Natural Fires in Large Scale Compartments

A British Steel Technical,
Fire Research Station
Collaborative Project

British Steel

Department of Environment
Building Research Establishment
Fire Research Station

Natural Fires In Large Scale Compartments - A British Steel Technical, Fire Research Station Collaborative Project

by

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PREFACE

During 1993, British Steel Technical, Swinden Laboratories in collaboration with the Building Research Establishment, Fire Research Station carried out a series of nine tests to simulate the behaviour of natural fires in large scale compartments. The programme which was sponsored by the Department of the Environment and British Steel Sections, Plates and Commercial Steels, was specifically aimed at validating for large compartments the 'Time Equivalent' formula given in EC1: Actions on Structures Exposed to Fire.

This report prepared by British Steel Technical, describes the design and construction of the test compartment and experimental programme. It includes details regarding the installation of protected and unprotected steel members together with thermocouple arrangements for measuring both atmosphere and steel temperatures. Analysis of the data with reference to the Time Equivalent formula is presented as well as other aspects which have important direct relevance to both EC1 and EC3.

In addition to the above, the Fire Research Station under the direction of Dr. Cooke carried out measurements which included thermal radiation, gas analysis, air flow and crib weight loss. A report covering this work will be available in due course.

British Steel and the Department of the Environment recognise the experimental data and the analysis already undertaken will be of benefit to researchers in further understanding the behaviour of fire in buildings and have kindly agreed to making this report available.

Dr. B.R. Kirby
British Steel Technical, Swinden Laboratories
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SUMMARY

British Steel Technical, Swinden Laboratories, in collaboration with the Building Research Establishment, Fire Research Station, have conducted a series of nine fire tests to simulate the behaviour of natural fires in large scale compartments. The programme sponsored by the UK Department of the Environment and British Steel Sections, Plates & Commercial Steels, was aimed at investigating whether the relationship for time equivalent of fire severity presented in Eurocode 1, can be safely applied to buildings with large compartments.

The tests were carried out in a purpose built compartment 23 m long x 6 m wide x 3 m high constructed within the BRE ex-airship hangar testing facility at Cardington in Bedfordshire and was designed to represent a 'slice' through a much larger compartment. In the programme, the influence of fire loading and ventilation on fire severity was examined and involved growing fires as well as simultaneous ignition, changes in lining material and compartment geometry.

Evaluation of the results has shown that the time equivalent relationship presented in the September 1992 draft of EC1, can be safely adopted by using a value of $c = 0.09$ to describe the thermal characteristics of compartments constructed with realistic insulating materials. This value is given in DIN 18230: Part 1 :1982 as well as the CIB W14 report (1986) and it would therefore appear reasonable to adopt other values of 0.07 and 0.05 for compartments with lower insulating performance. However, it is not recommended to use the value of $c = 0.06$ given in EC1, for the general case.

Since the programme was initiated, EC1 has been revised in which 'c' has been replaced by 'k_b' and assigned new lower values of 0.04, 0.055 and 0.07. These would give rise to unsafe assessments.

Measurements of time equivalent obtained from both unprotected and heavily protected members indicate that the EC1 formula, while safe, does not provide a unique value for the fire compartment but may also depend upon other factors such as limiting temperature and the characteristics of the fire protection system. This is not new and there is justification for re-examining previous theories.

For a given set of fire conditions, the difference in equivalent fire severity between a growing fire and simultaneous ignition was found to be negligible. However, by repeating the fire conditions in a compartment $\frac{1}{4}$ of its original size, the severity of the fire was effectively reduced by approximately 25%. The results were also analysed with respect to other time equivalent relationships.

Analysis of the data was extended to examine the formula given in EC3 Part 1.2, for calculating the temperature rise of protected steel members using the thermal cycles of the 'local' combustion gases. In the case of Vicuclad, good agreement was obtained between maximum recorded and calculated temperatures providing the thermal conductivity at elevated temperatures was used in the analysis. Suggestions are made for still further refinement.

The use of the parametric time temperature relationship given in EC1 for describing the heating cycles of the combustion gases, could not be extended to cover the insulated compartment fires. However, in one test that was examined, good agreement was achieved based upon an alternative Pettersson analysis.

NATURAL FIRES IN LARGE SCALE COMPARTMENTS - A BRITISH STEEL TECHNICAL, FIRE RESEARCH STATION COLLABORATIVE PROJECT

1. INTRODUCTION

Structural fire engineering safety design has developed to a stage whereby calculation methods are being proposed in the formulation of National and international Codes and Standards. In particular, in draft Eurocode 1: Basis of Design and Actions on Structures, a section has been devoted to Actions on Structures Exposed to Fire(1). This includes an expression referred to as the 'Equivalent Time of Fire Exposure' and enables the severity of a real compartment fire within a building, to be calculated in terms of an equivalent period of heating in a standard furnace test (BS476, ISO834) given by:-

$$t_{e,d} = q_{fd} \cdot c' \cdot w_f \cdot y_{n1} \cdot y_{n2} \cdots \quad \text{min}$$

where q_{fd} = design fire load density per unit floor area, MJ/m^2

c' = conversion factor which takes account of the thermal properties of the enclosure, min(MJ/m^2)

w_f = ventilation factor

y_{n1} = safety factors

A full explanation of the parameters and how they are used is provided in Appendix 1.

The potential advantage of such an expression is that it provides the designer with a method for determining the severity of the fire which is independent of the size and type of structural members and, where fire protection is necessary, the type and thickness of cover required.

One of the most recent important studies which involved critically examining time equivalent methods of calculation for unprotected steel was conducted by British Steel Technical in collaboration with the Building Research Establishment, Fire Research Station(2,3). This investigation entailed subjecting a range of unprotected steel members, beams and columns used in normal construction, to different fire loading and ventilation conditions. A total of twenty-three tests were carried out in a compartment 50 m^2 in plan x 4 m high in which both wood and plastic were used as the fuel. In addition, the thermal insulation characteristics of the compartment were also varied from insulating brick and fibre, to plasterboard and concrete.

The information which led to the relationship given in Eurocode 1 has however, only been accepted for compartments with floor areas up to 60 m^2. Consequently, the UK Department of the Environment expressed concern that the Eurocode proposal may not be applied conservatively to larger more realistic compartments, particularly in buildings with compartments having large depth to height ratios such as those often found in modern open plan offices. An investigation was therefore deemed necessary to validate the fire engineering calculations appropriate to large scale compartments. As a result, the Department of the Environment and British Steel Sections, Plates & Commercial Steels (SPCS), commissioned British Steel Technical, Swinden Laboratories to conduct a series of nine fire tests. These were carried out in collaboration with the Building Research Establishment (BRE) Fire Research Station, within a purpose built compartment inside the BRE large building test facility at Cardington.

This report has been prepared in order to provide a means by which all of the data and the preliminary analysis developed by British Steel Technical are presented under one cover.

At the time the work was instigated, the relevant section of draft EC1 covering structural fire safety was published within Part 10: Actions on Structures Exposed to Fire, September 92(1). This has since been revised both in format and technical content. The equivalent time of fire exposure is now described in EC1:Part 2.7 of the April 1993 draft(4) as:-

$$t_{e,d} = q_{fd} \cdot k_b \cdot w_f$$

where q_{fd} and w_f = essentially as before, see Appendix 1, and

k_b = conversion factor to account for the thermal properties of the enclosure *but note that new values were assigned.*

The April 1993 draft of EC1 now contains amendments dated June 1993.

2. ANALYTICAL PROCEDURES

2.1 Time Equivalent of Fire Exposure

2.1.1 Eurocode 1

In the investigation, the method employed to validate the time equivalent equation involves a graphical analysis of the experimental data based upon the temperatures attained by steel elements. This is illustrated in Fig. 1 in which the maximum temperature experienced by a structural member in a real fire, is equated to a period of heating (t_e) for the same member size to attain an identical temperature in the standard furnace test (BS476 or ISO834). It is therefore essential that reliable thermal data from the latter were available for the member sizes incorporated in the experimental natural fires. Since the tests were intended to cover a range of fire severities and the influence of growing fires on the maximum steel temperatures was unknown, the compartment contained both protected and unprotected members.

2.1.2 Alternative Relationships

As well as analysing the results with respect to the Eurocode equation, the results of the test programme are compared with other expressions used for describing the severity of fires. These are referred to by the following authors/working groups:

CIB W14	(5)
Law	(6)
Pettersson	(7)
Harmathy	(8)

Details of the above relationships are included in Appendix 1.

2.2 Additional Analyses

2.2.1 Heating Rates of Protected Members

During recent years, relationships have been developed for calculating the thermal response of steel members protected by non-reactive fire protection systems. In general, separate formulae for lightly and heavily protected systems have been in existence with the latter taking into account the heat capacity of the insulation itself. These have been brought together in EC3:Part 1.2(9) in the form of a single expression which is described in Appendix 2. This expression will be used for comparing the calculated behaviour of the structural elements with the measured response under natural fire conditions.

2.2.2 Parametric Time Temperature Curves

In EC1:Part 2.7 formulae for calculating the time temperature history of compartment fires are presented based upon factors such as fire loading, compartment geometry and ventilation as well as the thermal properties of the materials used in construction of the enclosure, see Appendix 3. For the fire conditions studied in the programme, numerical solutions for each of the nine tests are compared with the measured thermal histories.

3. TEST DETAILS

3.1 Compartment Construction and Dimensions

The fire tests were conducted in a compartment built inside the BRE large building test facility at Cardington in Bedfordshire. Overall, the compartment measured 23.120 m long x 6.125 m wide x 3.075 m high and was designed to represent a 'slice' through a much larger compartment 46 m deep, of infinite width and having an effective (internal) depth to height ratio of 16:1. A general view of the structure is shown in Fig. 2.

In the construction of the compartment and its linings the following materials were used:-

Roof

Structure: Reinforced autoclaved aerated concrete slabs, 6.0 x 0.7 x 0.200 m thick (ρ = 450 kg/m^3)

Lining: 2 x 25 mm layers of standard grade ceramic fibre blanket (ρ = 128 kg/m^3) fixed with stainless steel pins.

Additionally for Test 8 only:

2 x 12.5 mm sheets of Fireline plasterboard fixed onto 47 x 75 mm timber studs at 400 mm centres

Walls

Structure: Lightweight concrete blocks, 440 x 215 x 215 mm thick (ρ = 1375 kg/m^3)

Lining: 2 x 25 mm layers of standard grade ceramic fibre blanket (ρ = 128 kg/m^3) fixed with stainless steel pins.

Additionally for Test 8 only:

2 x 12.5 mm sheets of Fireline plasterboard fixed onto 47 x 47 mm timber studs at 600 mm centres

Floor

Structure: Dense concrete ~75 mm thick

Lining: 125 mm deep layer of fluid sand, $\rho \simeq 1750$ kg/m^3

For the purpose of fire engineering calculations, details on the relevant physical properties for each material are given in Table 1.

Taking into account the lining materials, the internal dimensions of the compartment were as follows:-

Tests 1-6, 9	Length	=	22.855 m
	Height	=	2.750 m
	Width	=	5.595 m
Test 7	Length	=	5.595 m
(¼ size - square)	Height	=	2.750 m
	Width	=	5.595 m
Test 8	Length	=	22.780m
(Fireline plasterboard)	Height	=	2.680 m
	Width	=	5.465 m

Ventilation was provided at one end only with a maximum opening being the full width and height of the compartment. Lightweight concrete blocks were used to construct temporary walls to reduce the ventilation from fully open, $^1/_1$, to $^1/_8$ of the available ventilation area. In the reduced size compartment, Test 7, the ventilation conditions of ¼ opening represent the same ratio of ventilation area to floor area as adopted in Tests 1 and 2. Figure 3 illustrates how the ventilation conditions were achieved. Note however, from Test 3 onwards, an insulated steel column with an overall width of 400 mm was placed directly against the opening. For the purpose of calculating the horizontal dimensions of the openings, this was treated as part of the structure.

3.2 Fire Loading

Figures 4 and 5 show the general and detailed layout of 33 x 1 m square cribs distributed to provide a uniform fire load density. In the reduced size compartment, Test 7, nine cribs were used.

Each crib was constructed using 1 m lengths of 50 x 50 mm softwood (Western Hemlock) kiln dried to 10% moisture content. These were stacked with alternate layers at right angles leaving a gap of 50 mm between each stick, see Fig. 6. On average, a 1 m length of softwood weighed 1 kg.

3.3 Instrumentation

Three measuring stations at crib lines 2 (back), 6 (middle) and 10 (front) were adopted for monitoring both atmosphere temperatures and the temperatures attained by a total of twelve short lengths of protected and unprotected steel members.

3.3.1 Atmosphere Temperatures (Figs. 7(a), (b) and (c))

Along each of the crib lines 2, 6 and 10, eleven 3 mm diameter chromel/alumel thermocouples were fixed with their hot junctions located 300 mm below the roof. These were used to measure the horizontal temperature profiles across the width of the compartment.

Vertical temperature profiles were measured directly above cribs 2B, 6B and 10B as well as mid-centre to cribs B-C and 5-6. In each case, a series of five thermocouples were attached at intervals of 300 mm to a steel bar suspended from the roof. The uppermost thermocouples over cribs 2B, 6B and 10B acted in a dual role in that they also measured the horizontal temperature profiles.

3.3.2 Steel Temperatures

For the purpose of determining values of time equivalent, 254 x 146 mm x 43 kg/m universal beams and 203 x 203 mm x 52 kg/m universal columns were selected. These sections are commonly used in the UK fire resistance testing furnaces and therefore thermal data are available on both protected and unprotected members.

A total of twelve short lengths of beams and columns (six of each) were fabricated with end plates and threaded bars. The sections were fixed to the underside of the insulated roof slabs at each measuring station, see Figs. 7(a) and (b), with a beam alternating with a column both across and along the length of the compartment. Each member was positioned directly over, or equidistant between the cribs.

In order to simulate as near as possible the thermal effects of beams supporting a dense concrete floor, 900 x 300 x 50 mm paving slabs were placed upon the upper flanges with a thin layer (~0-2 mm) of cement paste between the concrete and steel surfaces. By using threaded bar, the assemblies could then be secured against the underside of the roof. The slabs were replaced after each test.

The steel sections were instrumented with 3 mm diameter chromel/alumel thermocouples placed in tight fit holes drilled into the flanges and webs, as indicated in Figs. 8 and 9. This method of fixing had proven itself in the past and avoided problems concerning reliability resulting from repeated exposure to high temperatures and iron oxide, scale detachment.

When the members were finally positioned, the lower flange of the beams and the complete temperature profile across the column sections were all located approximately 300 mm below the roof, i.e. in the same horizontal plane as the thermocouples used to measure the atmosphere temperatures. Associated with each beam and column the hot junction of an atmosphere thermocouple was situated on both sides of the member, approximately 125-150 mm from either a flange surface or flange tip. In the data analysis/sheets these are referred to as 'local' atmosphere temperatures and are used in the subsequent heat transfer calculations.

3.4 Fire Protection

In the South side of the compartment, the beams and columns were fire protected with 20 mm and 30 mm Vicuclad boarding respectively. This was supplied and fitted by Promat Fire Protection using normal fixing methods although the detailing was modified to ensure that the position of the noggings did not influence the steel temperatures around the thermocouple positions, see Figs. 8, 9 and 10.

For Tests 1 and 2 Vicuclad Grade 900 was used. However, as a result of the duration and severity of the fires being well in excess of those for which the protection was intended to experience, resulting in loss of integrity, the Vicuclad was subsequently supplied to a higher specification, Grade 1050. In addition, since only thermal data were required, the fire protection was supported mechanically using nichrome wire and chicken wire mesh. No further problems regarding loss in integrity were experienced.

Following Test 3, the unprotected column on crib line 6 was insulated by FRS personnel with two x 20 mm layers of ceramic fibre board. This remained in place for the remainder of the programme. 70 mm Vicuclad board was also introduced into Tests 6, 8 and 9 and was fixed to the unprotected column on grid line 10 in the same manner as the columns protected with 30 mm board.

Test 7 was conducted in a reduced size compartment and consequently only the steelwork on crib line 10 was exposed to fire. For this test only, both pairs of beams and columns were protected using the 20 mm and 30 mm Vicuclad.

Throughout the programme, the Vicuclad fire protection was removed after each test and the steel members cleaned from adhesive and loose scale before refitting.

3.5 BS476 Fire Tests - Background Data for Determining Equivalent Fire Exposure

During the last few years, British Steel Technical has conducted a considerable number of fire resistance tests at the independent laboratories of LPC - Borehamwood and Warrington Fire Research Centre. The results from much of this work on unprotected steel is reported in Refs. 10 and 11 and these have been used to provide appropriate average heating curves. Data for the unprotected sections are presented in Fig. 11.

British Steel Technical has also recently conducted two tests on a 254 x 146 mm x 43 kg/m universal beam protected with 20 mm Vicuclad. Heating curves are presented in Fig. 12 together with similar data provided by courtesy of Promat Fire Protection, for a 203 x 203 mm x 52 kg/m universal column protected with 30 mm and 70 mm Vicuclad.

4. TEST PROGRAMME

Tests 1-6 were conducted in the full size compartment lined with ceramic fibre in which the fire load density was maintained at either 20 or 40 kg of wood/m^2 of floor area and the ventilation varied from fully open at the front ($^1/_1$) to $^1/_8$ opening. In each test, up to three cribs were initially ignited at the compartment rear on grid line 1 and the fire allowed to progress naturally.

Test 7 was carried out in a reduced size compartment, 25% of its original plan area. With respect to the variables given in the Eurocode time equivalent formula, the fire conditions were designed to replicate Test 2 by using a fire load density of 20 kg/m^2 of floor area and for the same opening height, a constant ratio of ventilation area to floor area. The fire loading was distributed between nine cribs and these were ignited simultaneously. Atmosphere and steel temperatures were only monitored across the measuring station on crib line 10 (front).

Test 8 was designed to demonstrate the influence of a plasterboard lining on fire severity by repeating Test 2. However, due to the room taken up by the plasterboard fixing system, the internal dimensions of the compartment were slightly reduced.

In Test 9, the fire loading and ventilation conditions of Test 2 were again repeated in which all the cribs were ignited 'simultaneously'.

The entire test programme is summarised in Table 2 together with the important compartment dimensions and fire parameters used in the time equivalent method of calculation described in Eurocode 1. The latter are based upon the September 1992 draft on which this investigation was instigated, as well as the April 1993 draft containing the Berlin amendments of June 1993. For comparison, the key parameters used to calculate alternative time equivalent relationships previously referenced, are presented in Appendix Table A1.1.

5. RESULTS AND DISCUSSION

Atmosphere and steel temperature data recorded by British Steel Technical for the nine tests are presented in a series of Annexes and are available separately. These also include a graphical representation for each group of thermocouples. Photographs illustrating the various fire conditions and different stages during the tests are shown in Figs. 13-24.

5.1 General Observations

With the exception of Tests 7 and 9, the fires were ignited at the rear of the compartment on crib line 1. In all cases, the pattern of growth was similar whereby fire spread to adjacent lines of cribs was initially slow followed by a period of rapid development towards crib line 11 at the front. The time from ignition to complete development varied from approximately 9-30 min in Tests 1-6 to 40 min in Test 8 for the plasterboard lined compartment. A detailed history of each fire was recorded by FRS staff.

Once a fire had fully developed, the cribs from the middle to the rear of the compartment were starved of oxygen, with the result that combustion ceased. Preferential burning continued near the opening and as the fuel was consumed, the fire progressed slowly back towards the rear.

Although the cribs in Test 9 were ignited 'simultaneously', once the fire had established itself, the pattern of behaviour displayed in the growing fires was repeated.

The thermal histories of the atmosphere gases averaged across the compartment are shown in Figs. 25-33. In the full size compartment tests, these illustrate the progression of the fire described above by the initial peak and dwell in temperatures monitored by the thermocouples on crib line 2 in contrast to the uninterrupted heating and cooling cycles generally experienced by the thermocouples on crib line 10 at the front.

Figures 34-42 show the horizontal temperature distributions across the width of the compartment at three stages during the fire tests. In general, these were uniform at each measuring station and reflect the even rates of combustion once the fires had reached the fully developed stage.

The vertical temperature profiles of the hot gases measured both above and between the cribs are illustrated within the appropriate data sheets and are therefore, not reproduced in the main report. Despite measurements taken directly over the burning cribs, the maximum temperatures were found to occur at 0.3 m below the roof, i.e. approximately 1.6-2.0 m above the top surface of the cribs.

During the first test, part of the Vicuclad boarding around the three beam sections became detached as well as joints opening up in the encasement protecting the centre column. The times at which this occurred can be identified by the change in steel heating rates shown in the graphical analysis accompanying the relevant data sheets. This loss in integrity was primarily due to the hot gases achieving temperatures of around 1200°C which is in excess of that for which the binder in the Vicuclad was designed to withstand*. While the Vicuclad protection in the second test was provided with additional mechanical support and proved to be largely satisfactory, Vicuclad Grade 1050 containing a more resilient binder, was used in the remainder of the test programme.

Fire growth in Test 8 containing the plasterboard lining was particularly slow, due to the release of water vapour suppressing the temperature of the hot gases. However, the developing fire was eventually assisted by flaming of the combustible surfaces particularly along the lining to the roof and upper walls as shown in Fig. 16.

Once the atmosphere temperatures in Test 8 had peaked, joints in the plasterboard lining the roof were seen to separate thereby exposing the timber studs. Eventually the complete timber stud framing became directly involved in the fire. Since failure of the roof lining system occurred while the temperatures of the hot gases were well above those of the protected steel members, i.e. there was net heat transfer to steelwork, the timber roof studs therefore effectively increased the severity of the test by contributing an additional 667 kg of wood (adjusted to 10% moisture content) to the fire loading.

While the wall linings suffered a similar fate, this did not occur until near the completion of the fire test. By this time, the original fire loading was almost exhausted, see Fig. 23, and with the exception of the column protected with 70 mm Vicuclad, maximum steel temperatures had already been attained.

5.2 Time Equivalent

5.2.1 Eurocode 1

Table 3 presents a summary of the results in which maximum temperatures recorded by the steel members are given (beams:average lower flange, columns: average flange and/or web) together with the corresponding times taken to achieve identical temperatures in the BS476 fire resistance test, i.e. time equivalent.

Values of t_e measured for the individual members protected with 20 and 30 mm Vicuclad (South side) have been averaged to obtain the overall time equivalent for each test. These are compared with t_e calculated using a thermal inertia for the compartment which equates to $c = 0.09$, as implied in the September 92 draft of the Eurocode.

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* The maximum temperatures attained by the combustion gases in BS476:Part 20 or hydrocarbon furnace tests are 1153°C (4 h) and 1100°C (2 h) respectively.

