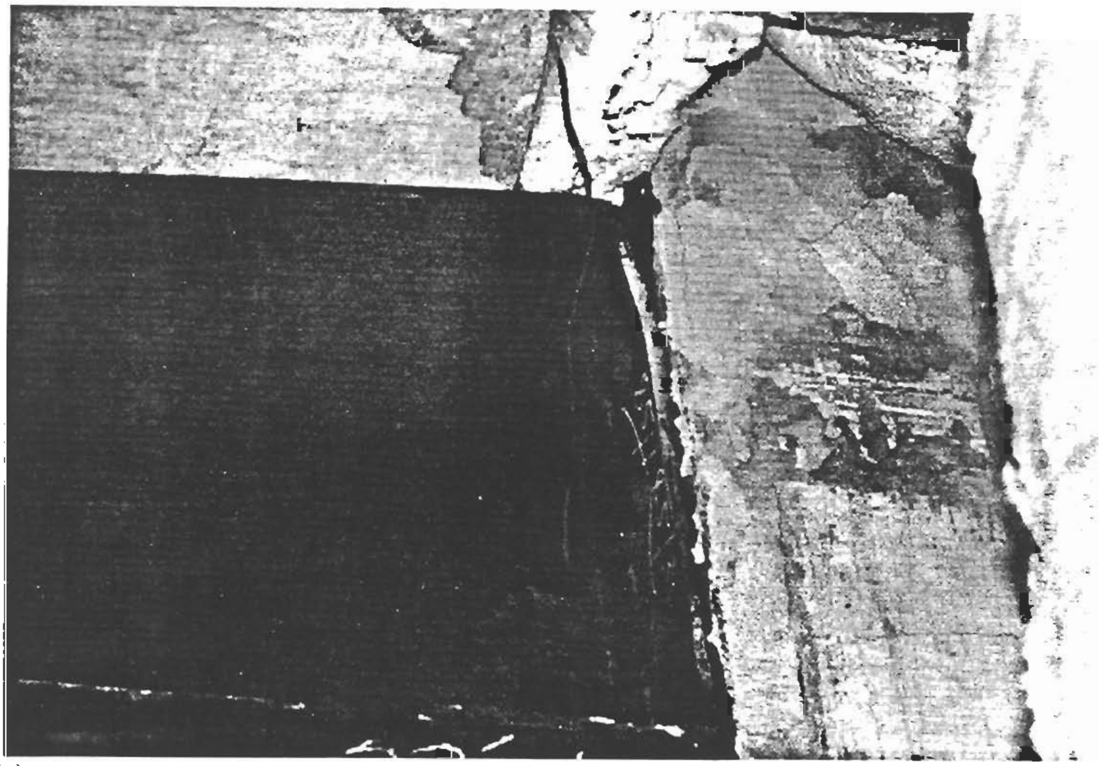


STEEL TEMPERATURES IN INDICATIVE COLUMN FIG. 20



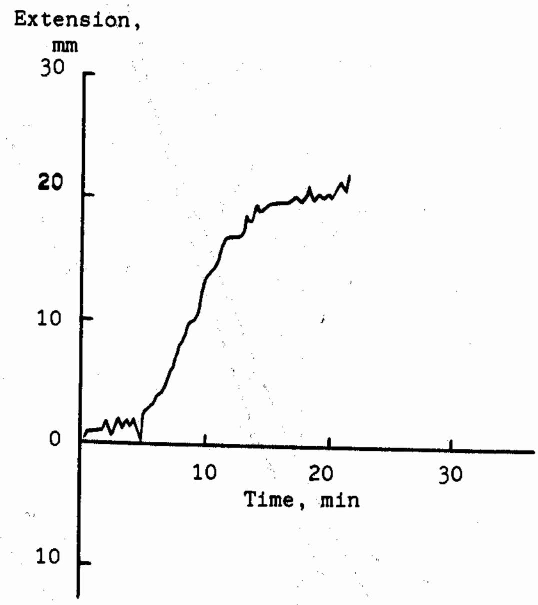
CENTRAL VERTICAL DEFLECTION RECORDED ON THE BEAM DURING THE TEST FIG. 21

(a)



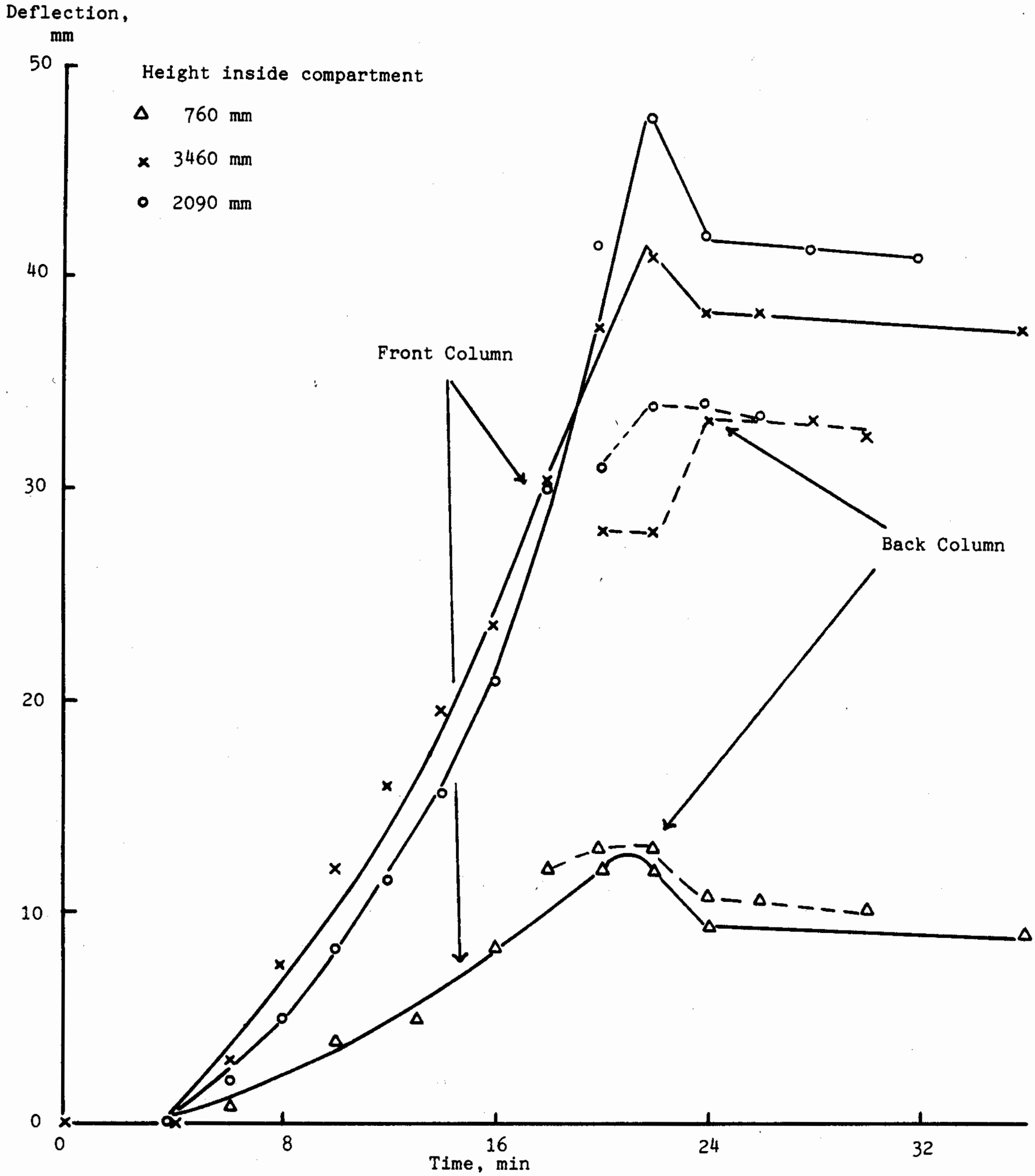
(b)