An examination of the results in the first six tests shows that by setting c equal to 0.09, values of the ratio t_e $^{measured}/_{calculated}$ for Tests 3-6 are around 1.0 but are much greater than unity in the fully ventilated fires, viz. Tests 1 and 2. In particular, the calculated value of t_e for Test 2 underestimates the measured fire severity by 41% and therefore implies that adopting c = 0.09 is unconservative. This should however, be examined in terms of the practical solutions which may be envisaged in building design. By including a ceramic fibre lining, the thermal behaviour of the compartment was more akin to a furnace than a room in a building. This can be seen by comparing the thermal absorptivity of the ceramic fibre [$(\sqrt{(\lambda\rho\ c_p)} = 0.898$ W $h^{\frac{1}{2}}/m^2$ °K] with a maximum permitted value of 12.0 W $h^{\frac{1}{2}}/m^2$ °K for a room to remain classed as an 'insulated' compartment. The difference is at least an order of magnitude. Even allowing for the concrete walls and roof in calculating the thermal absorptivity, the total structure is still regarded as highly insulating.

The influence of a less insulated compartment, but sufficiently high to still warrant a value of c = 0.09, is demonstrated by the results obtained from Test 8 containing the plasterboard lining. In Test 8, the fire conditions of those adopted in Test 2 were repeated since these showed the greatest variance with respect to the calculated behaviour. The calculated time equivalent for Test 8 = 57.0 - 71.8 min (the latter indicates the contribution of the timber roof studs to the fire loading) compares with a measured average t_e of 67.5 min. This provides values of the ratio t_e $^{measured}/_{calculated}$ of between 0.94 and 1.18. Assuming therefore, that the inclusion of the additional fire loading in contributing towards fire severity is valid, then the adoption of c = 0.09 for 'insulated' compartments using conventional construction materials is reasonable. It follows therefore, that had a plasterboard lining been included in Tests 1 and 3-6 there would have been a significant reduction in measured fire severity by possibly as much as 33%, resulting in values of t_e $^{measured}/_{calculated}$ much lower than unity.

Since the use of c = 0.09 appears valid for 'insulated' compartments it is reasonable to adopt values of c = 0.07 and c = 0.05 for categories of compartments with poorer thermal performance as recommended in the CIB W14 report(5) and DIN 18230:Part 1:1982(12). The use of c = 0.06 is not however recommended for the general case.

In the more recent draft of Eurocode 1 dated April 1993, the influence of thermal absorptivity on fire severity is described by the factor 'k_b' in which values of 0.04, 0.055 and 0.07 are recommended with the latter being adopted for the general case. It is clear from Table 3 that assigning 0.07 to k_b and consequently 0.055 and 0.04 for less insulating compartments is questionable.

5.2.2 Alternative Time Equivalent Relationships

Table 4 shows the measured values of t_e compared with the calculated values according to CIB W14, Law, Pettersson and Harmathy. With respect to the four relationships the closest safe agreement is obtained using the Pettersson analysis in which

$$t_e = 0.067 \times q_{tf} \times \left(\frac{A_v \sqrt{h}}{A_t} \right)_f^{-\frac{1}{2}} \qquad \text{minutes}$$

In the above equation both q_{tf} and $(^{A_v \sqrt{h}}/_{A_t})_f$ have been modified to allow for the thermal properties of the structure although the use of $k_f = 3$ for Tests 1 and 2, is still inadequate to describe the fire severity.

However, the Pettersson approach considerably overestimates fire severity at very low opening factors since t_e tends to infinity as the opening factor approaches zero. This is illustrated in Test 6 in which the measured t_e was 110.5 min and 195 min for the members protected with 20/30 mm and 70 mm Vicuclad respectively, compared to t_e calculated = 254.1 min.

5.2.3 Alternative Methods

The correlations between calculated time equivalent and measured fire severity have been based upon beams and columns protected with 20 and 30 mm Vicuclad. These thicknesses of protection have been evaluated in the BS476 fire resistance test for periods up to 150 min and would generally be applied to structural elements requiring up to 2 h fire resistance.

While the temperatures attained by the unprotected members in the majority of the test programme were considerably higher than the available furnace data, in Tests 6 and 8 comparisons could be made between the calculated and measured behaviour. In each case, t_e measured for the unprotected steelwork was considerably lower than the calculated value and therefore for the normal failure temperatures expected by steel structures, analyses based upon the 20 and 30 mm thicknesses of fire protection provide conservative solutions. In contrast however, the introduction of 70 mm Vicuclad in Tests 6, 8 and 9 shows the measured values of t_e were considerably greater than the calculated response.

The observations made above imply that the Eurocode method of determining the equivalent fire resistance does not provide a unique value for each set of compartment conditions but must partly depend upon whether the members are protected and the level of protection. This suggests that in analysing the time equivalent of fire severity, additional factors should be included such as the limiting (critical) temperature for the structural element as well as the thickness and thermal properties of the insulation itself. The approach described is not new but is covered in the work by Pettersson et al(13) and should be re-examined. Reference 13 presents a detailed graphical analysis in which the equivalent time of fire severity can be determined from a knowledge of: fire load density, ventilation, thermal properties of the compartment linked to: the critical temperature of the structural element and a combined factor for the fire protection and geometric properties of the section:

$$\frac{\lambda_i}{d_i} \frac{A_i}{V_s}$$

where λ_i = thermal conductivity of the insulation
d_i = thickness of insulation
A_i = internal surface area of the insulation/unit length
V_s = volume of steel/unit length

5.3 Growing Fire v Simultaneous Ignition

In Test 9, the fire conditions of Test 2 were repeated to establish whether a growing fire would result in a significant difference in equivalent fire severity as opposed to simultaneous ignition. The former would be more representative of fires in large compartments in which ignition would normally occur at one source.

From Table 3, values of t_e $^{\text{measured}}/_{\text{calculated}}$ for Tests 2 and 9* are 1.41 and 1.38 respectively, a variance of approximately 2%. In terms of conducting fire tests this is not regarded as significant.

5.4 Large v Small Compartments

Test 7 repeated the fire conditions of Test 2 based upon the same magnitude of parameters defined in the Eurocode. While the atmosphere temperatures in Test 7 were higher, > 1260°C, the ratios of t_e $^{\text{measured}}/_{\text{calculated}}$ were 1.41 and 1.07 for the large and small compartments respectively. In practice, for the fire conditions evaluated, this represents a reduction in fire severity of 25% when calculating t_e for small scale compartments.

5.5 Heat Transfer Calculation Methods- Protected Members

The results of the test programme have been used to assess whether the relationship for calculating the temperature rise of protected steel members given in EC3:Part 1.2(9), see Appendix 2, is appropriate to severe natural fires.

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* The difference in the calculated values of t_e is due to the column placed at the front opening after Test 2 slightly modifying the ventilation conditions.

For the Viculad fire protection, it was initially found that the use of ambient temperature thermal properties grossly underestimated the maximum steel temperatures recorded during the tests. However, by modifying the thermal conductivity parameter with values representative of its elevated temperature response(14), with the exception of Test 1, reasonable agreement was obtained. In the analysis, the thermal conductivity of the Vicuclad was based upon the mean temperature between the 'local' atmosphere and the corresponding steel member.

Figures 43-59 compare the calculated and recorded heating curves over the entire test programme for all the steel members protected with either 20, 30 or 70 mm Vicuclad. Out of a total of 51 protected members studied, the variances between maximum calculated and recorded steel temperatures were within the following temperature bands:

$>50°C$ = 4 members
$\geq 35°C \leq 50°C$ = 9 members
$<35°C$ = 38 members

It is likely that by allowing for moisture content and incorporating changes in density/specific heat, closer agreement would be found.

The evaluation conducted therefore provides confidence in the methodology.

5.6 Parametric Time Temperature Curves

The parametric time temperature relationship given in EC1 Part 2.7 and presented in Appendix 3, may be used to describe the thermal history of the combustion gases within a compartment. In its scope of application, certain limits are placed upon the physical parameters e.g. maximum compartment floor area = 100 m^2, permitted range of thermal absorptivity, $\sqrt{(\lambda \rho c_p)}$, = 1000-2000 J/m^2 s$^{\frac{1}{2}}$°K opening factor, $(A_v \sqrt{h} / A_t)$, between 0.02 and 0.2 m$^{\frac{1}{2}}$. While for the most part, the parameters adopted in the test programme fell outside these limits, an assessment was therefore made as to whether the relationship could be extended to cover the test conditions evaluated.

For each test, two parametric time temperature curves are shown in Figs. 25-33 accompanying the average atmosphere temperatures recorded on crib lines 2, 6 and 10. The cases examined were based upon: (a) the thermal properties of the linings coupled with the concrete walls and roof, (b) the thermal properties of the linings on their own. In both analyses, the calculated time temperature curves underestimate the measured fire behaviour.

An alternative approach to predicting fire behaviour which has been applied to Test 4, can be made on the basis of the Pettersson calculation method(13). However, in view of the different thermal histories on each crib line and the difficulty in relating these to a single calculated heating and cooling cycle, the comparison was conducted on the basis of the calculated net heat transfer to the beams and columns protected with 20 and 30 mm Vicuclad. The calculation procedure has also been applied to the heating cycle predicted by the Eurocode parametric time temperature relationship.

The results of the analysis are shown in Figs. 60 and 61 in which the maximum temperatures attained by the beams and columns calculated from the corresponding 'local' atmosphere temperatures agree with the calculated response based upon Pettersson's fire curve. In contrast, the steel temperatures calculated from the Eurocode heating cycle underestimate the fire severity.

6. CONCLUSIONS

A programme of natural fire tests has been carried out with the main purpose of assessing whether the relationship for time equivalent of fire severity, t_e, given in Eurocode 1 'Actions on Structures Exposed to Fire' is appropriate to large scale compartments. From the results and analysis the following conclusions have been reached.

1. In the September 1992 draft of EC1 the equivalent time of fire severity was calculated from the relationship $t_e = qcw$. For the parameter 'c', which represents the thermal characteristics of the compartment boundaries, it was generally assumed that reference could be made to DIN 18230:Part 1:1982(12) and CIB W14(5) in which values of 0.05, 0.07 and 0.09 could be assigned for specific ranges of thermal inertia. The results have shown the relationship provides safe solutions when c = 0.09 for insulated compartments constructed with the type of materials normally used in buildings. This has been validated for equivalent periods of fire severity up to 150 min.

2. Based upon the results for an insulated compartment, it is considered that the formula given in the September 1992 draft would also provide safe solutions when values of c = 0.05 and 0.07 (given in Refs. 5 and 12) are used for compartment boundaries with higher ranges of thermal inertia. However, the use of c = 0.06 proposed in the Eurocode for the general case cannot be supported.

3. In the April 1993 draft of EC1, t_e is determined from q, k_b and w in which 'k_b' replaces 'c' given in the September draft. New values representing the thermal inertia for the compartment are introduced as 0.04, 0.055 and 0.07 with 0.07 being applied to both insulated compartments and the general case. From the results obtained for the insulated compartment fires within this study, these cannot be supported.

   It is recommended that k_b should be reassigned values of 0.05, 0.07 and 0.09 for the appropriate ranges of thermal inertia.

4. The correlation between the measured and calculated values of t_e has been made on the basis of protected steel elements using Vicuclad in thicknesses of 20 and 30 mm. However, for several of the later tests in which correlations could also be made using unprotected steel and steel protected with 70 mm Vicuclad, results of the former gave lower values of equivalent fire severity, whereas those of the heavily protected members, were greater than the calculated response. This implies that the equivalent fire severity is not a unique value for a specific set of fire conditions as described in the Eurocode, but may also be linked to other parameters such as: the critical temperature of the structural element and the properties and section factor for the insulation. While the Eurocode equation is still valid, and has been shown to provide safe solutions for large scale compartments, there is a case for re-examining the parameters in the manner described in Pettersson's analysis.

5. The influence of a growing fire on equivalent fire severity was not found to be significant compared with the same fire conditions involving simultaneous ignition.

6. When the large scale compartment was reduced to a much smaller compartment having $\frac{1}{4}$ of the floor area, the measured fire severity was reduced by approximately 25% for the same fire loading and ventilation conditions as defined by the Eurocode formula.

7. Comparison of the results with other relationships for calculating the equivalent fire severity produced wide variations in correlations. The closest solutions were generally obtained using Pettersson's approach.

8. The analysis of the results was extended to examine whether the heat transfer calculation method given in EC3:Part 1.2 for protected steel elements could be applied to severe natural fire heating conditions. In general, good agreement could be obtained between calculated and measured response for all thicknesses of Vicuclad used provided the elevated temperature values for thermal conductivity were used. Further accuracy in calculating net heat transfer may be possible by including inter alia the effect of moisture and changes in specific heat.

9. A comparison of the measured heating curves obtained in each test with those calculated using the parametric time temperature relationship given in EC1, indicated that the latter underestimated the fire severity for insulated compartments. However, further limited analysis based upon net heat transfer to the protected steel elements demonstrated the compartment fire could be described by a single time temperature curve based upon Pettersson's analysis. Further work in this area is recommended.

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This report is published with the permission of Dr. R. Baker, Director of Research and Development, British Steel Technical.

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JK

TABLE 1
AMBIENT TEMPERATURE PROPERTIES OF THE MATERIALS USED IN THE TEST COMPARTMENT

Structure	Material	Density ρ kg/m^3	Specific Heat c_p J/kg °K	Thermal Conductivity λ W/m °K	$b = \sqrt{\lambda \rho c_p}$ W h$^{\frac{1}{2}}$/m^2 °K (J/m^2 s$^{\frac{1}{2}}$ °K)
Walls	Lightweight Concrete Blocks	1375	753	0.42	11.01 (660.6)
Roof	Autoclaved Aerated Concrete Slabs	450	1050	0.16	4.59 (275.4)
Floor	Fluid Sand	1750	800	1.0	19.75 (1185)
Lining (1)	Ceramic Fibre	128	1130	0.02	0.898 (53.88)
Lining (2)	Fireline Plasterboard	900	1250	0.24	8.68 (520.8)

TABLE 2
SUMMARY OF THE PARAMETERS ADOPTED IN THE NATURAL FIRES TEST PROGRAMME AND THE TIME EQUIVALENT PREDICTIONS BASED UPON DRAFT EUROCODES DATED SEPTEMBER 17 1992 AND APRIL 1993

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Compartment Size	Full size	Full size	Full size	Full size	Full size	Full size	¼ size	Full size	Full size
Walls and Ceiling Lining	Ceramic fibre	Ceramic fibre	Ceramic fibre	Ceramic fibre	Ceramic fibre	Ceramic fibre	Ceramic fibre	Plaster-board	Ceramic fibre
Fire Load Density, kg/m^2 of Floor	40	20	20	40	20	20	20	20.6	20
Ventilation$^{\times}$	$1/1$	$1/1$	$1/2$	$1/2$	$1/4$	$1/8$	$1/4$	$1/1$	$1/1$
Ventilation Factor, w_f	1.4795	1.4795	2.3087	2.3087	2.9396	3.2760	1.4790	1.5737	1.4795
Fire Load Density, q_f (MJ/m^2 of Floor)	759.9	380.1	380.1	759.9	380.1	380.1	380.1	402.3/ 507.2$^+$	380.1
Ignition/Fire Progress*	Growing	Growing	Growing	Growing	Growing	Growing	Simult-aneous	Growing	Simult-aneous

EUROCODE 1: ACTIONS ON STRUCTURES EXPOSED TO FIRE
PART 10A: GENERAL PRINCIPLES AND NOMINAL THERMAL ACTIONS
SEPTEMBER 17, 1992

Thermal Properties: $b = \sqrt{\rho c_p \lambda}$ $(W h^{1/2}/m^2\ {}^{\circ}K)$	<12	<12	<12	<12	<12	<12	<12	<12	<12
Insulation Factor: c	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Time Equivalent t_e (minutes)	101.2	50.6	79.0	157.9	100.6	112.1	50.6	57.0/ 71.9$^+$	50.6

EUROCODE 1: PART 2.7 ACTIONS ON STRUCTURES EXPOSED TO FIRE
ENV 1991-2-7 APRIL 1993

Thermal Properties: $b = \sqrt{\rho c_p \lambda}$ $(W h^{1/2}/m^2\ {}^{\circ}K)$	<720	<720	<720	<720	<720	<720	<720	<720	<720
Insulation Factor: c	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Time Equivalent t_e (minutes)	76.7	39.4	61.4	122.8	78.2	87.2	39.4	44.3/ 55.9$^+$	39.4

× Represents fraction of front wall open

* Growing fire initiated by igniting up to three cribs on crib line 1

\+ Modified fire loading due to the timber stud framing supporting the plasterboard lining to the roof

TABLE 3
SUMMARY OF TEST RESULTS COMPARING MEASURED TIME EQUIVALENT TO PREDICTED VALUES BASED UPON EUROCODE 1 DRAFTS DATED SEPTEMBER 1992 AND APRIL 1993

Location/ Steel Member Type	Maximum Temperatures (°C) and Equivalent Fire Resistance, t_e (min)																	
	Test 1		Test 2		Test 3		Test 4		Test 5		Test 6		Test 7		Test 8		Test 9	
	North Side	South Side	North Side	South Side	North Side	South Side	North Side	South Side	North Side	South Side	North Side	South Side	North Side	South Side	North Side	South Side	North Side	South Side
BACK Beam, °C min	1198.5 ⩾60	*	1114.5 ⩾60	470.5 73	109.5 ⩾60	506.5 80	1122.5 ⩾60	705.5 144	1034.0 ⩾60	568.5 94	744.0 32	639.5 114	N/A	N/A	874.0 53.5	427.5 66.5	1180.5 ⩾60	493.5 78
Column, °C min	1195.5 ⩾60	588 115	1120.5 ⩾60	378.0 72	1101.0 ⩾60	400.5 75	1114.5 ⩾60	616.5 121	1034.5 ⩾60	493.0 92	742.0 32	605.0 119	N/A	N/A	861.0 52	361.0 69.5	1182.0 ⩾60	379.0 72
MIDDLE Beam, °C min	1230.5 ⩾60	*	1145.5 ⩾60	505.0 80	1180.0 ⩾60	572.0 95	1199.0 ⩾60	742.0 160	1118.5 ⩾60	602.5 103	713.5 27.5	623.0 109	N/A	N/A	1021.0 ⩾60	454.0 70	1187.0 ⩾60	541.0 88
Column, °C min	1248.0 ⩾60	*	1162.0 ⩾60	428.5 79	1171.0 ⩾60	442.0 81.5	A (517.5) ?	653.0 127.5	A (417.0) ?	521.5 98	A (517.5) ?	590.0 116	N/A	N/A	A (370.5) ?	382.0 72.5	A (398.0) ?	403.5 76.5
FRONT Beam, °C min	1173.5 ⩾60	*	1043.5 ⩾60	420.0 64	1111.5 ⩾60	507.5 80	1222.0 ⩾60	759.0 168	1147.0 ⩾60	625.0 110	741.5 32	580.5 97	C (342.0) 53.5	350.0 55	956.0 >60	403.5 62	992.0 >60	440.0 68
Column, °C min	1192.0 ⩾60	616.5 121	1084.0 ⩾60	308.0 61	1126.0 ⩾60	418.0 77.5	1222.0 ⩾60	678.5 132	1160.5 ⩾60	538.0 102	B (450.8) 195	559.5 108	D (265.5) 55	258.0 54	B (248.8) 129.5	330.0 64	B (222.5) 122	308.5 61
Average Time Equivalent, t_e Measured	-	118	-	71.5	-	81.5	-	142	-	99.8	-	110.5	54.3		-	67.5	-	74
t_e Calculated using c = 0.09 (Eurocode 1: September 1992)		101.2		50.6		79.0		157.9		100.6		112.1	50.6			57.0/ 71.8		53.7
t_e $\frac{\text{Measured}}{\text{Calculated}}$		1.17		1.41		1.03		0.90		0.99		0.99	1.07			1.18/ 0.94		1.38
t_e Calculated using $k_b = 0.07$ (Eurocode 1: April 1993)		76.7		39.4		61.4		122.8		78.2		87.2	39.4			44.3/ 55.9		41.8
t_e $\frac{\text{Measured}}{\text{Calculated}}$		1.54		1.82		1.33		1.16		1.27		1.27	1.38			1.52/ 1.21		1.77

* Integrity of fire protection lost
? Equivalent fire resistance unknown

( ) Fire protected with:
A = 40 mm Ceramic fibre board
B = 70 mm Viculad
C = 20 mm Viculad } Duplicates of South side
D = 30 mm Viculad } and included in the averaging

TABLE 4
COMPARISON BETWEEN THE MEASURED TIME EQUIVALENT AND CALCULATED VALUES BASED UPON CIB W14(5), LAW(6), PETTERSSON(7) AND HARMATHY(8)

Time Equivalent Relationship	Test 1 min	Test 2 min	Test 3 min	Test 4 min	Test 5 min	Test 6 min	Test 7 min	Test 8 min	Test 9 min
Measured	118.0	71.5	81.5	142.0	99.8	110.5	54.3	67.5	74.0
CIB W14	85.3	42.7	70.8	141.6	97.7	197.3	38.5	47.0/ 59.3	44.3
Law	79.5	39.8	55.7	111.3	79.4	109.1	34.2	43.5/ 54.8	41.2
Pettersson	109.9	55.0	91.2	182.4	126.0	254.1	49.7	55.4/ 69.8	56.8
Harmathy	45.6	29.6	59.4	106.3	98.8	342.8	48.2	31.9/ 36.8	31.2

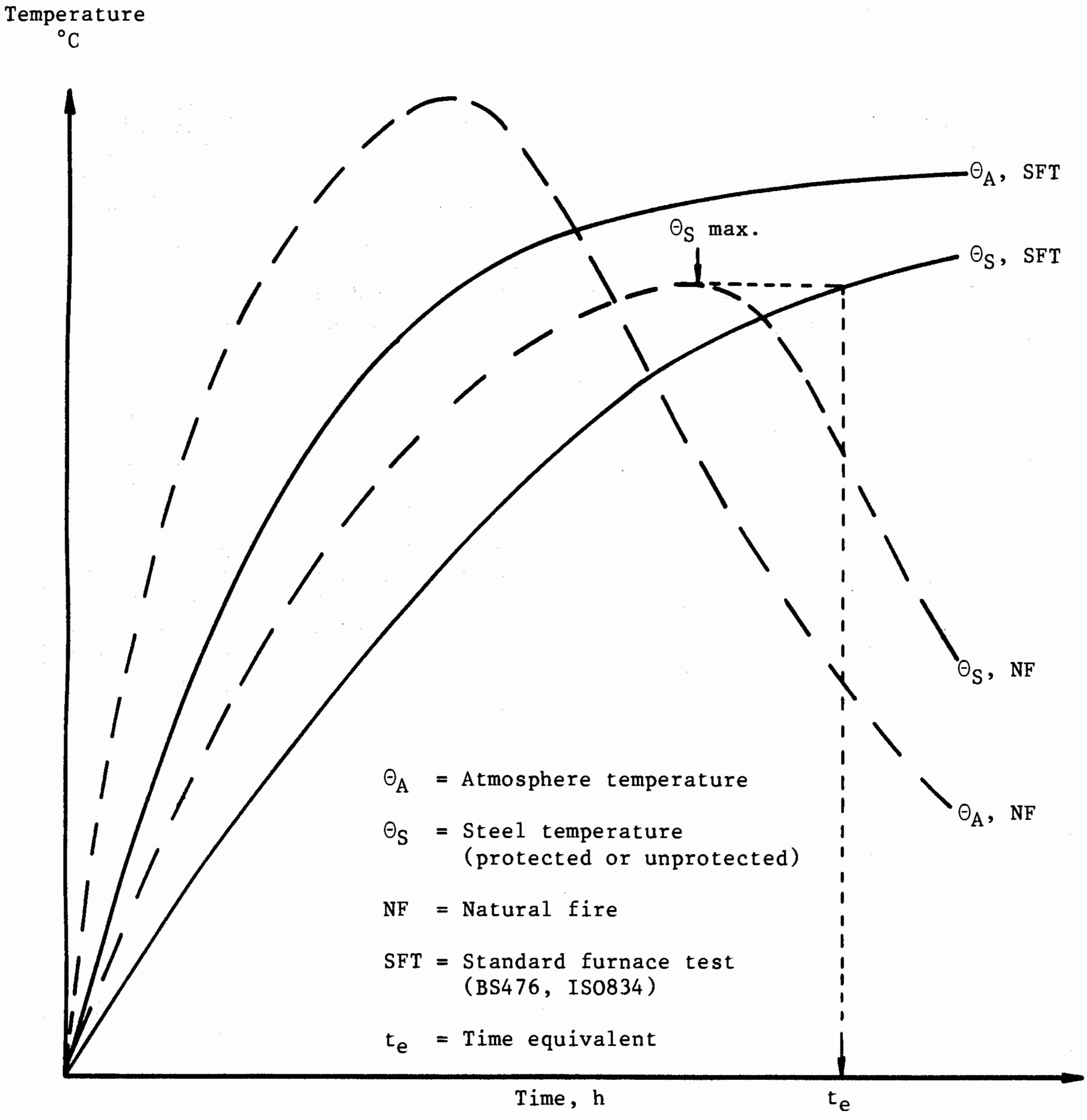


FIG. 1 **SCHEMATIC REPRESENTATION: DEFINITION OF EQUIVALENT TIME OF FIRE EXPOSURE, t_e** **(R4/1356)**

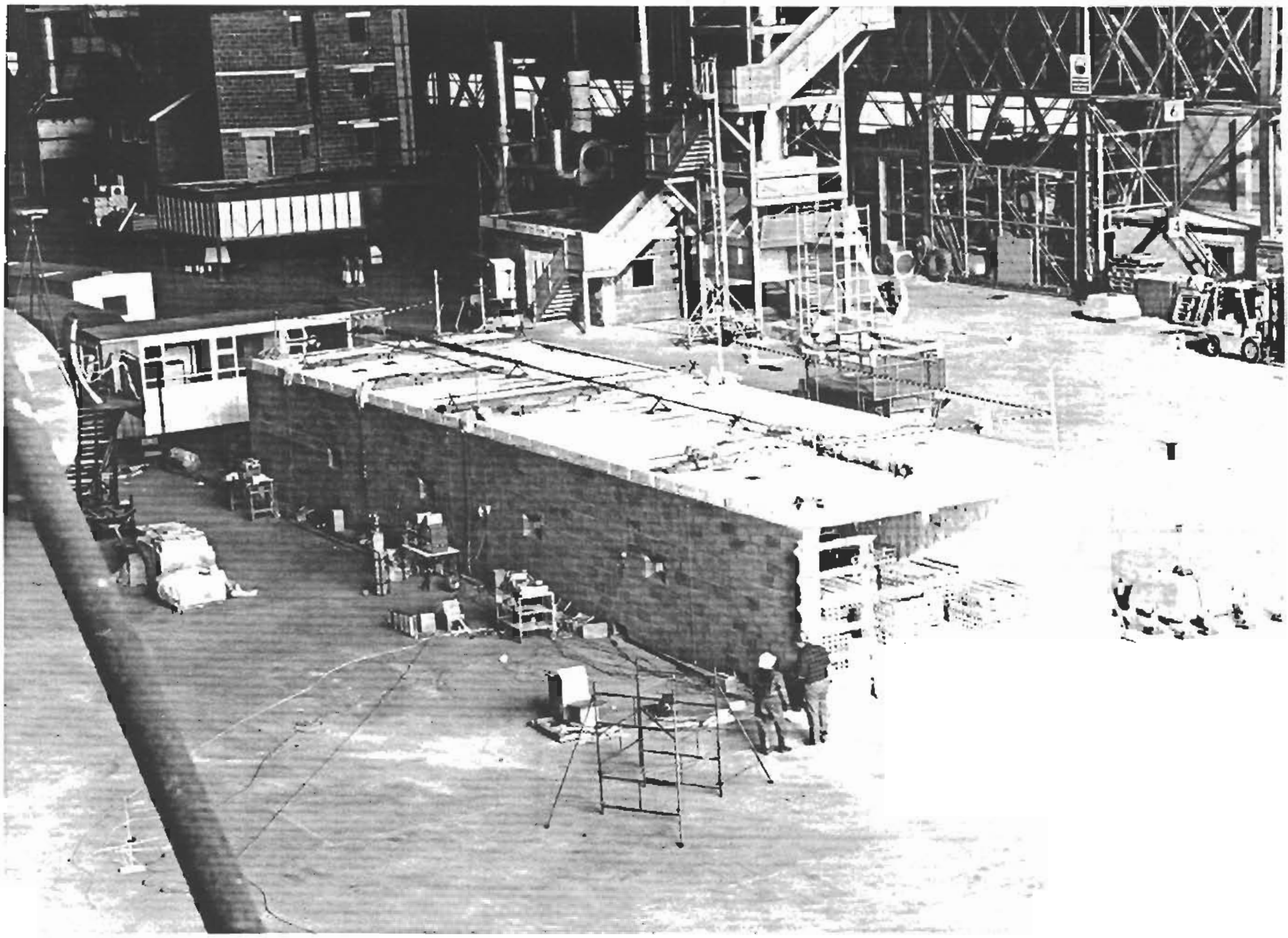
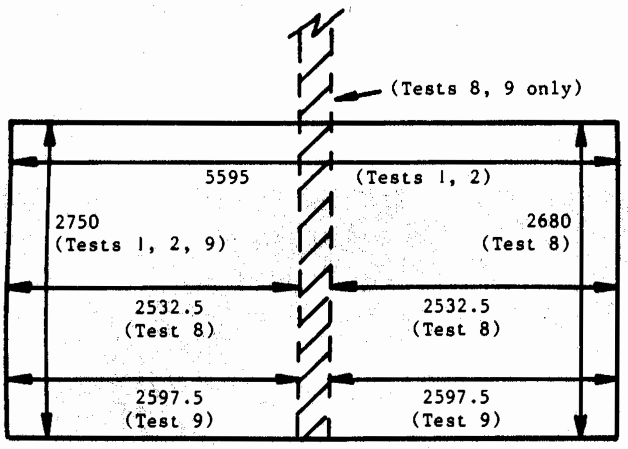
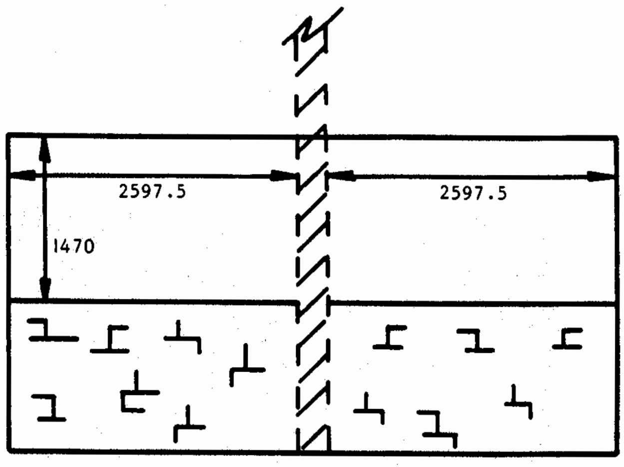


FIG. 2 GENERAL VIEW OF THE TEST COMPARTMENT



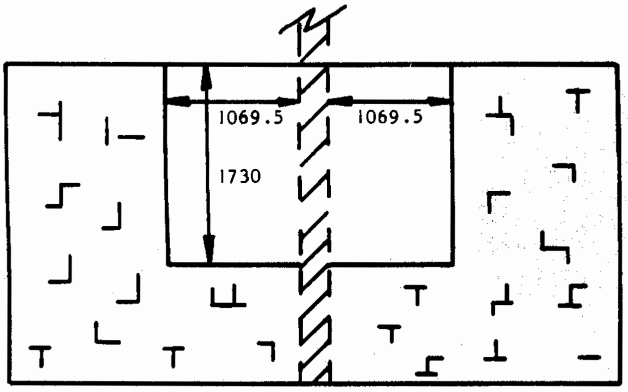
1/1 OPENING

TESTS 1, 2, 8 & 9



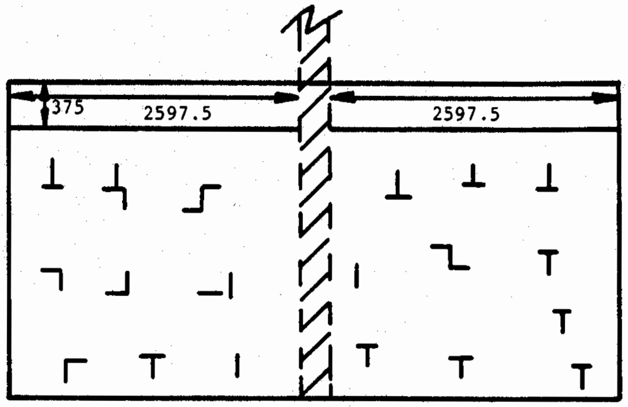
1/2 OPENING

TESTS 3 & 4



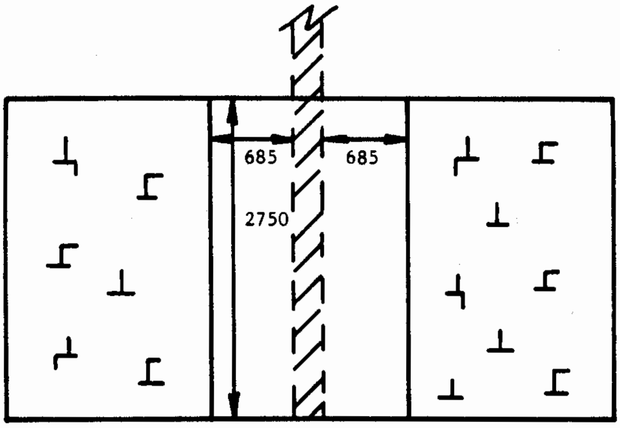
1/4 OPENING

TEST 5



1/8 OPENING

TEST 6



1/4 OPENING

TEST 7

Dimensions in mm

FIG. 3 DIMENSIONS OF THE VENTILATION OPENING CONDITIONS (R4/1357)

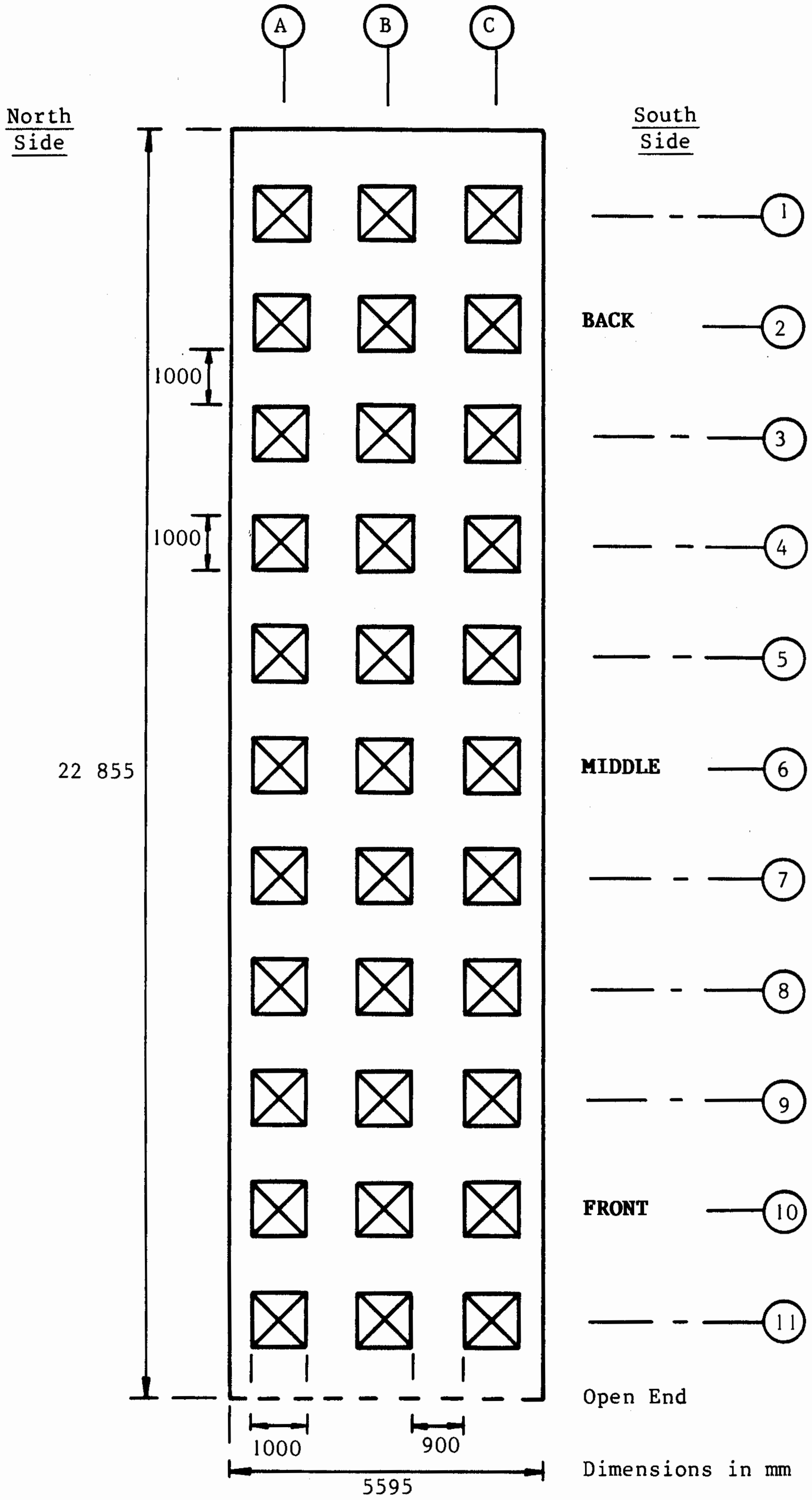


FIG. 4 COMPARTMENT PLAN SHOWING THE LAYOUT OF THE CRIBS WITH THE BACK, MIDDLE AND FRONT MEASURING STATIONS (R4/1358)