CONDITION OF THE TEST BEAM ON COMPLETION OF THE FIRE TEST FIG. 22



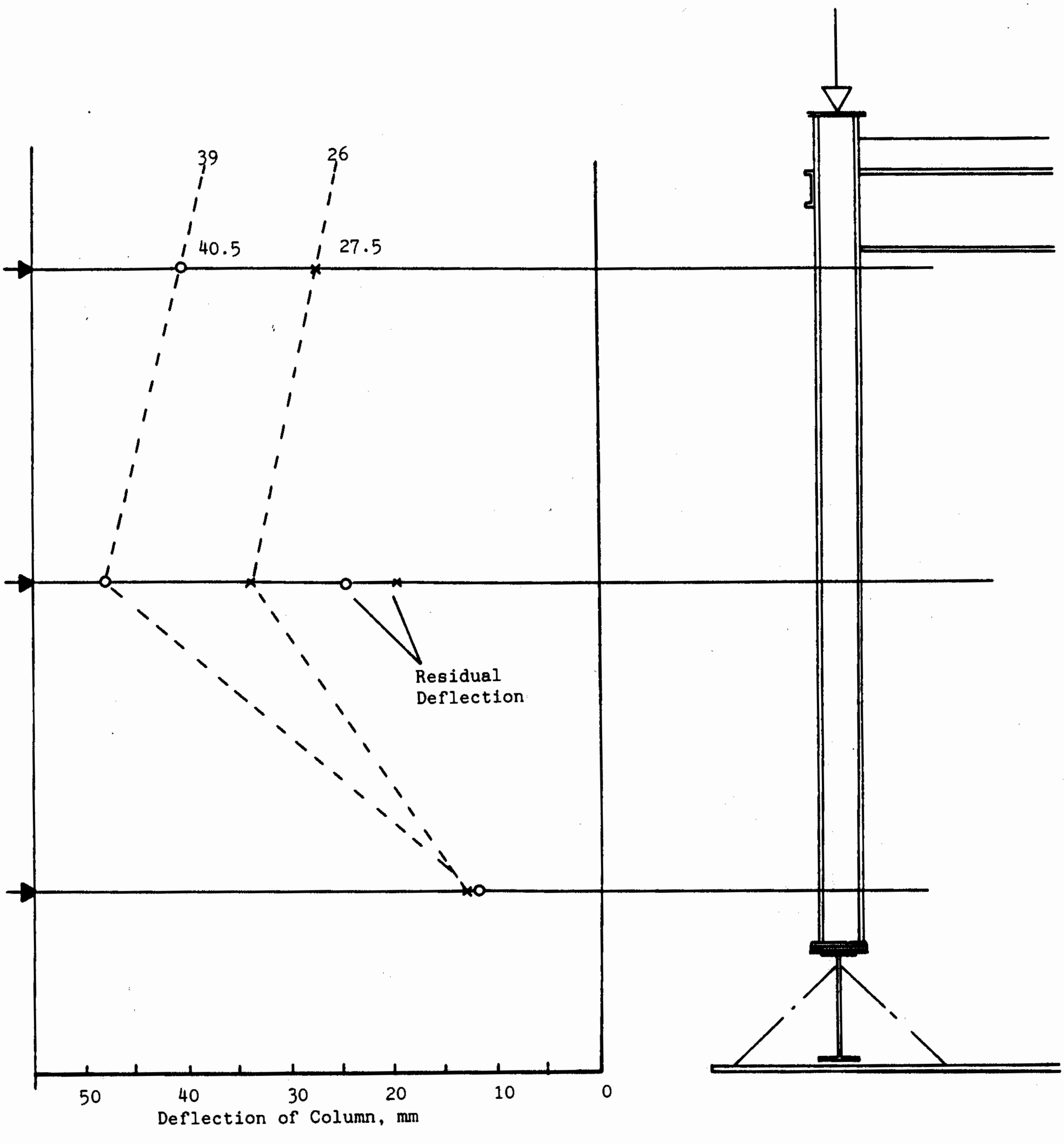
COLUMN EXTENSION MEASURED DURING THE TEST

FIG. 23
(R2/5313)