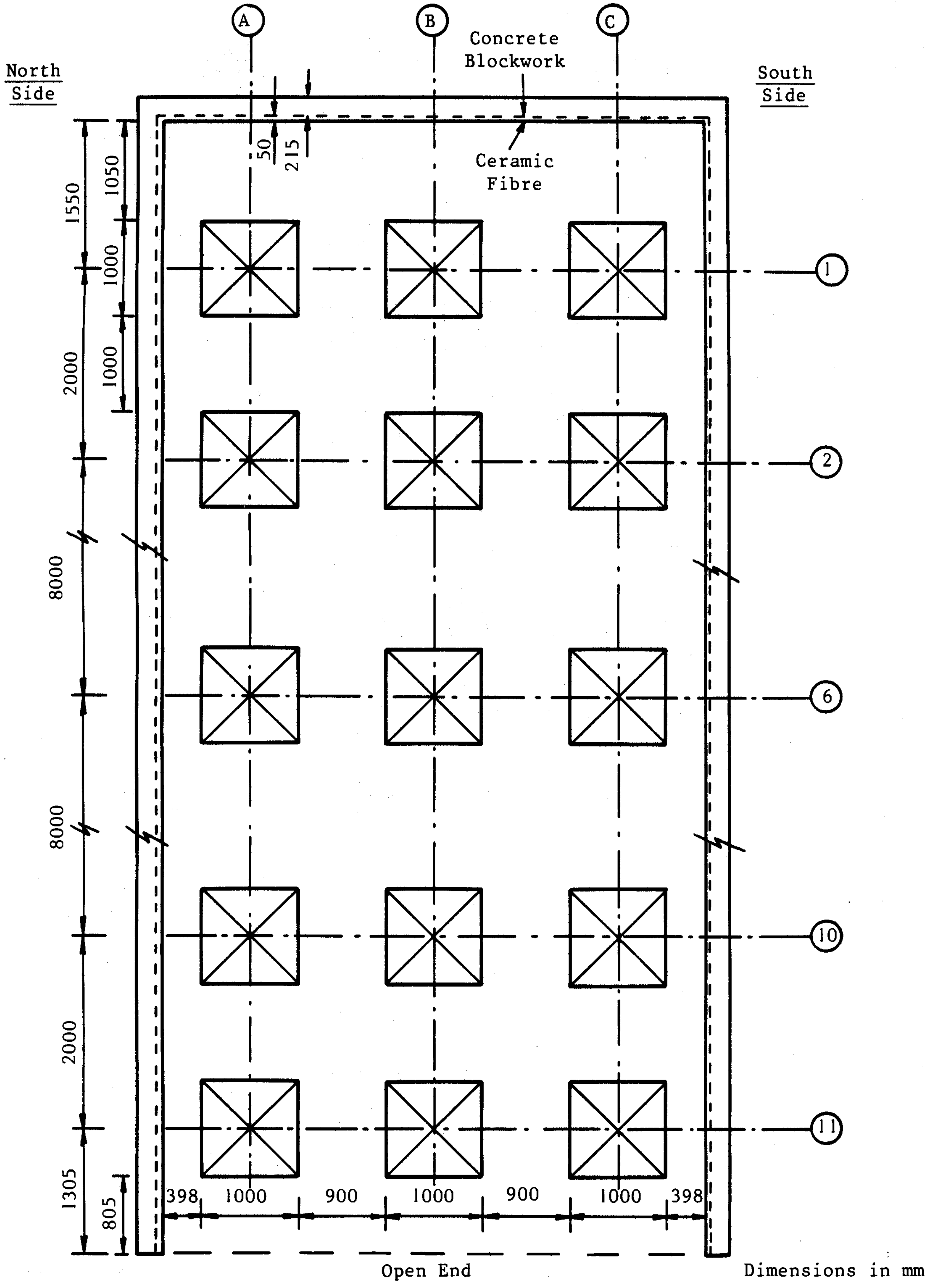


FIG. 5 **COMPARTMENT PLAN DETAILING THE LAYOUT OF THE CRIBS** **(R4/1359)**

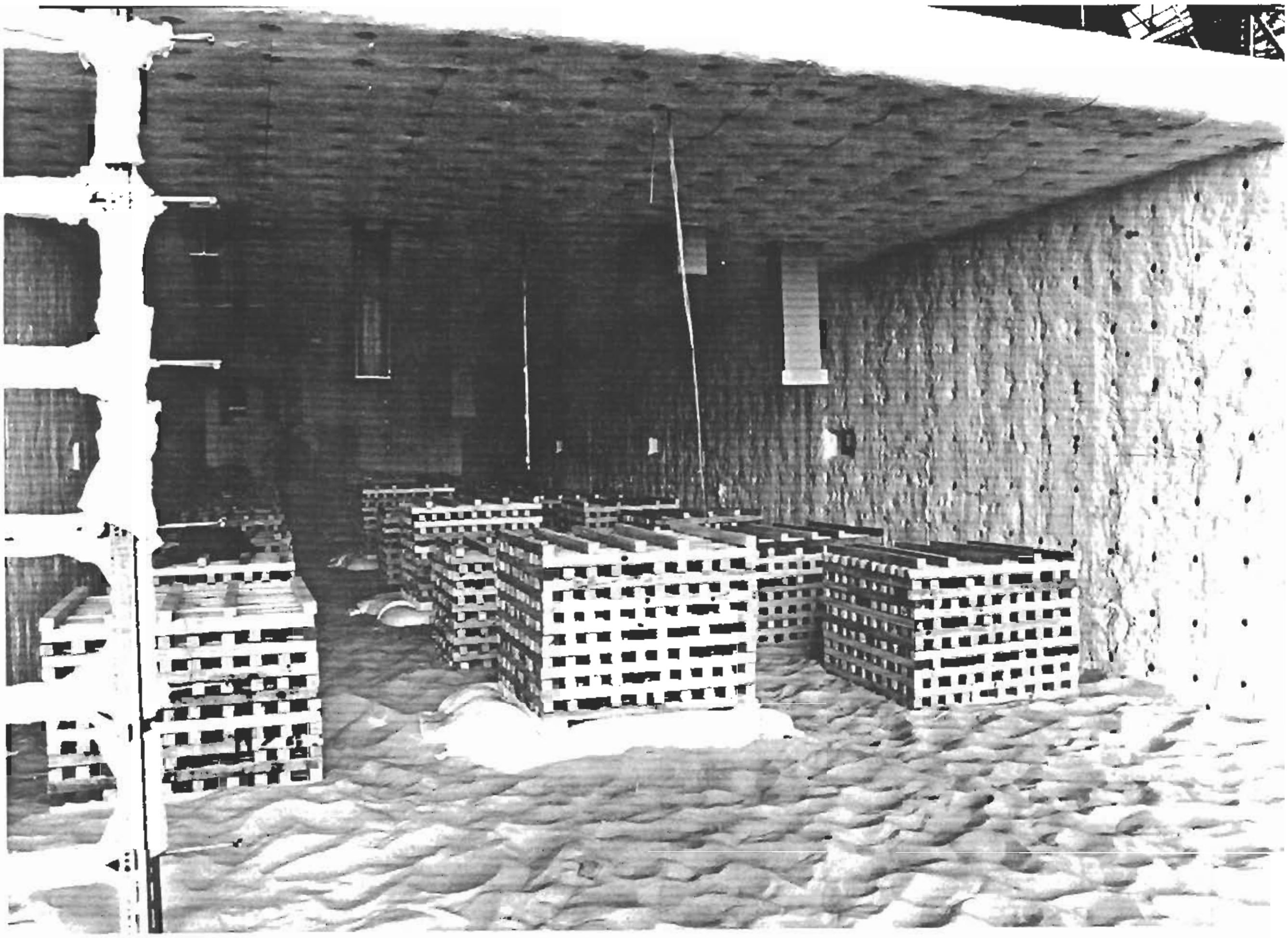


FIG. 6 CONSTRUCTION OF THE TIMBER CRIBS

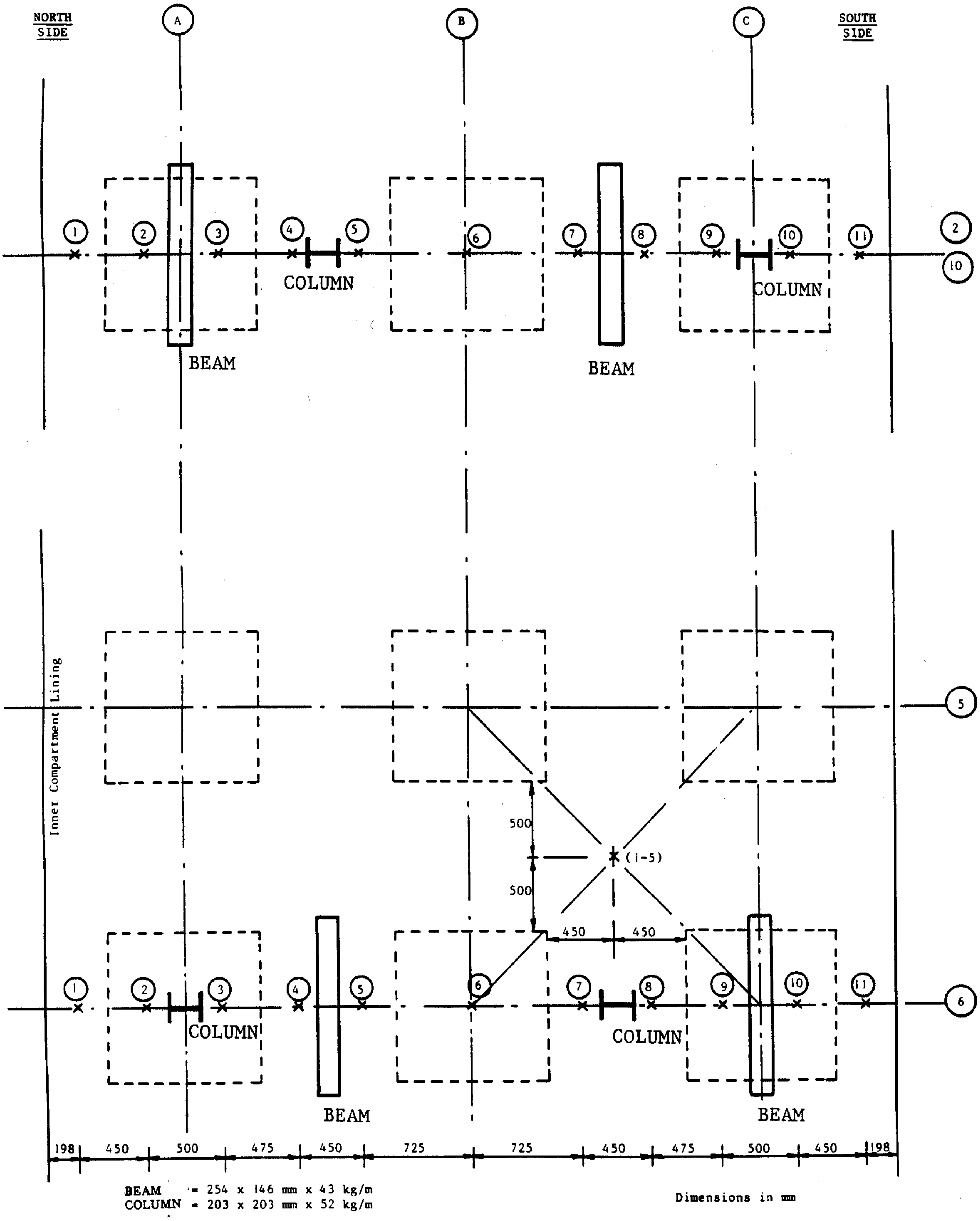


FIG. 7a COMPARTMENT PLAN DETAILING THE POSITION OF THE STEEL MEMBERS AND ATMOSPHERE THERMOCOUPLES (R4/1360)

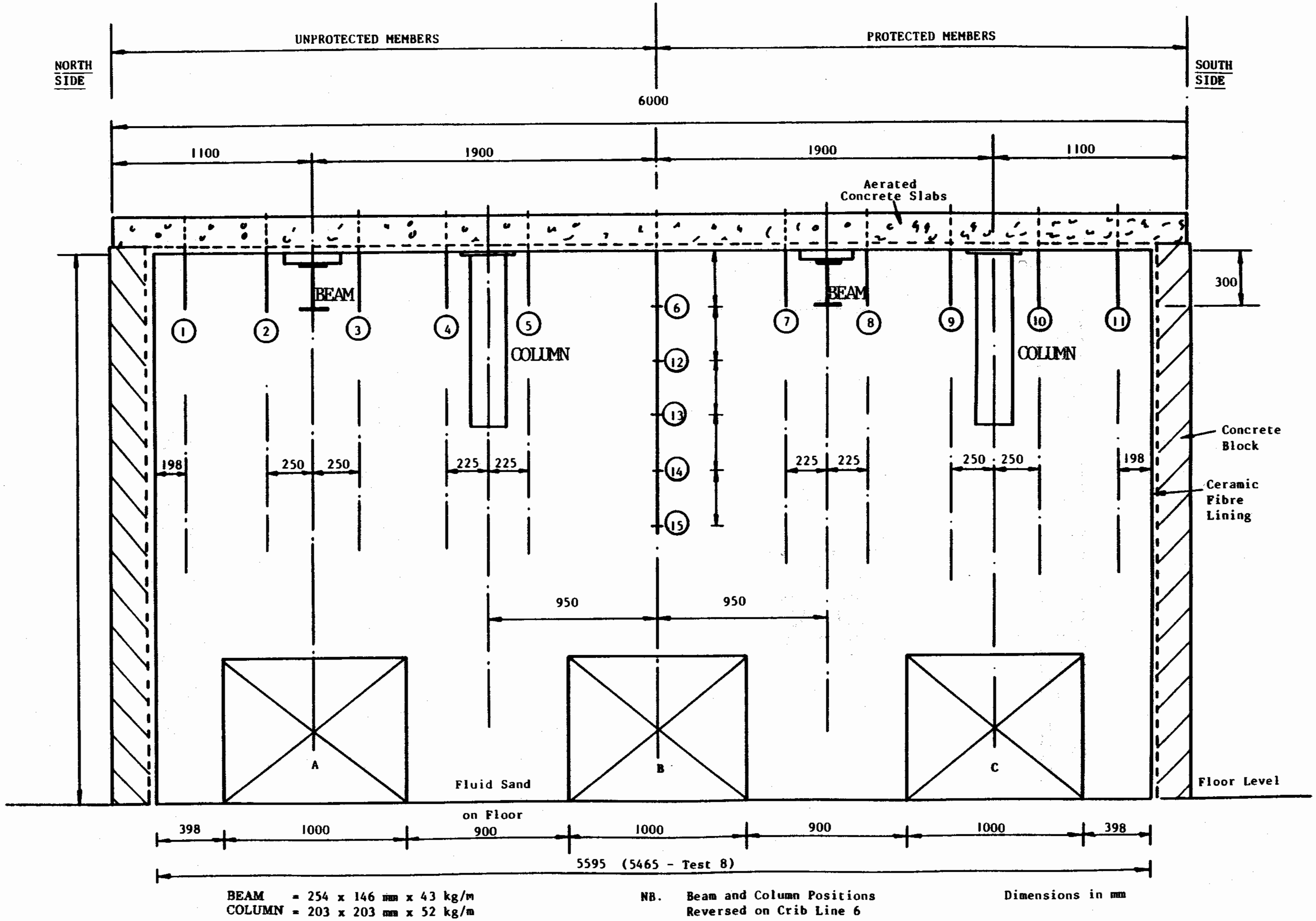


FIG. 7b SECTION THROUGH THE COMPARTMENT ON CRIB LINES 2, 6 AND 10 SHOWING STEEL AND THERMOCOUPLE LOCATIONS (R4/1361)

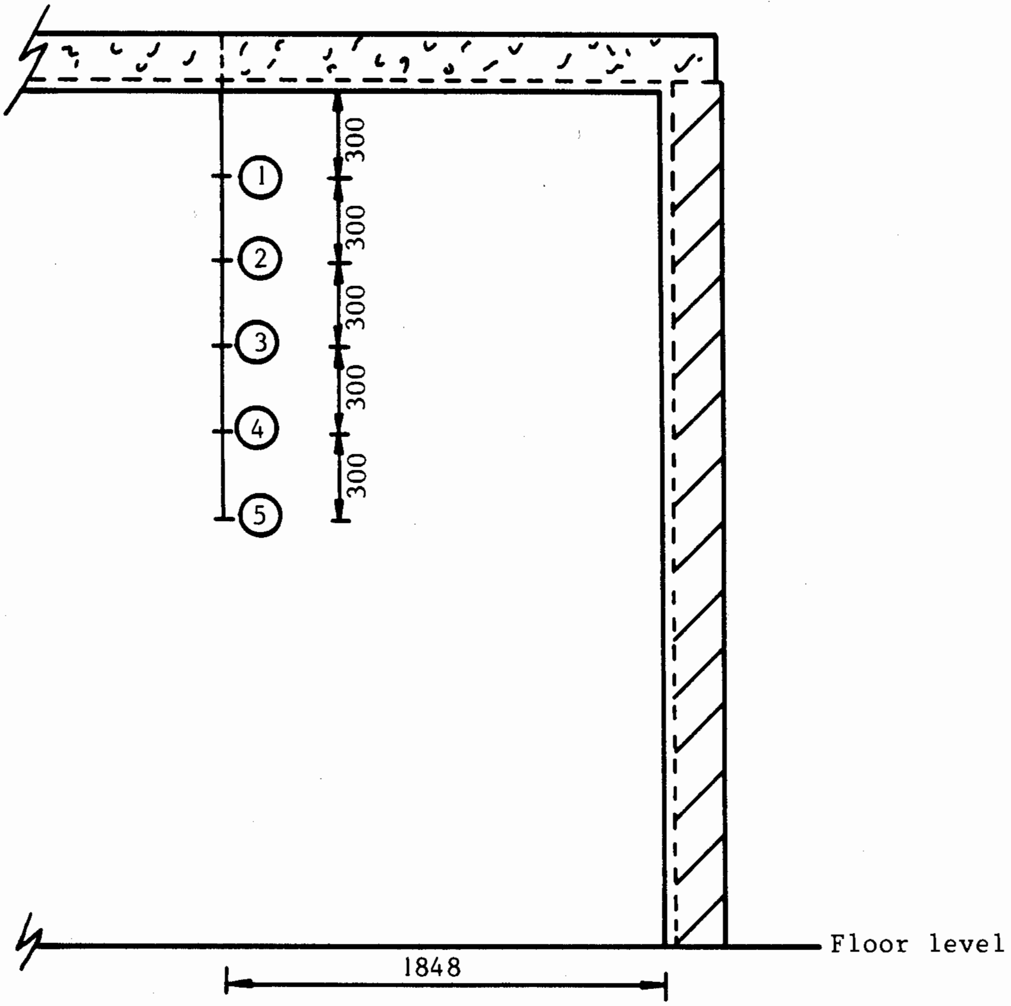


FIG. 7c SECTION THROUGH THE COMPARTMENT SHOWING THE THERMOCOUPLE LOCATIONS AT CRIB LINE 5/6 (R4/1362)

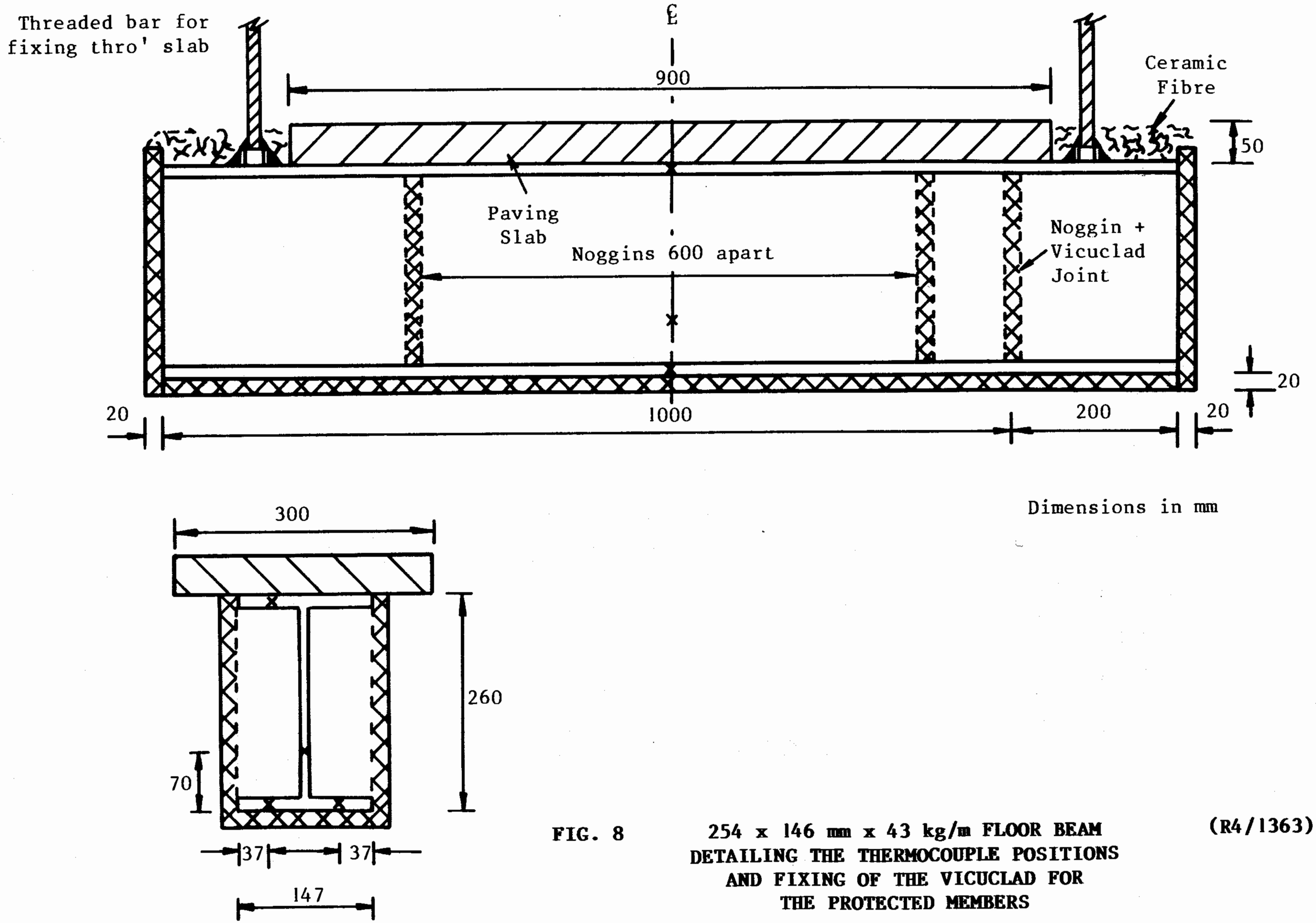
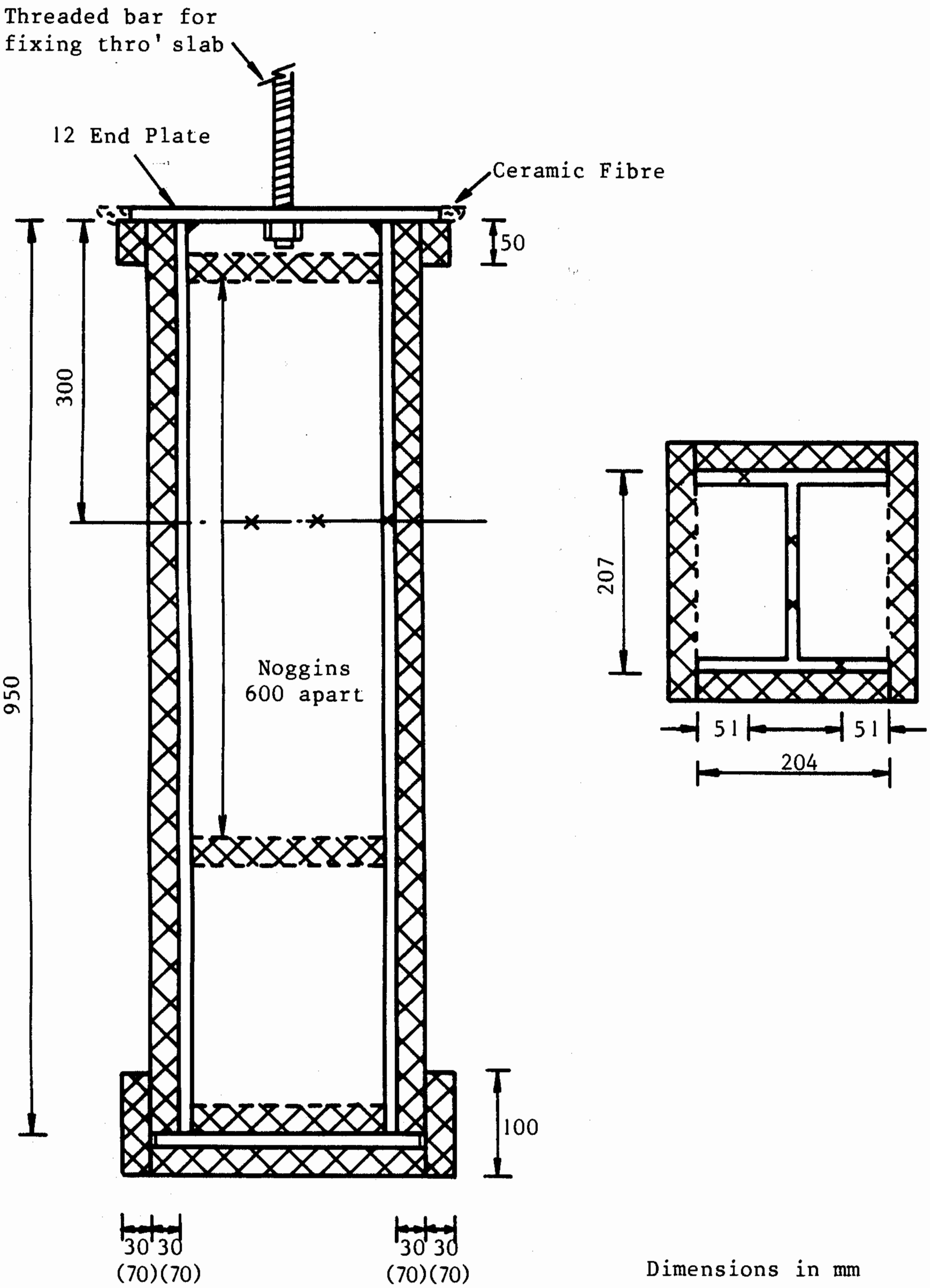


FIG. 8 254 x 146 mm x 43 kg/m FLOOR BEAM DETAILING THE THERMOCOUPLE POSITIONS AND FIXING OF THE VICUCLAD FOR THE PROTECTED MEMBERS

(R4/1363)



Dimensions in mm

FIG. 9 203 x 203 mm x 52 kg/m COLUMN DETAILING THE THERMOCOUPLE POSITIONS AND FIXING OF THE 30 mm AND 70 mm VICUCLAD FOR THE PROTECTED MEMBERS (R4/1364)

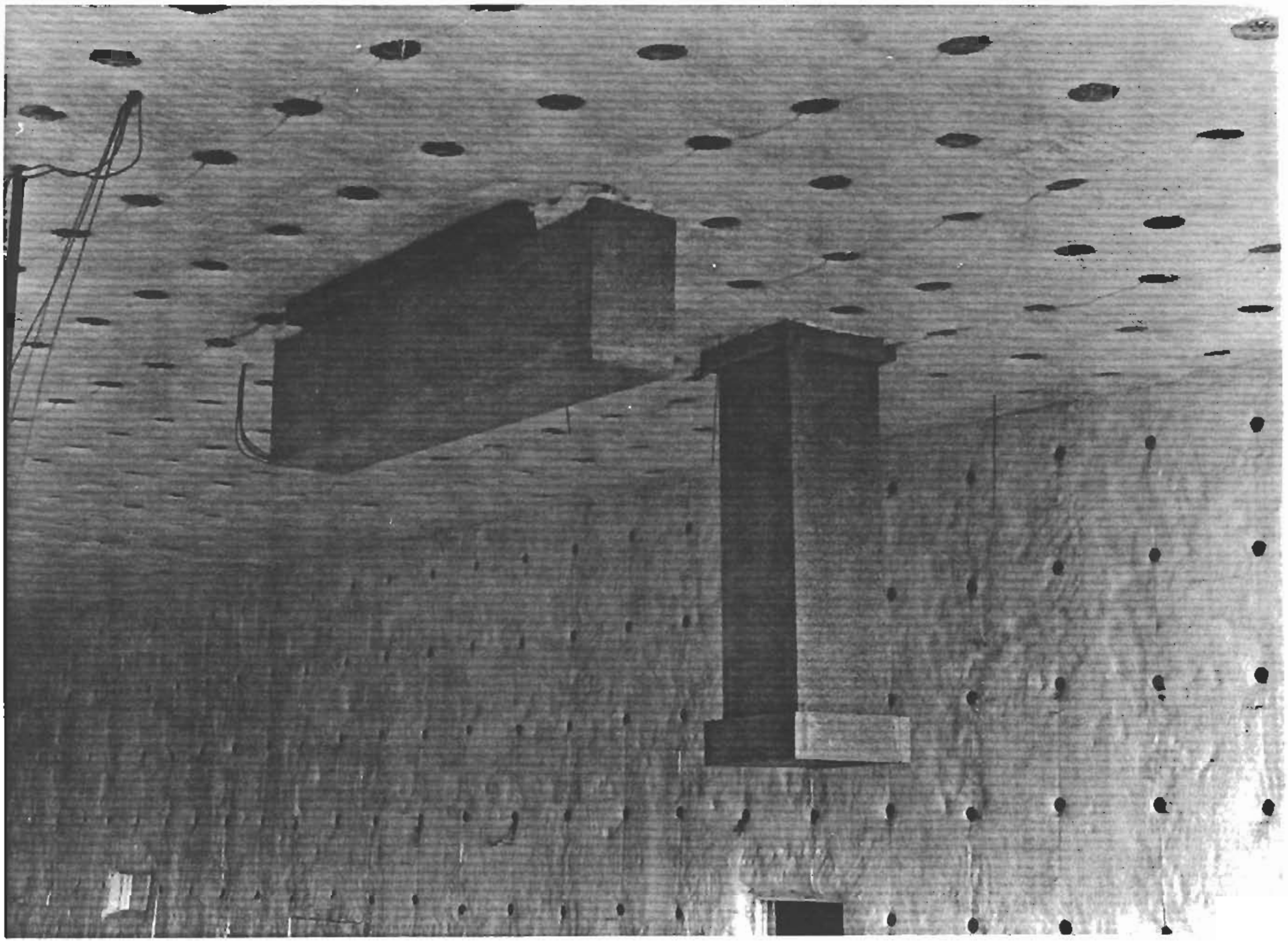


FIG. 10   BEAM AND COLUMN PROTECTED WITH VICUCLAD

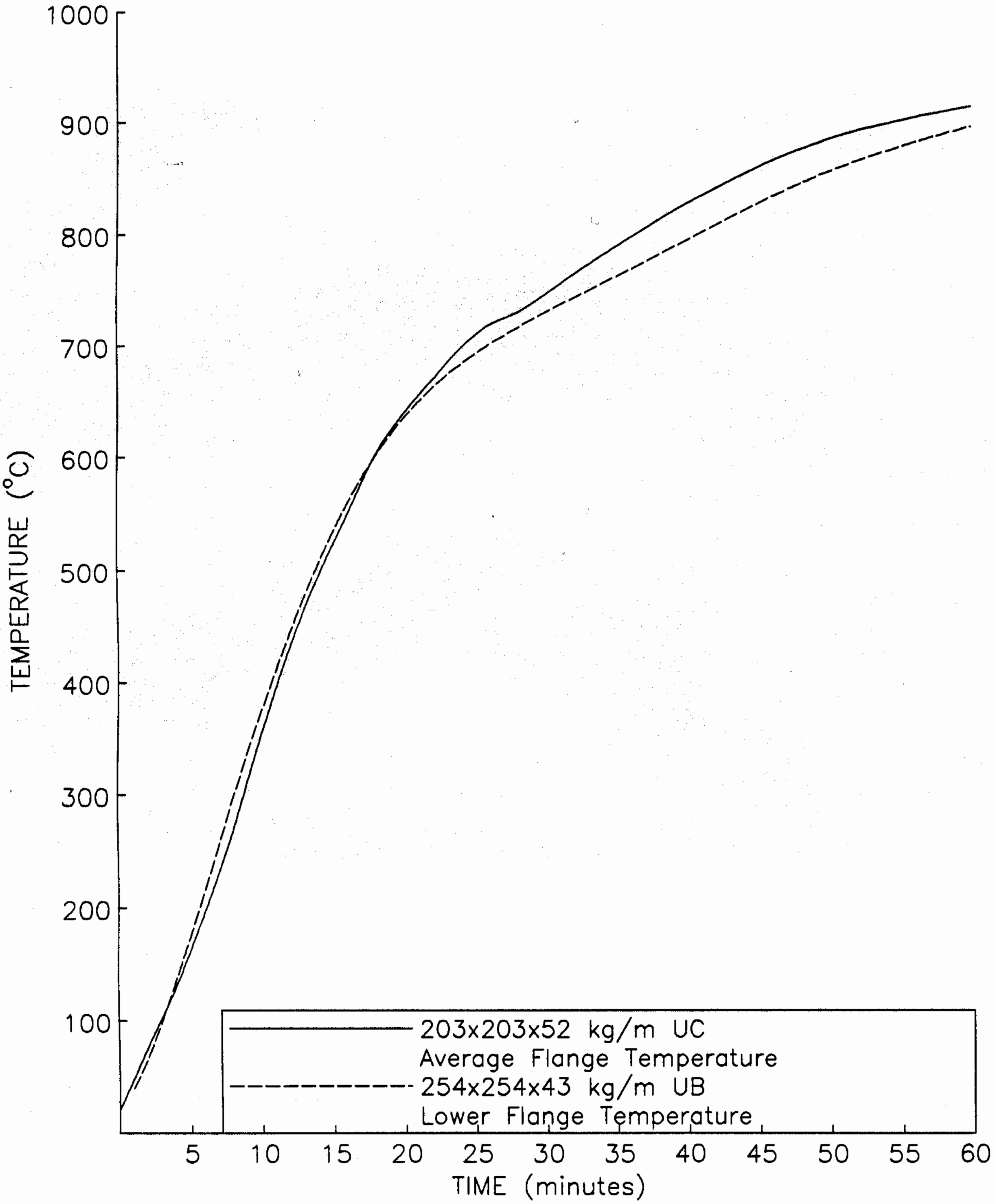


FIG. 11 HEATING CURVES OF UNPROTECTED STRUCTURAL STEEL MEMBERS IN THE BS476 FIRE RESISTANCE TEST USED FOR DETERMINING VALUES OF TIME EQUIVALENT

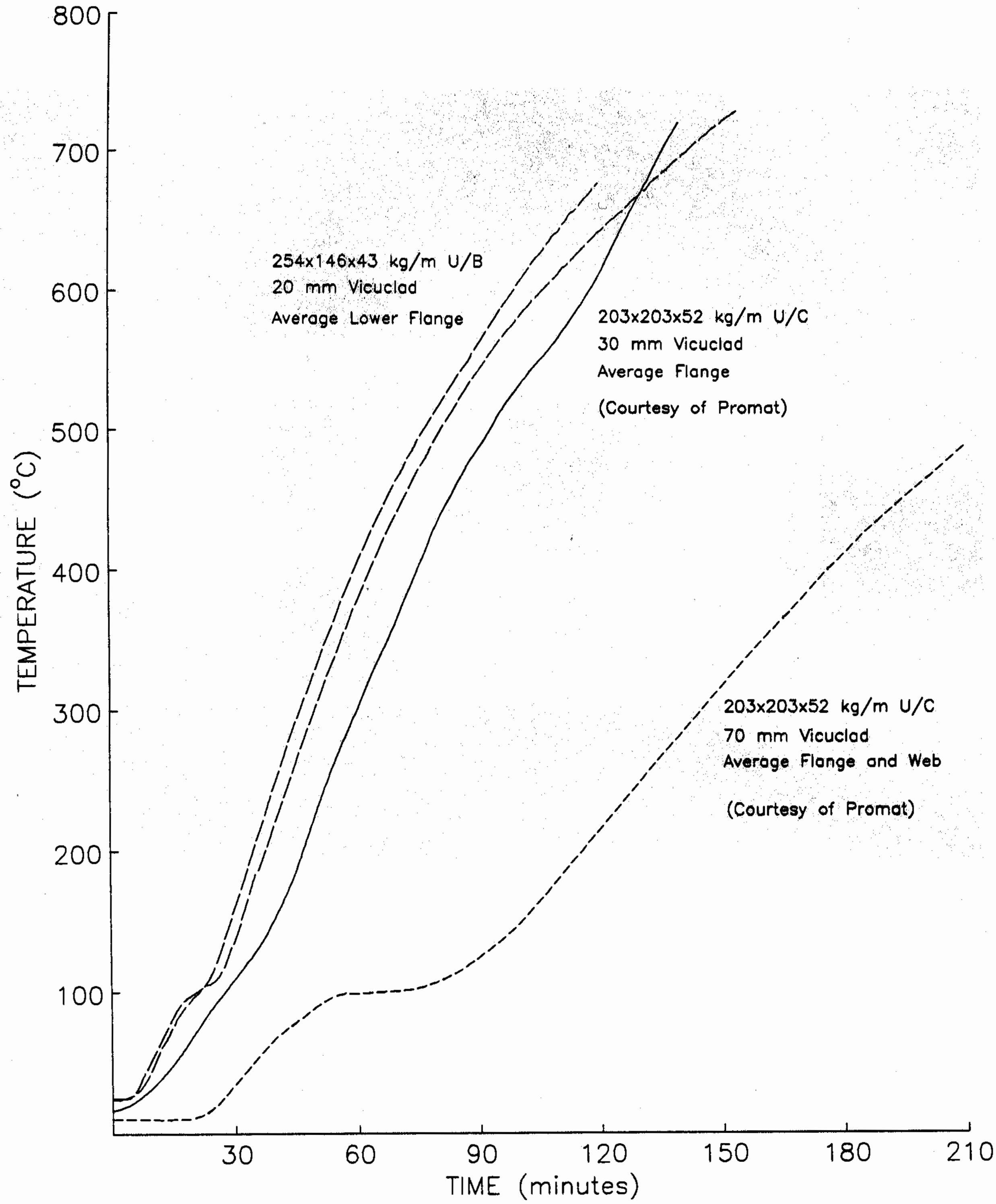


FIG. 12 HEATING CURVES OF PROTECTED STRUCTURAL STEEL MEMBERS IN THE BS476 FIRE RESISTANCE TEST USED FOR DETERMINING VALUES OF TIME EQUIVALENT

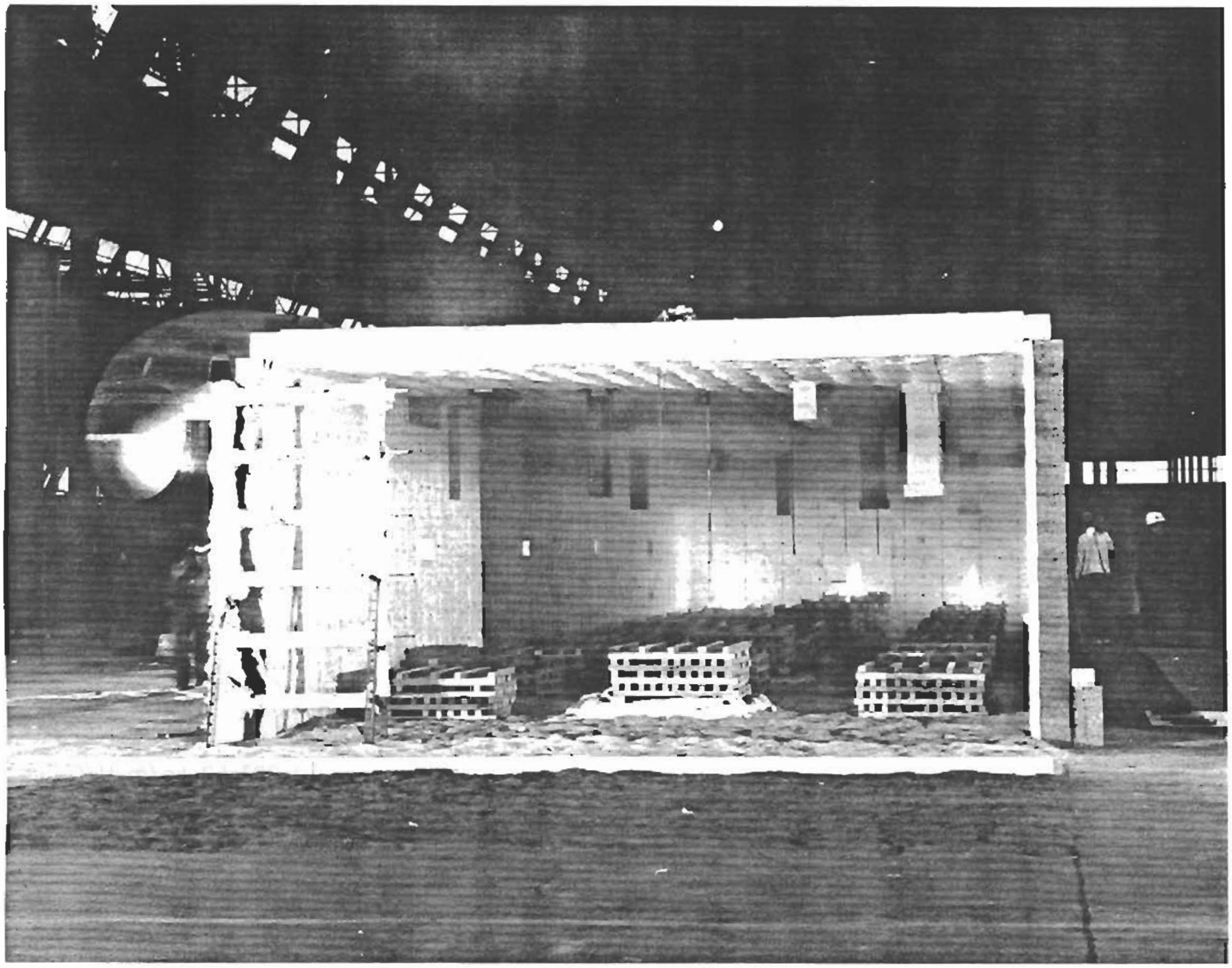


FIG. 13 TEST 2: IGNITION OF THE CRIBS ON CRIB LINE 1

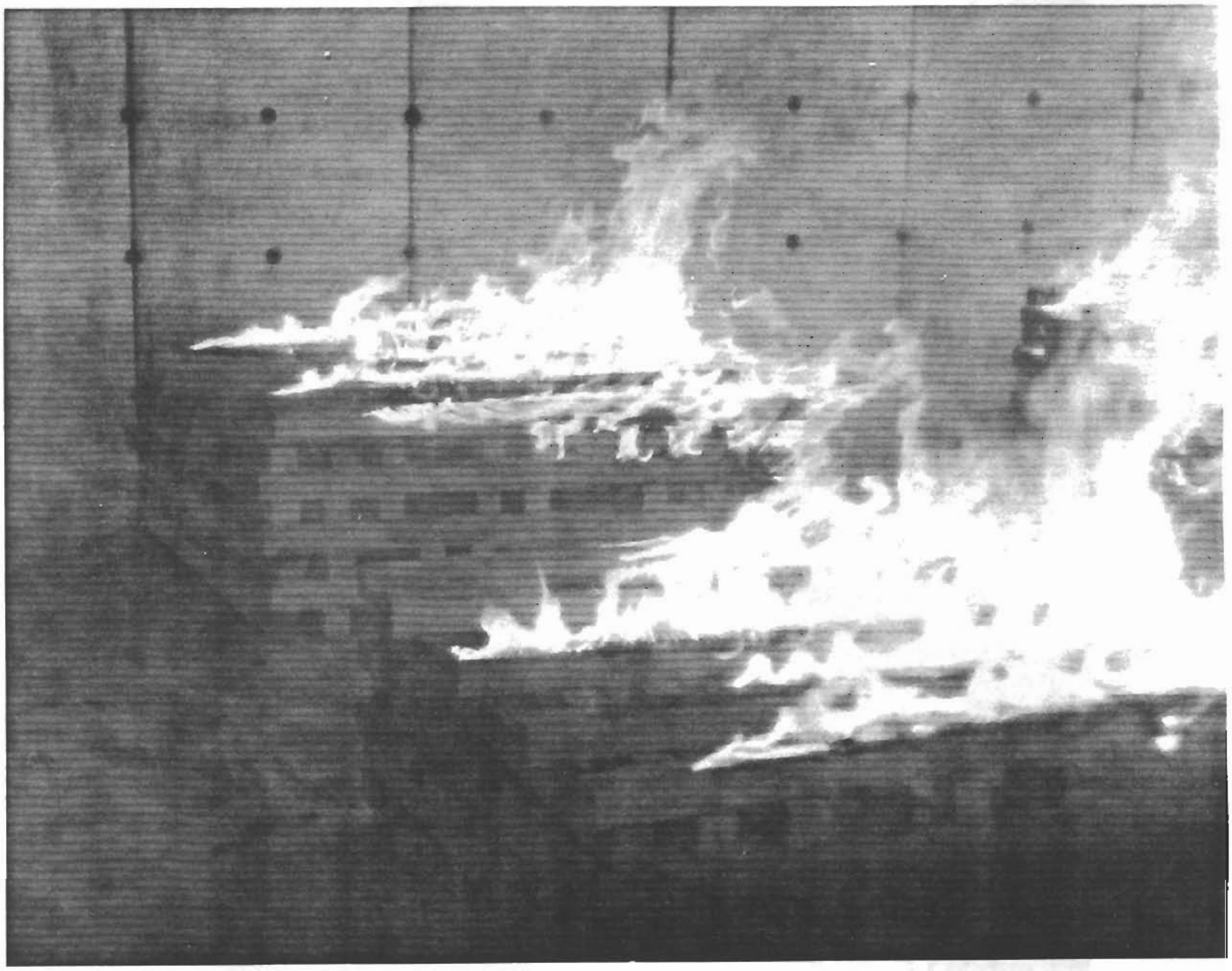
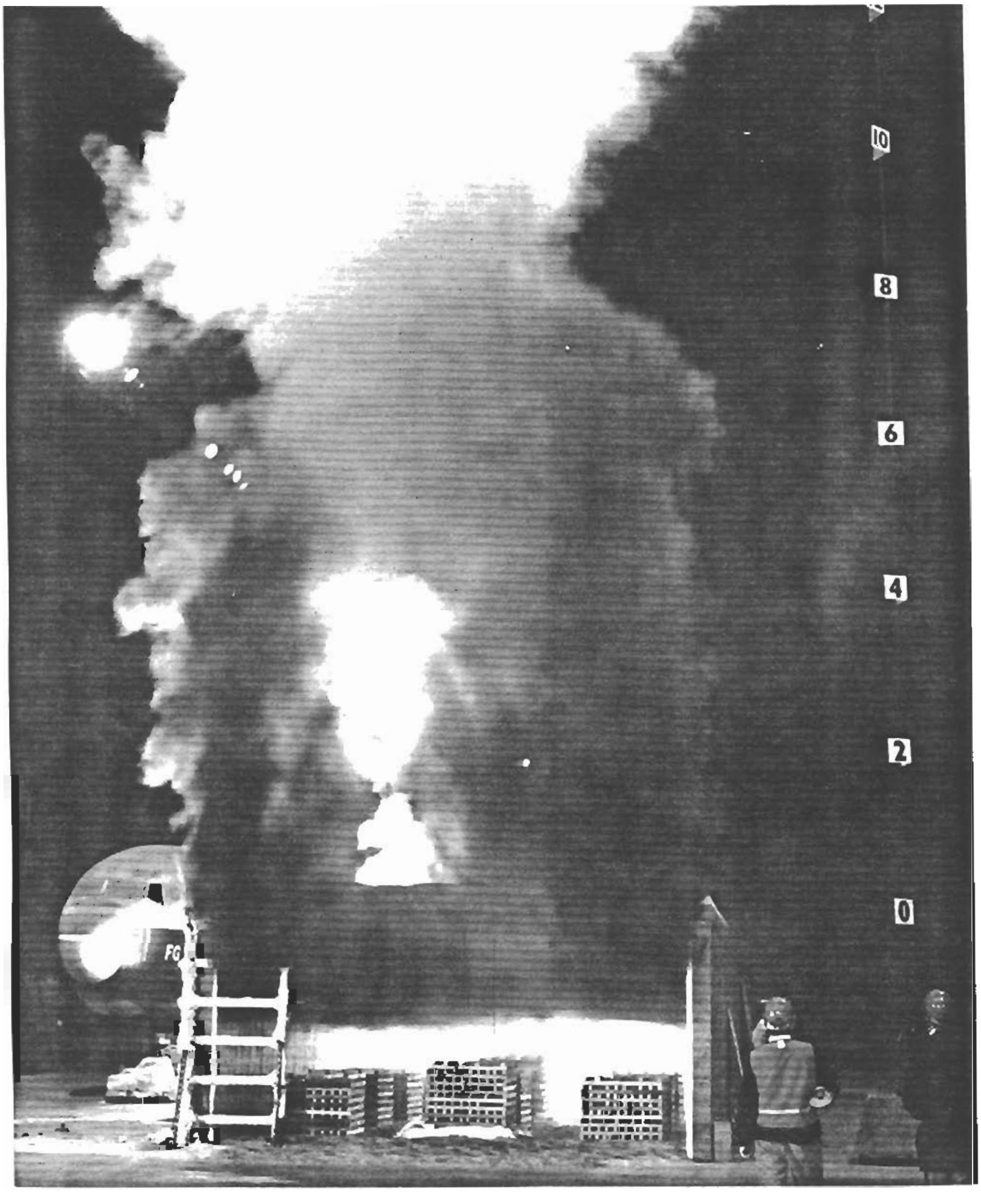