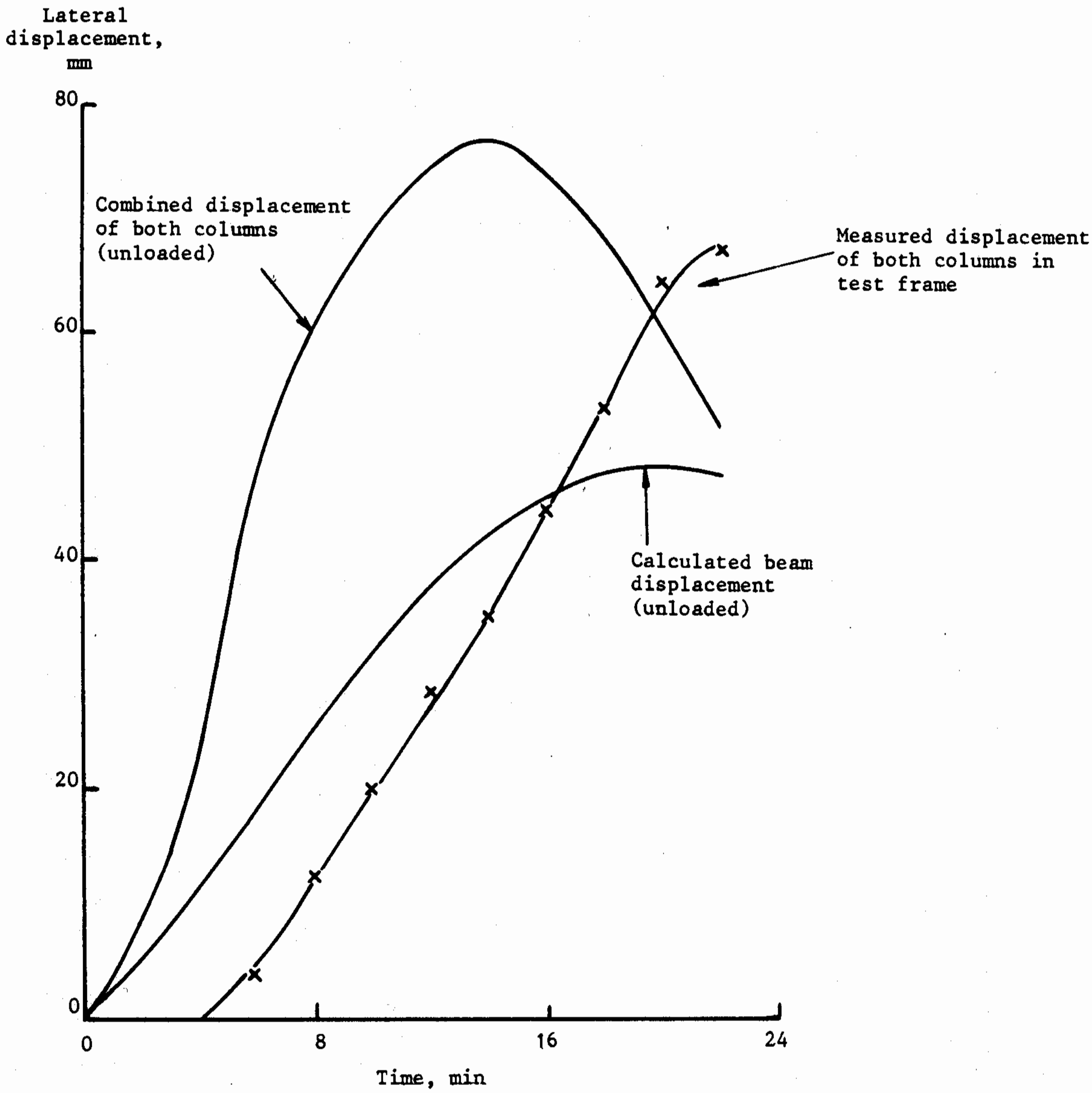
Beam length 4553

LATERAL DEFLECTION OF BLOCKED-IN COLUMNS MEASURED BY THE FRS DURING THE TEST FIG. 24
(R2/5314)



LATERAL DEFLECTION OF BLOCKED-IN COLUMNS AFTER 22 MINUTES

FIG. 25
(R2/5315)



CALCULATED AND MEASURED LATERAL DISPLACEMENT OF STEEL FRAME IN FIRE TEST

FIG. 26
(R2/5316)