FIG. 14 TEST 2: FIRE SPREAD TO ADJACENT CRIBS



Courtesy of Fire Research Station

FIG. 15 TEST 1: FIRE DEVELOPMENT TOWARDS THE FRONT OF THE COMPARTMENT

FIG. 16 TEST 8: FIRE SPREAD ALONG THE SURFACE OF THE PLASTERBOARD LINING

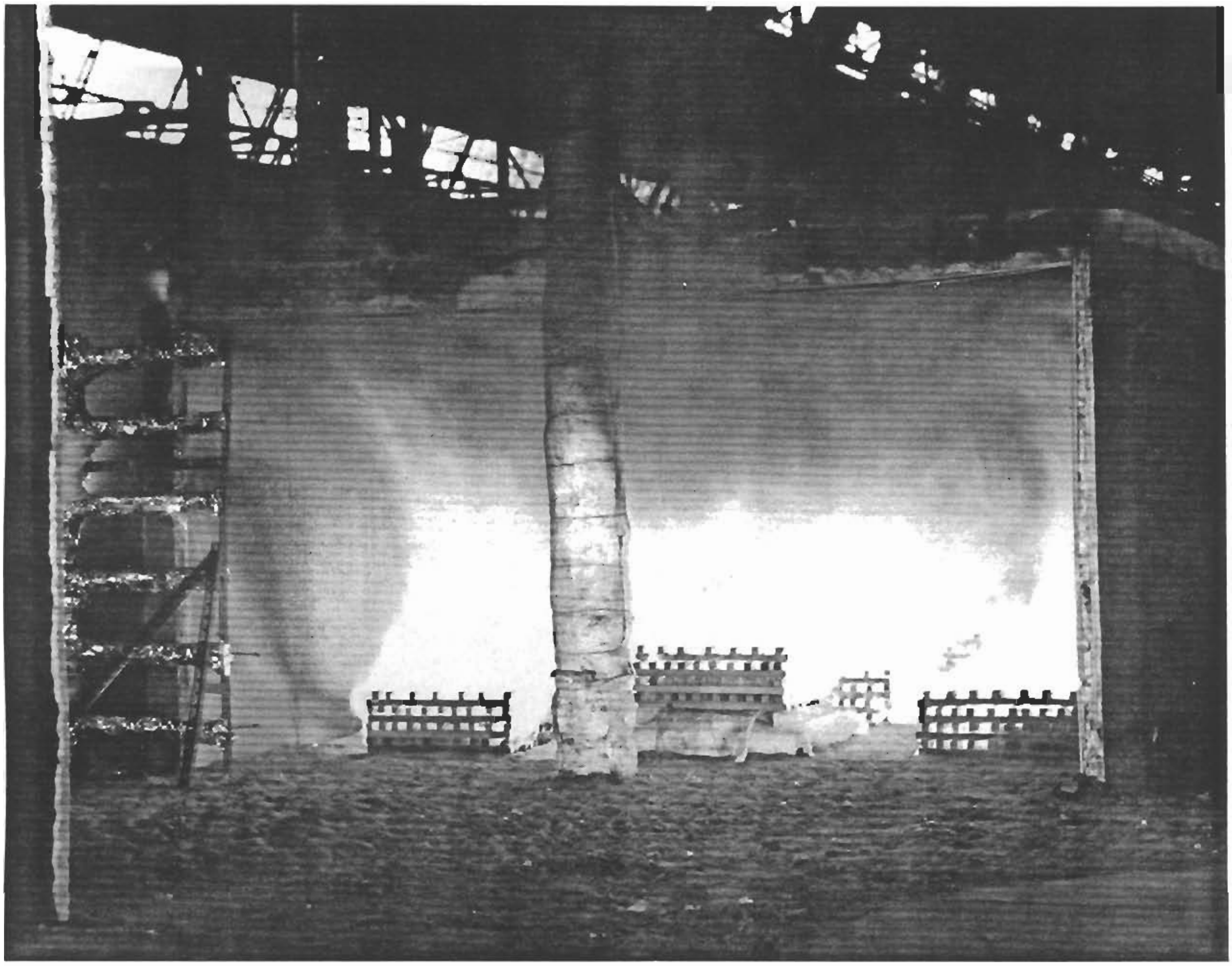


FIG. 17 TEST 8: INFLUENCE OF THE VENTILATION ON FLAME BEHAVIOUR

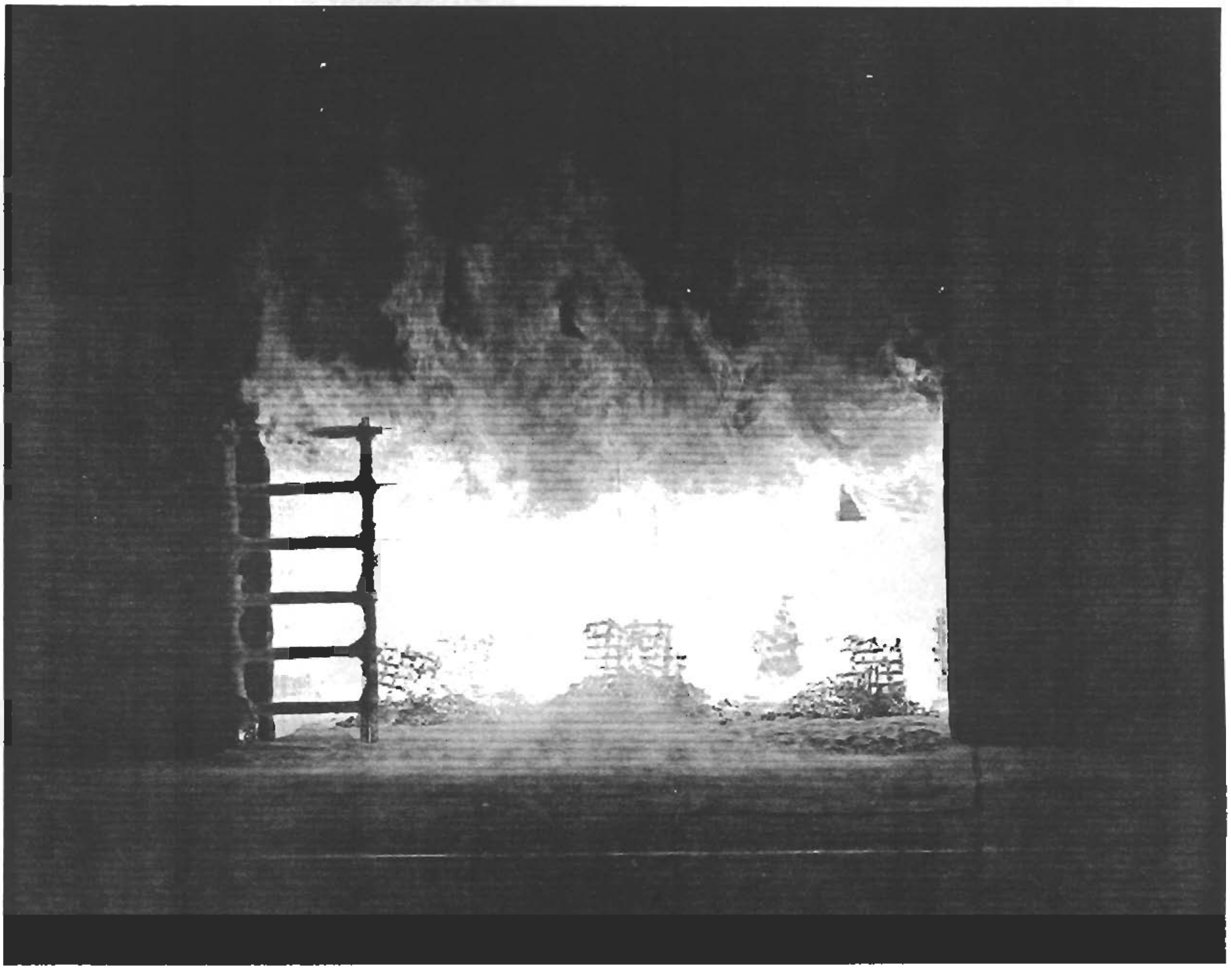


FIG. 18 TEST 1: TOTAL ENGULFMENT WITH THE FRONT LINE OF CRIBS BEGINNING TO COLLAPSE

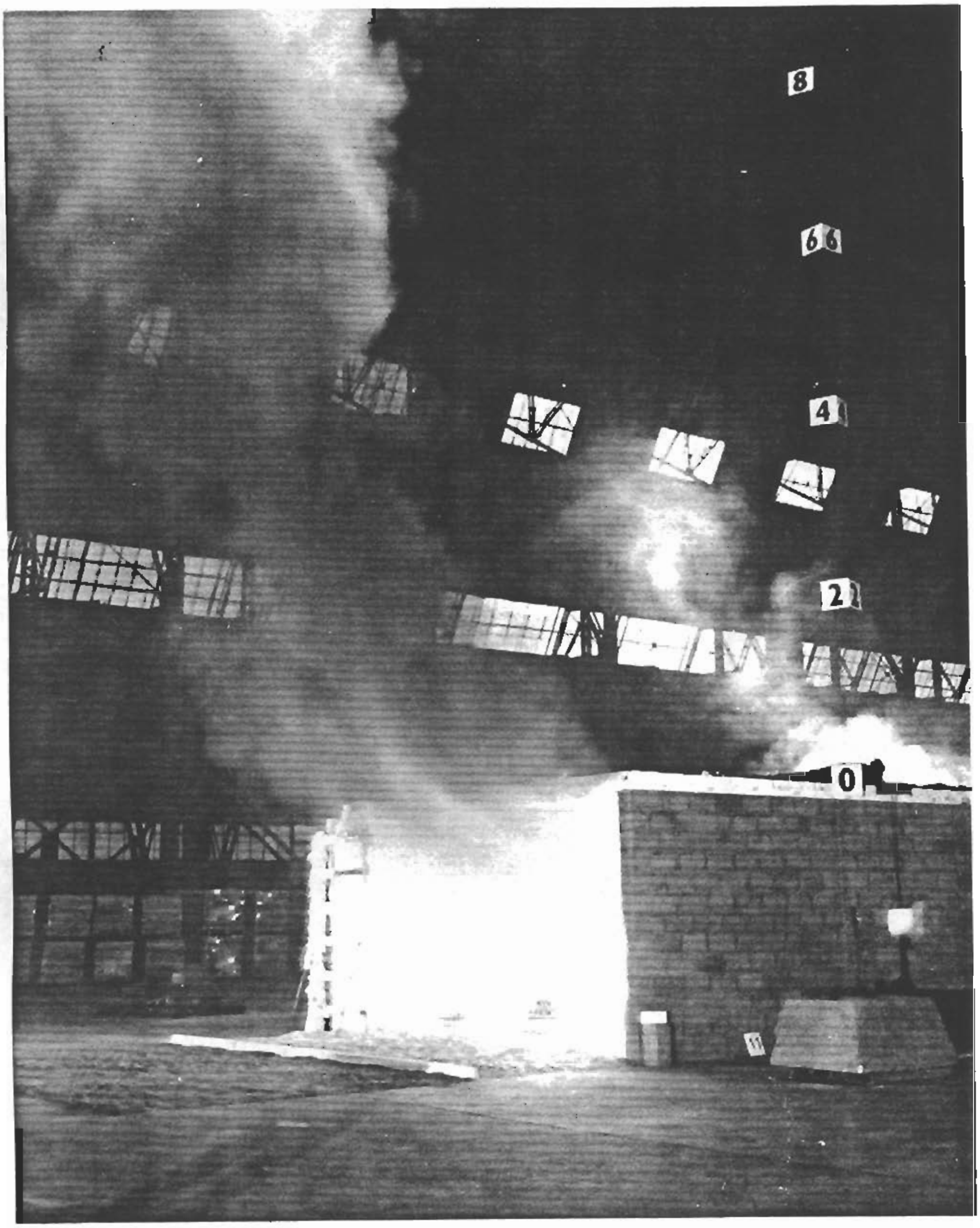


FIG. 19 TEST 2: FULLY DEVELOPED FIRE, $^1/_1$ VENTILATION

FIG. 20 TEST 4: FULLY DEVELOPED FIRE, $^{1}/_{2}$ VENTILATION

FIG. 21 TEST 6: FULLY DEVELOPED FIRE, 1/8 VENTILATION

FIG. 22 TEST 7: CLOSING STAGES OF THE FIRE IN THE REDUCED SIZE SIZE COMPARTMENT, 1/4 VENTILATION

FIG. 23 CLOSING STAGES OF THE PLASTERBOARD LINED COMPARTMENT. NOTE THE BURNT OUT TIMBER ROOF STUDS AND THE WALL LINING STILL LARGELY IN POSITION

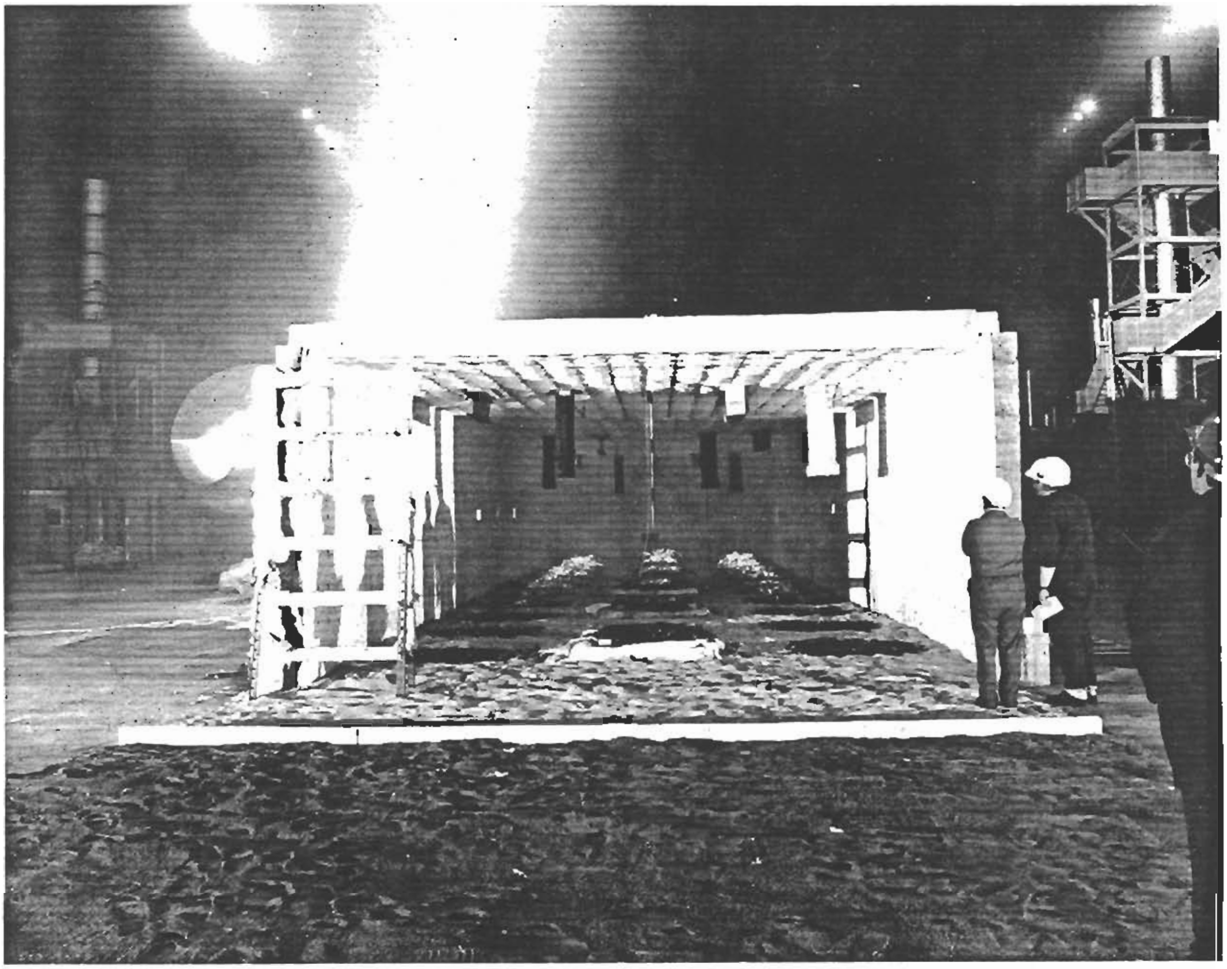


FIG. 24 COMPLETE COMBUSTION OF THE FIRE LOADING

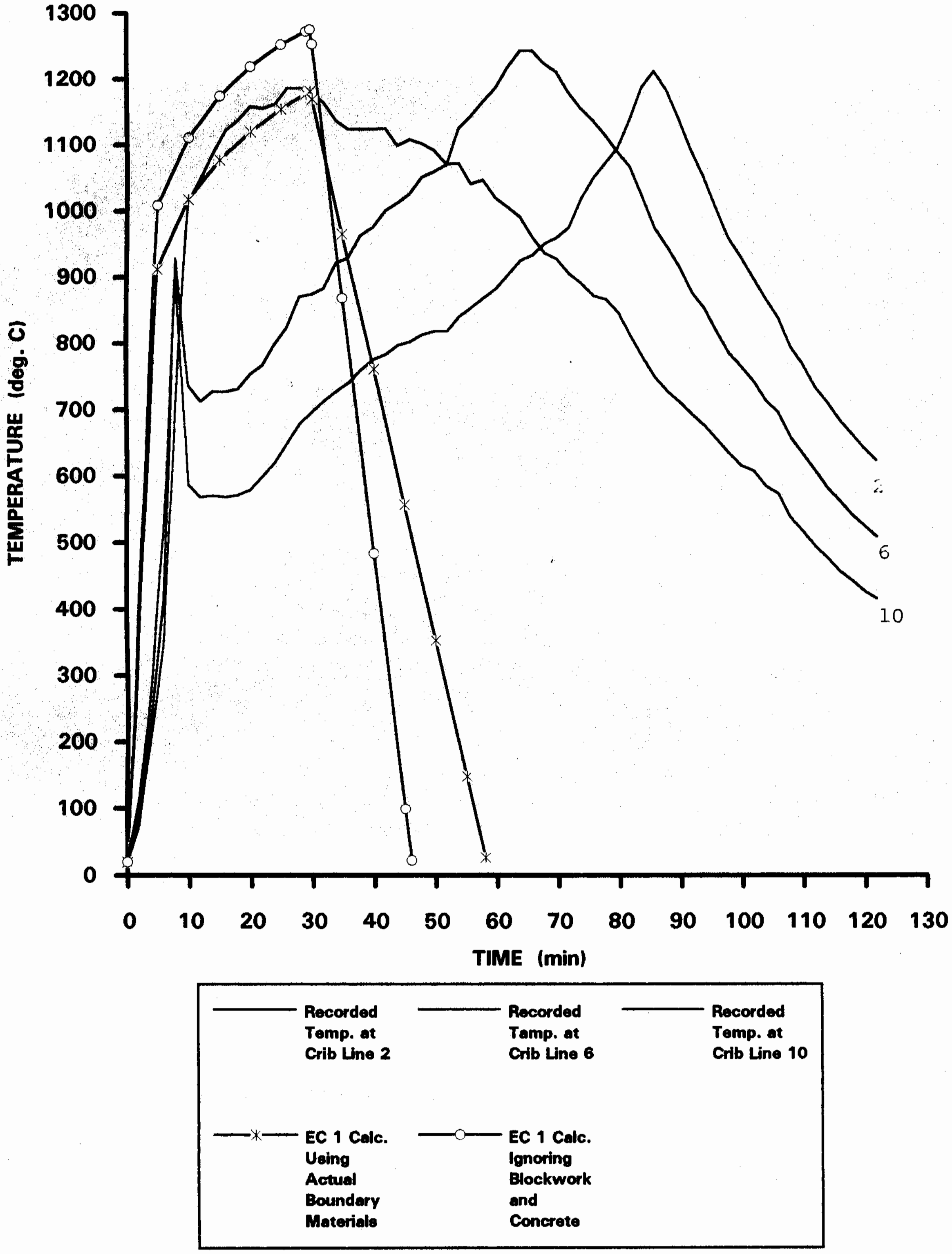


FIG. 25 CARDINGTON NATURAL FIRE TEST 1
AVERAGE ATMOSPHERE TEMPERATURE PROFILES

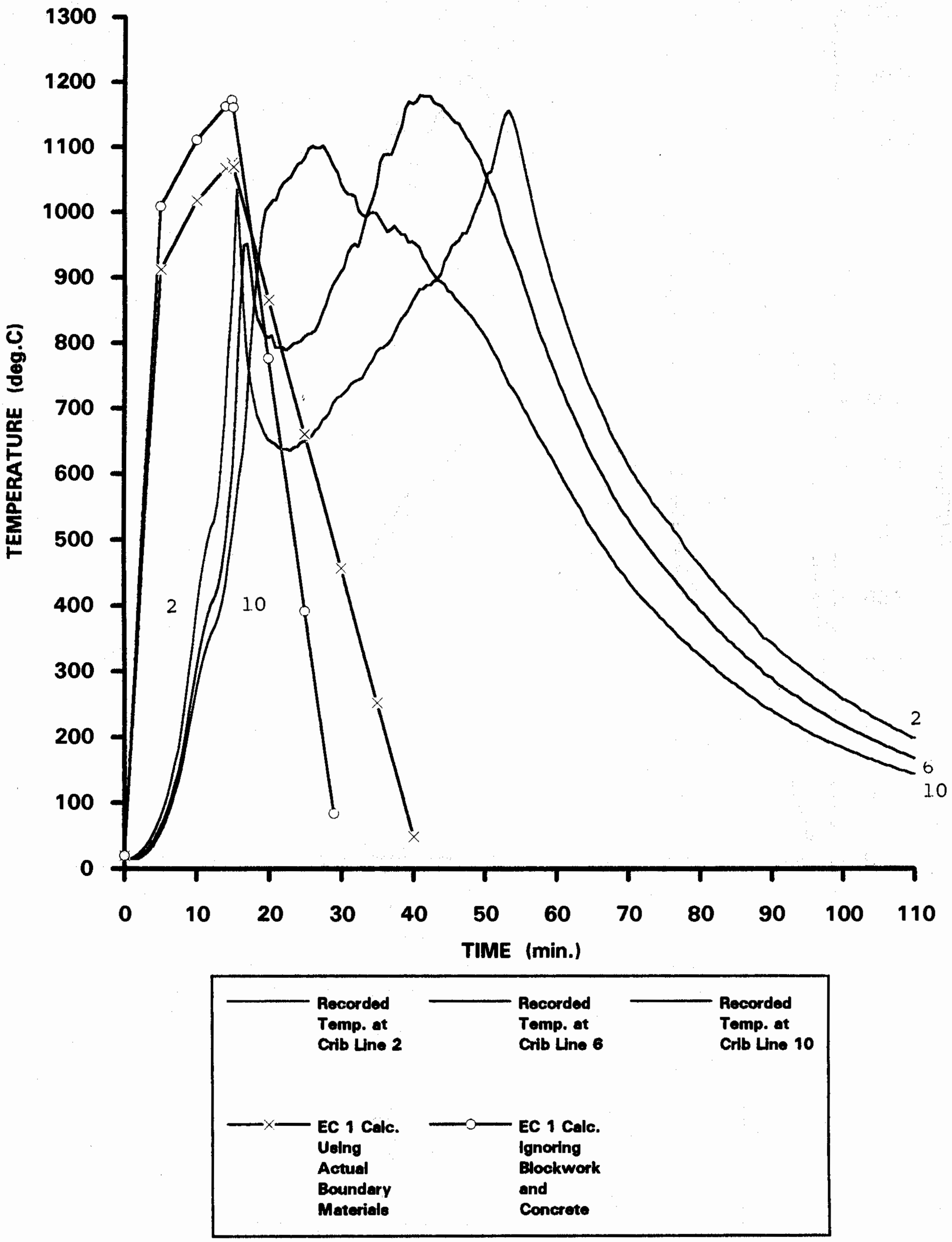


FIG. 26 CARDINGTON NATURAL FIRE TEST 2
AVERAGE ATMOSPHERE TEMPERATURE PROFILES

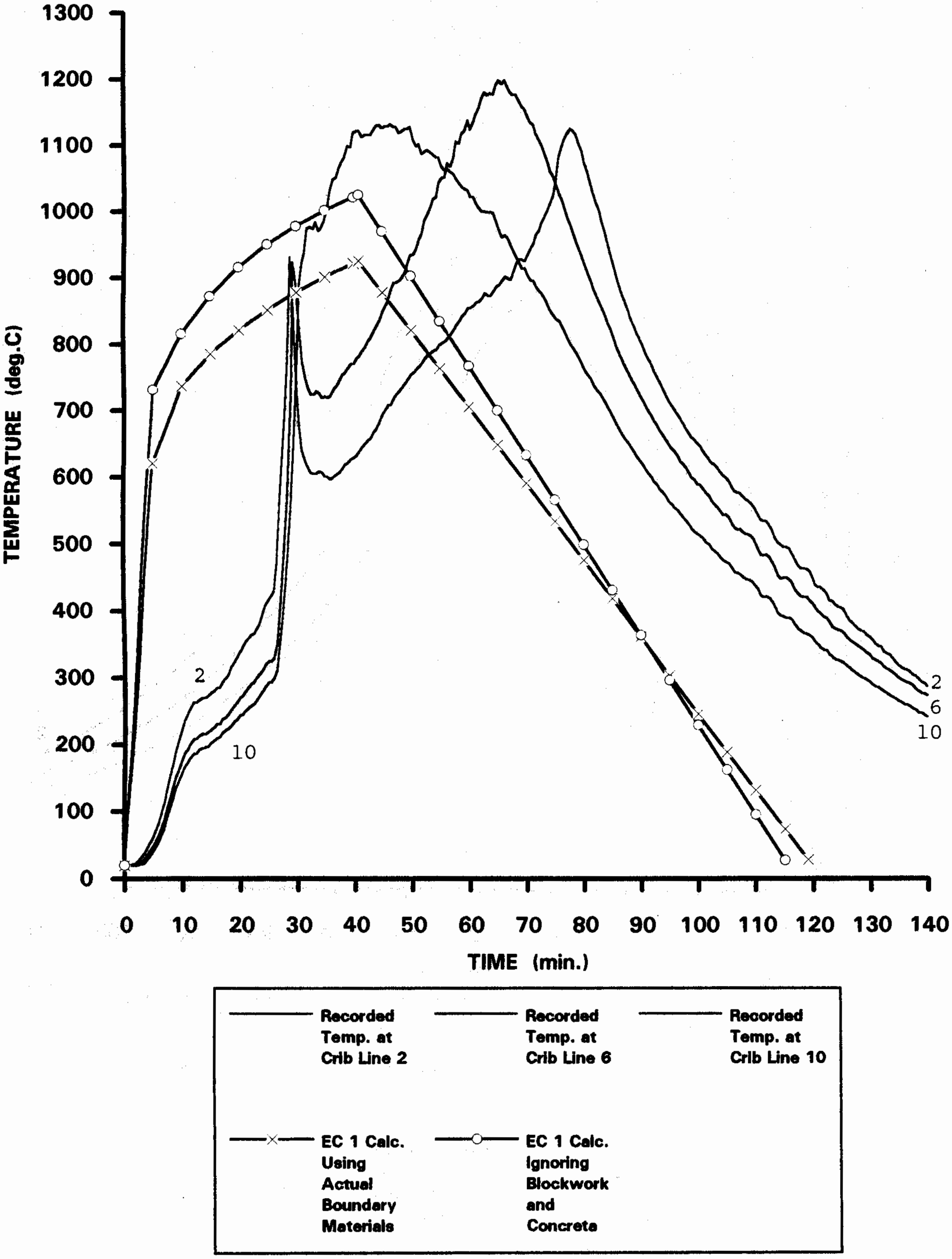


FIG. 27 CARDINGTON NATURAL FIRE TEST 3
AVERAGE ATMOSPHERE TEMPERATURE PROFILES

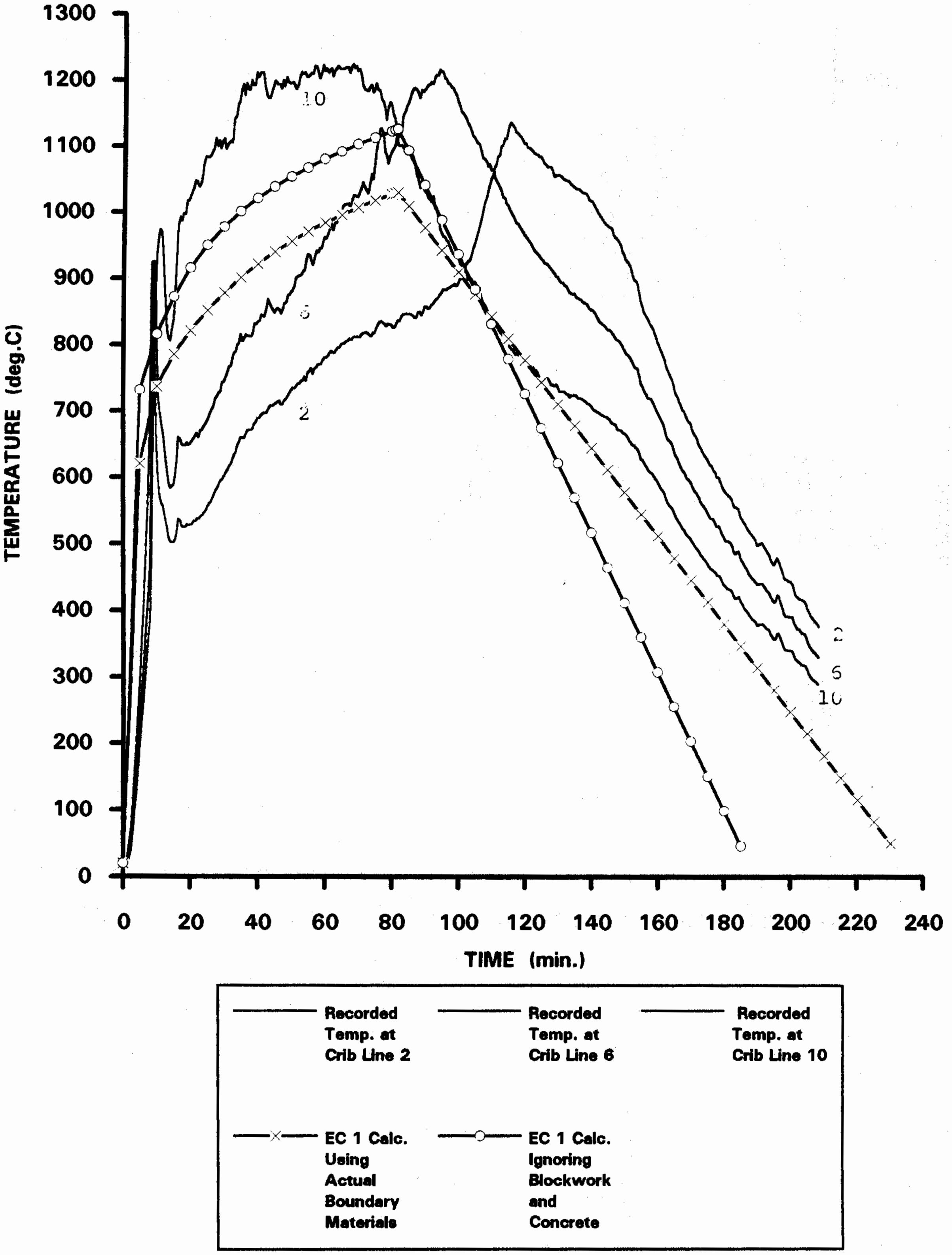


FIG. 28 CARDINGTON NATURAL FIRE TEST 4
AVERAGE ATMOSPHERE TEMPERATURE PROFILES

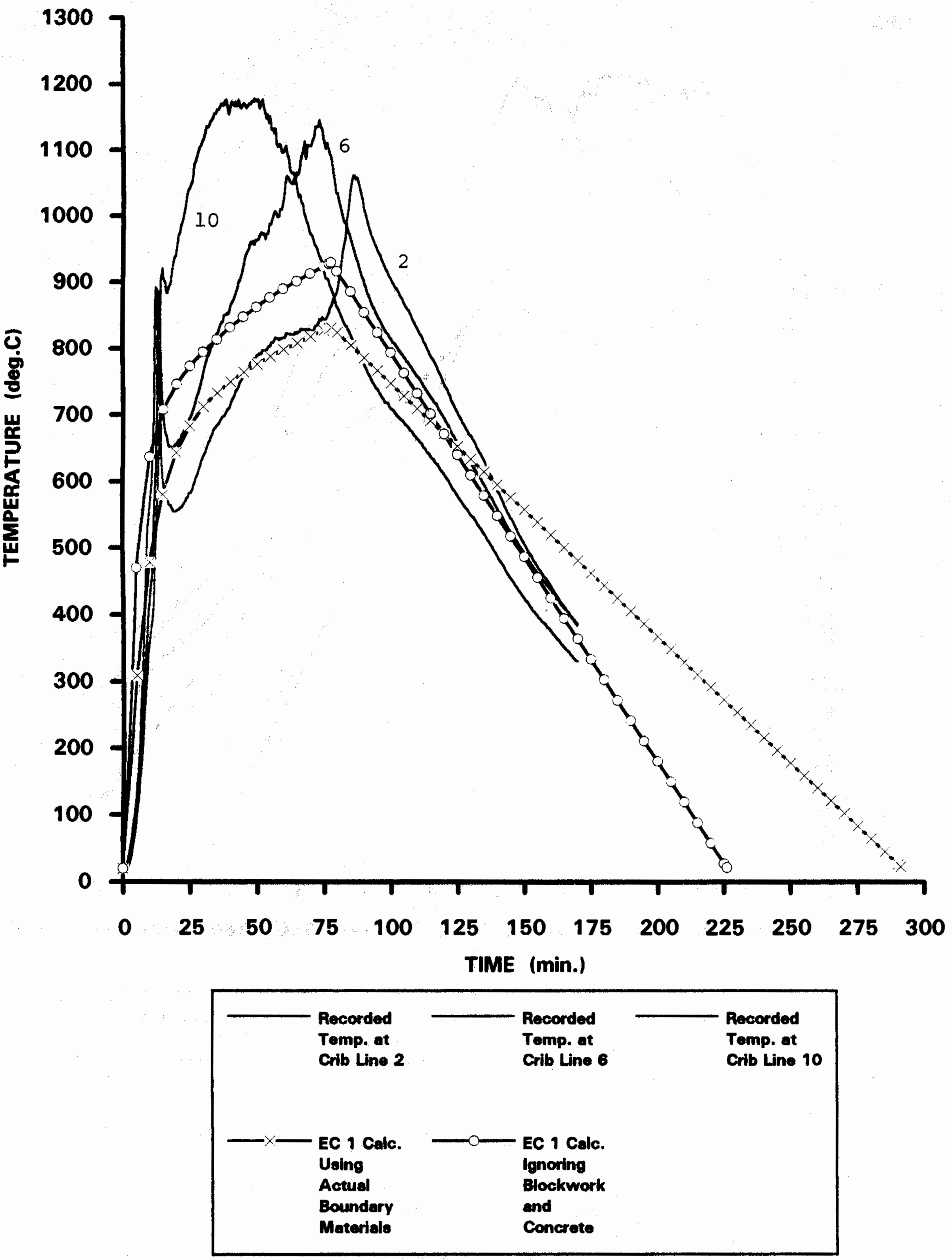


FIG. 29 CARDINGTON NATURAL FIRE TEST 5
AVERAGE ATMOSPHERE TEMPERATURE PROFILES

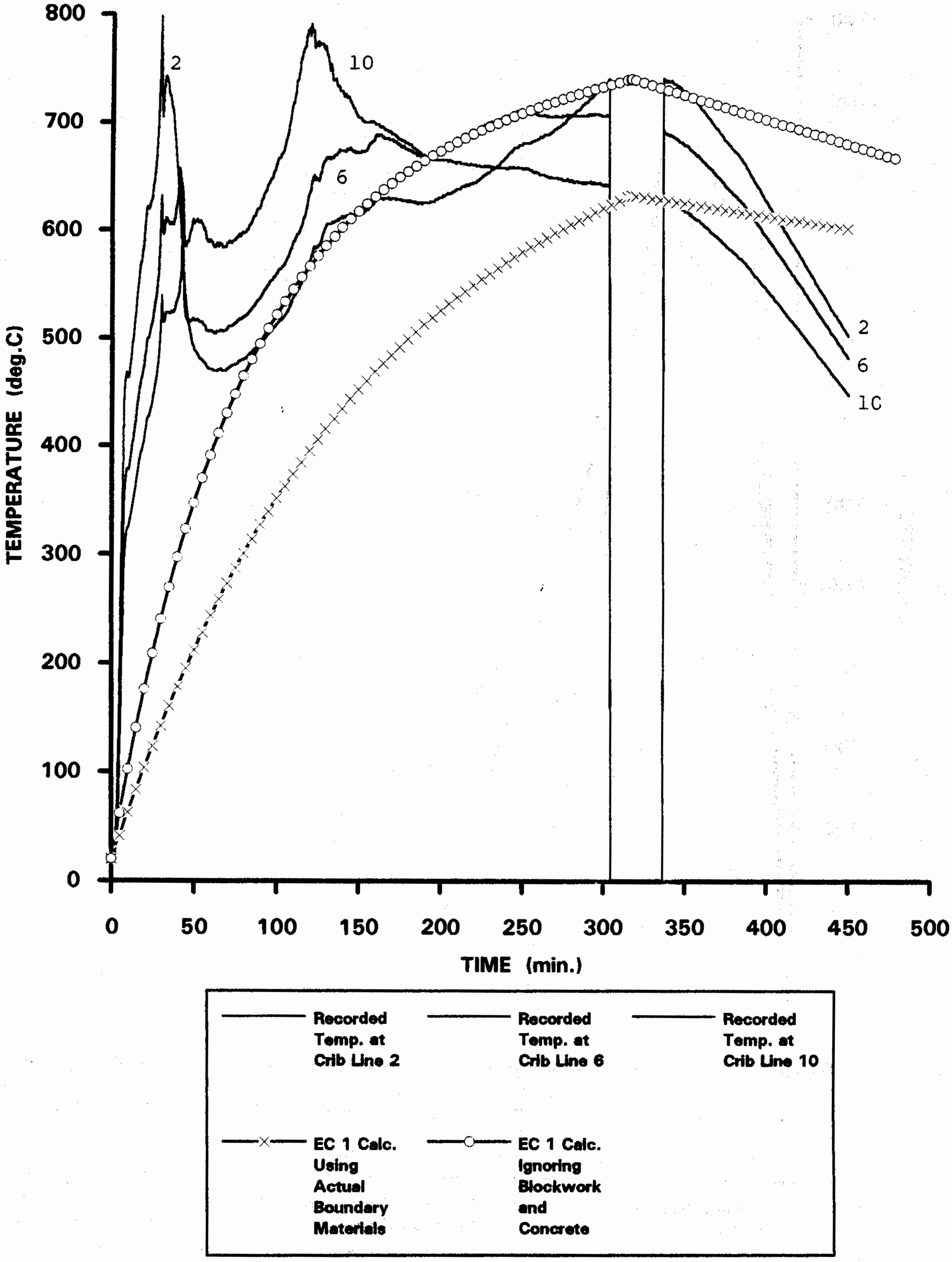


FIG. 30 CARDINGTON NATURAL FIRE TEST 6 AVERAGE ATMOSPHERE TEMPERATURE PROFILES

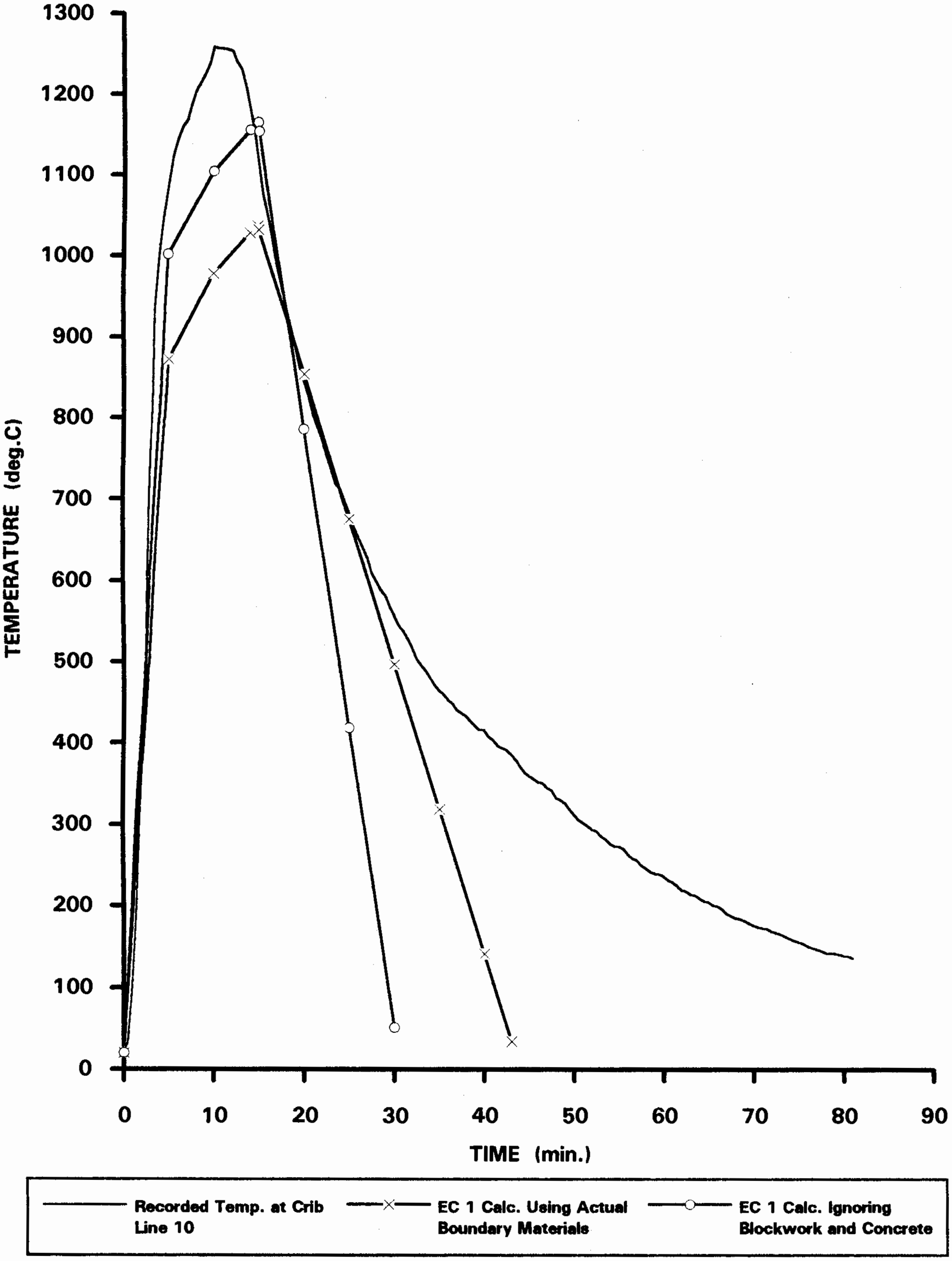


FIG. 31 CARDINGTON NATURAL FIRE TEST 7
AVERAGE ATMOSPHERE TEMPERATURE PROFILES

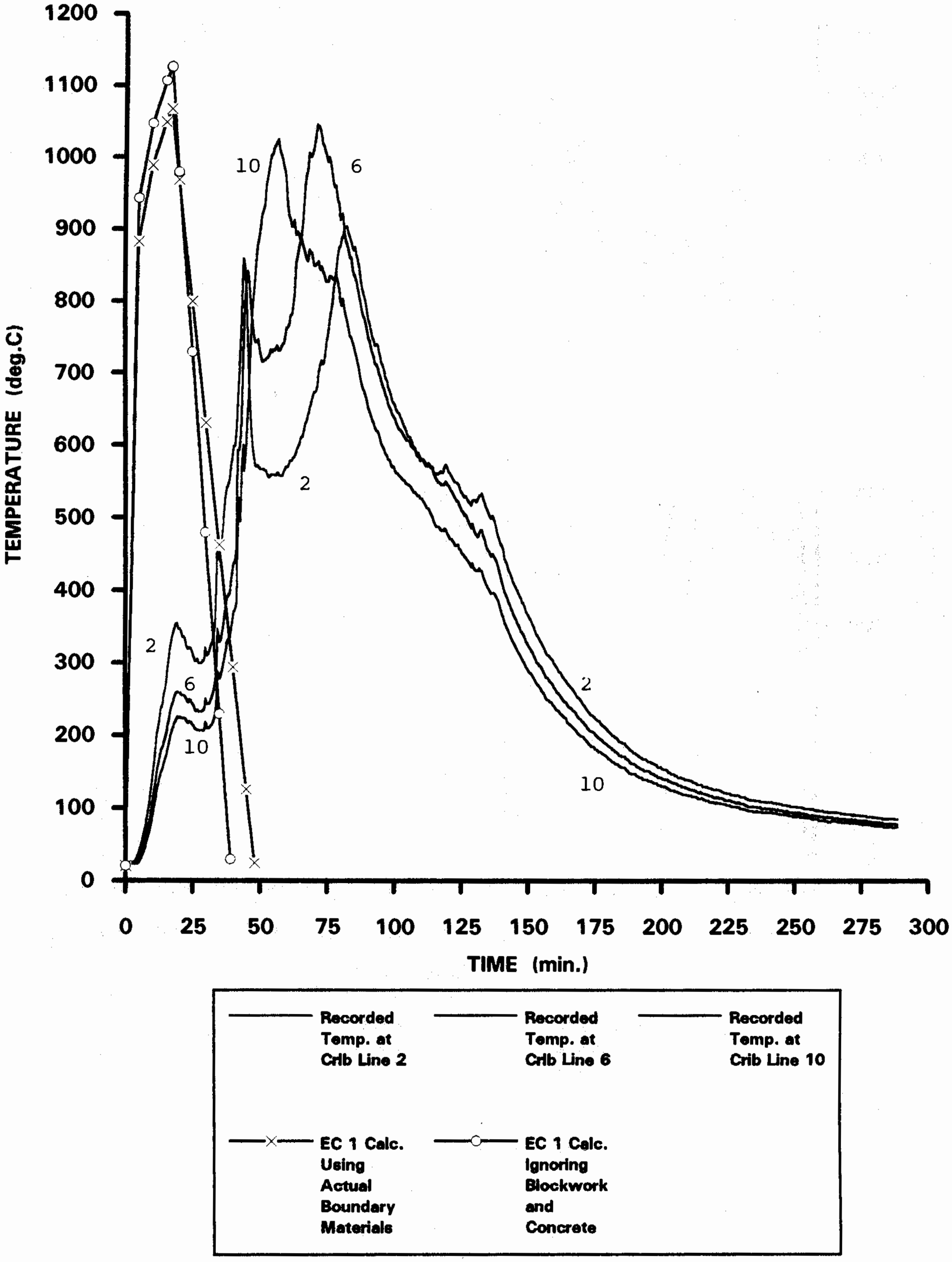


FIG. 32 CARDINGTON NATURAL FIRE TEST 8
AVERAGE ATMOSPHERE TEMPERATURE PROFILES

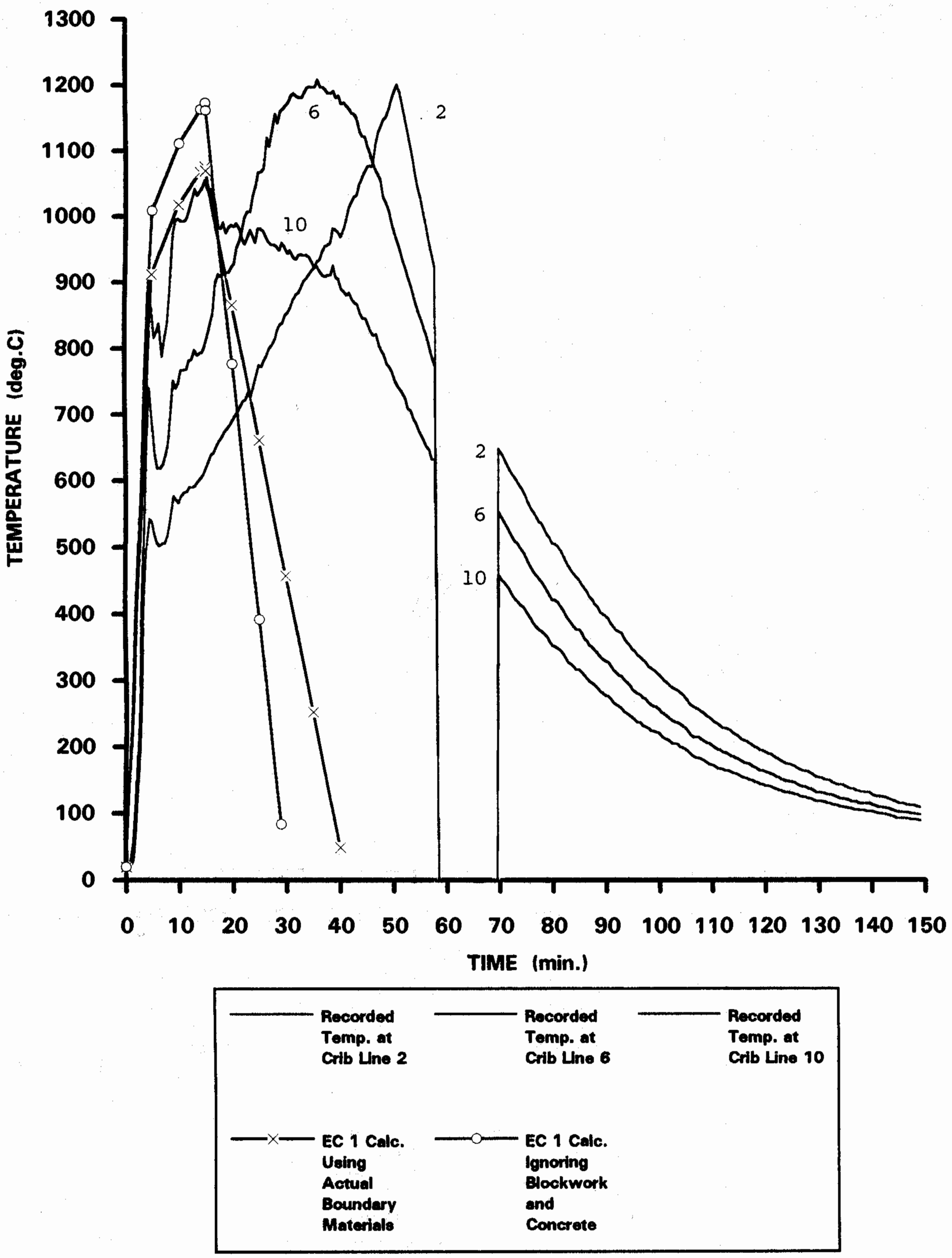


FIG. 33 CARDINGTON NATURAL FIRE TEST 9
AVERAGE ATMOSPHERE TEMPERATURE PROFILES

T/c	Cr2	Cr6	Cr10
1	901	883	736
2	855	883	723
3	875	909	718
4	856	919	725
5	878	915	737
6	916	941	698
7	935	953	725
8	921	955	718
9	926	955	706
10	922	948	728
11	925	931	739

Cr2	Cr6	Cr10
578	781	1199
575	759	1186
572	751	1184
577	736	1190
580	742	1199
580	739	1204
578	754	1170
580	750	1121
576	755	1099
584	758	1080
585	781	1073

Cr2	Cr6	Cr10
1212	1001	774
1219	1011	773
1219	1010	762
1215	987	767
1216	974	766
1230	970	748
1204	973	735
1198	968	727
1200	955	733
1213	959	733
1208	937	733

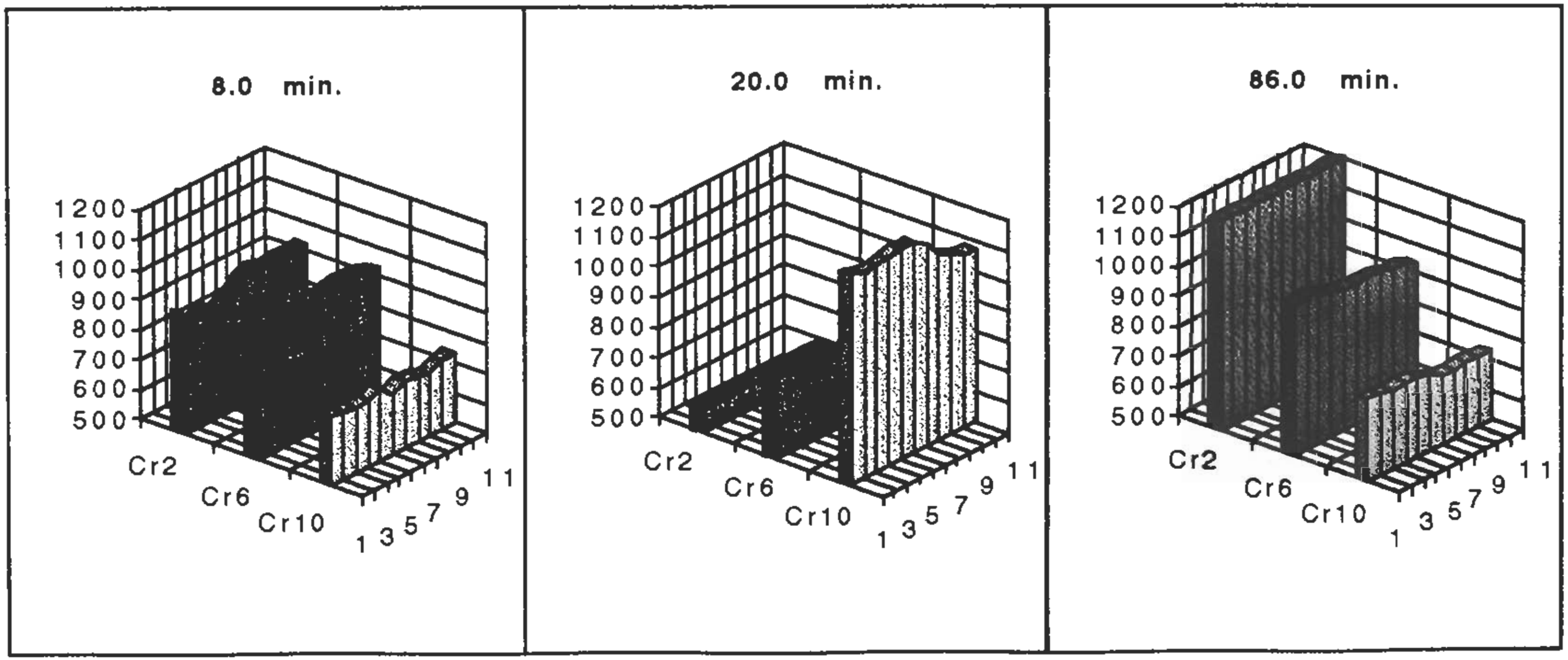
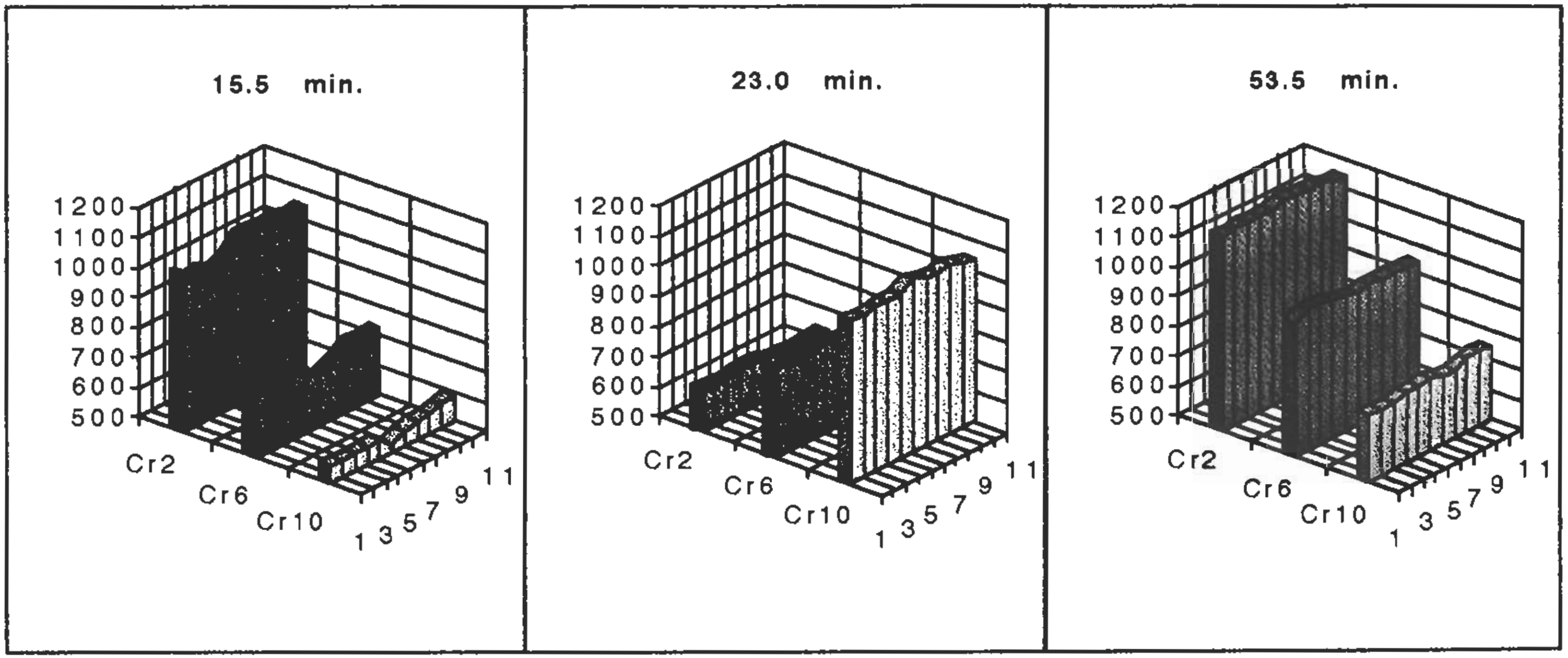


FIG. 34 TEST 1: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINES 2, 6 AND 10

T/c	Cr2	Cr6	Cr10
1	1029	706	562
2	1007	689	561
3	1004	702	559
4	990	717	560
5	1006	702	563
6	1055	661	528
7	1057	685	552
8	1053	699	565
9	1057	727	570
10	1045	721	579
11	1047	729	586

Cr2	Cr6	Cr10
642	797	1047
639	781	1041
638	784	1046
643	791	1045
642	798	1048
646	788	1078
630	787	1062
624	797	1057
622	794	1062
630	802	1052
632	820	1041

Cr2	Cr6	Cr10
1152	945	725
1153	970	725
1155	975	724
1155	961	738
1158	951	742
1172	942	744
1166	954	734
1163	947	729
1163	954	748
1145	948	754
1147	944	748



15.5 min.

23.0 min.

53.5 min.

FIG. 35 TEST 2: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINES 2, 6 AND 10

T/c	Cr2	Cr6	Cr10
1	875	733	566
2	862	722	570
3	876	722	571
4	865	733	560
5	922	722	556
6	961	703	525
7	969	713	546
8	960	730	553
9	960	741	553
10	979	732	566
11	978	735	564

Cr2	Cr6	Cr10
600	747	1025
599	731	1009
596	724	1017
598	723	1016
599	717	1037
600	708	1069
597	722	1067
592	715	1047
592	718	1027
597	722	1005
599	738	998

Cr2	Cr6	Cr10
1116	980	786
1118	987	795
1118	991	798
1114	980	805
1123	968	806
1130	957	799
1127	969	799
1133	981	801
1136	989	804
1135	994	811
1129	991	802

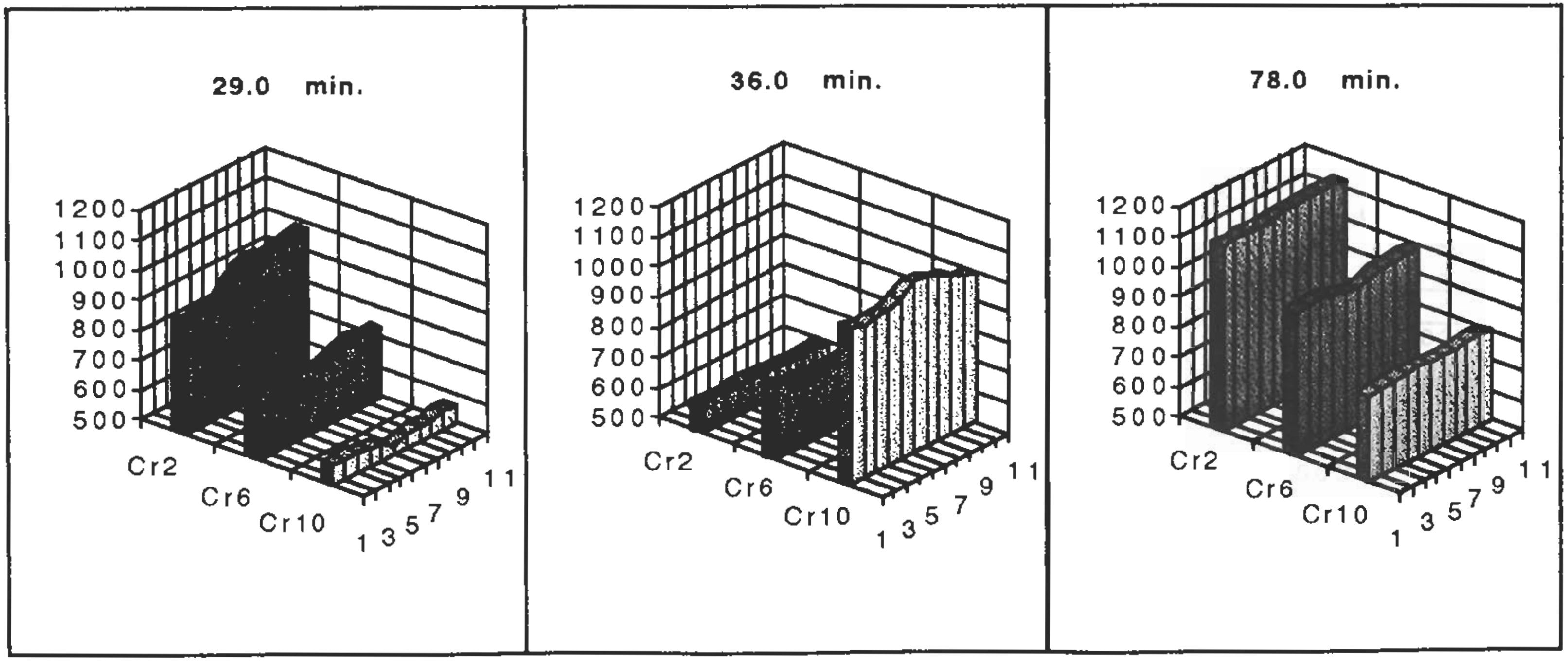


FIG. 36 TEST 3: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINES 2, 6 AND 10

T/c	Cr2	Cr6	Cr10
1	911	882	682
2	887	876	682
3	905	904	677
4	879	902	667
5	908	898	669
6	954	917	651
7	968	918	672
8	939	905	673
9	945	920	668
10	923	908	669
11	927	891	679

Cr2	Cr6	Cr10
500	595	880
501	600	891
499	583	878
499	589	857
498	581	823
500	566	825
501	585	809
502	581	781
503	588	777
509	592	743
510	601	761

Cr2	Cr6	Cr10
1136	1007	780
1146	1003	792
1142	1003	792
1130	1003	793
1126	996	791
1141	993	793
1134	1003	795
1133	1002	804
1135	1008	812
1143	1005	817
1143	1006	803

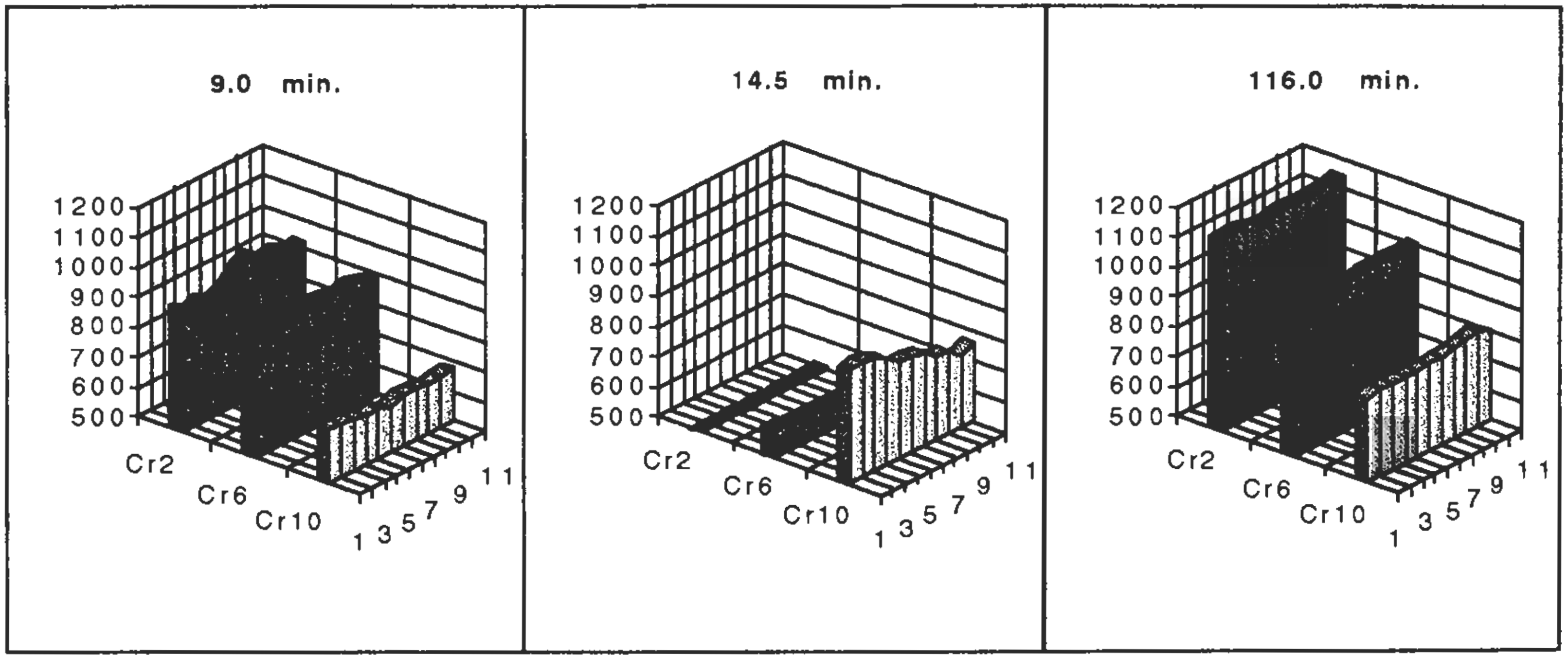


FIG. 37 TEST 4: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINES 2, 6 AND 10

T/c	Cr2	Cr6	Cr10
1	873	637	507
2	858	639	506
3	868	627	507
4	857	630	503
5	871	621	505
6	899	592	484
7	905	623	503
8	915	615	518
9	919	633	504
10	919	628	525
11	917	621	523

Cr2	Cr6	Cr10
554	676	937
554	665	924
554	651	916
555	656	898
559	655	954
557	643	992
552	644	990
551	654	979
553	653	970
558	656	959
560	665	961

Cr2	Cr6	Cr10
1052	933	804
1067	938	809
1065	947	812
1058	954	813
1054	957	811
1064	954	807
1070	957	805
1069	951	810
1066	954	806
1057	951	820
1052	953	817

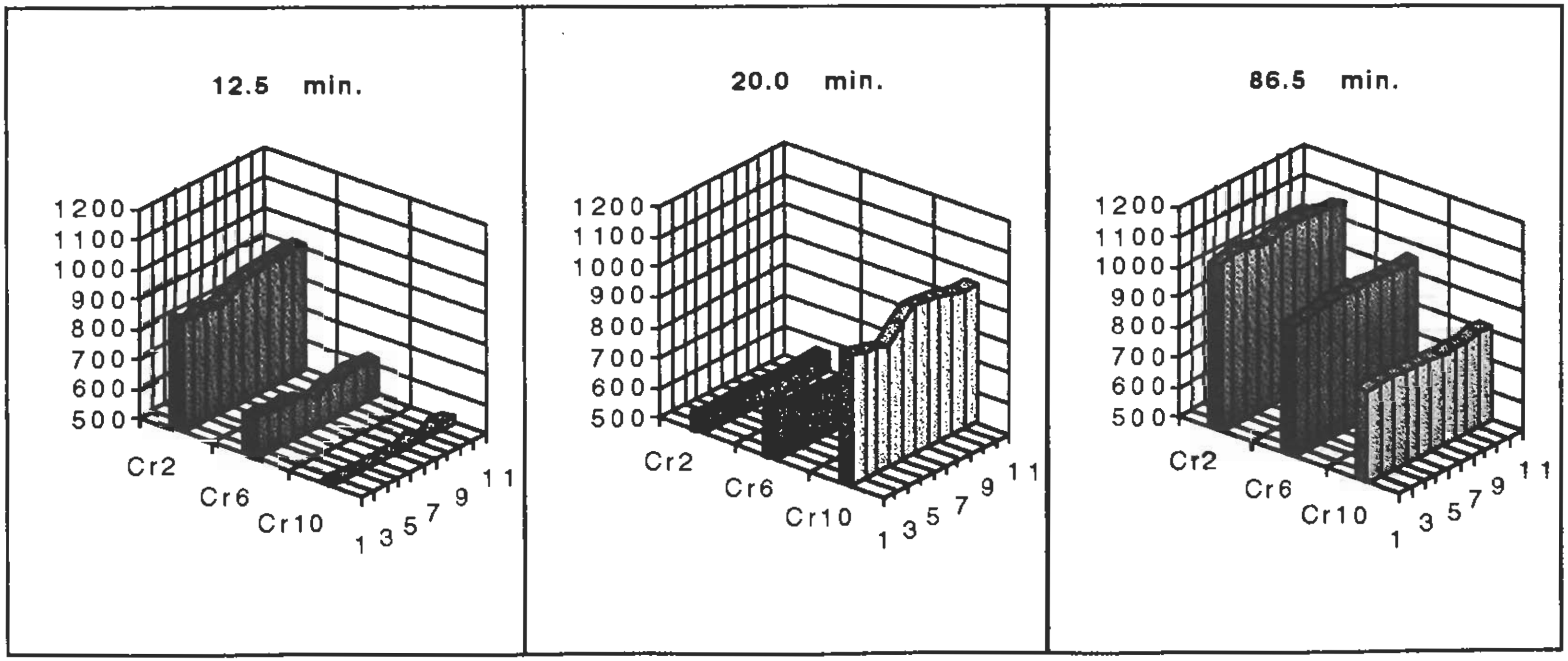


FIG. 38 TEST 5: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINES 2, 6 AND 10

T/c	Cr2	Cr6	Cr10
1	782	621	519
2	783	621	523
3	788	614	525
4	791	615	486
5	796	617	517
6	808	617	520
7	804	623	524
8	803	637	529
9	807	642	523
10	799	646	534
11	805	642	539

Cr2	Cr6	Cr10
465	510	573
468	509	587
471	506	610
473	509	598
474	508	577
470	505	573
464	502	577
465	505	582
467	507	589
470	508	582
472	509	586

Cr2	Cr6	Cr10
737	691	626
739	692	629
741	696	631
742	695	620
743	691	627
747	692	631
744	693	631
745	695	632
745	698	633
741	699	636
740	697	636

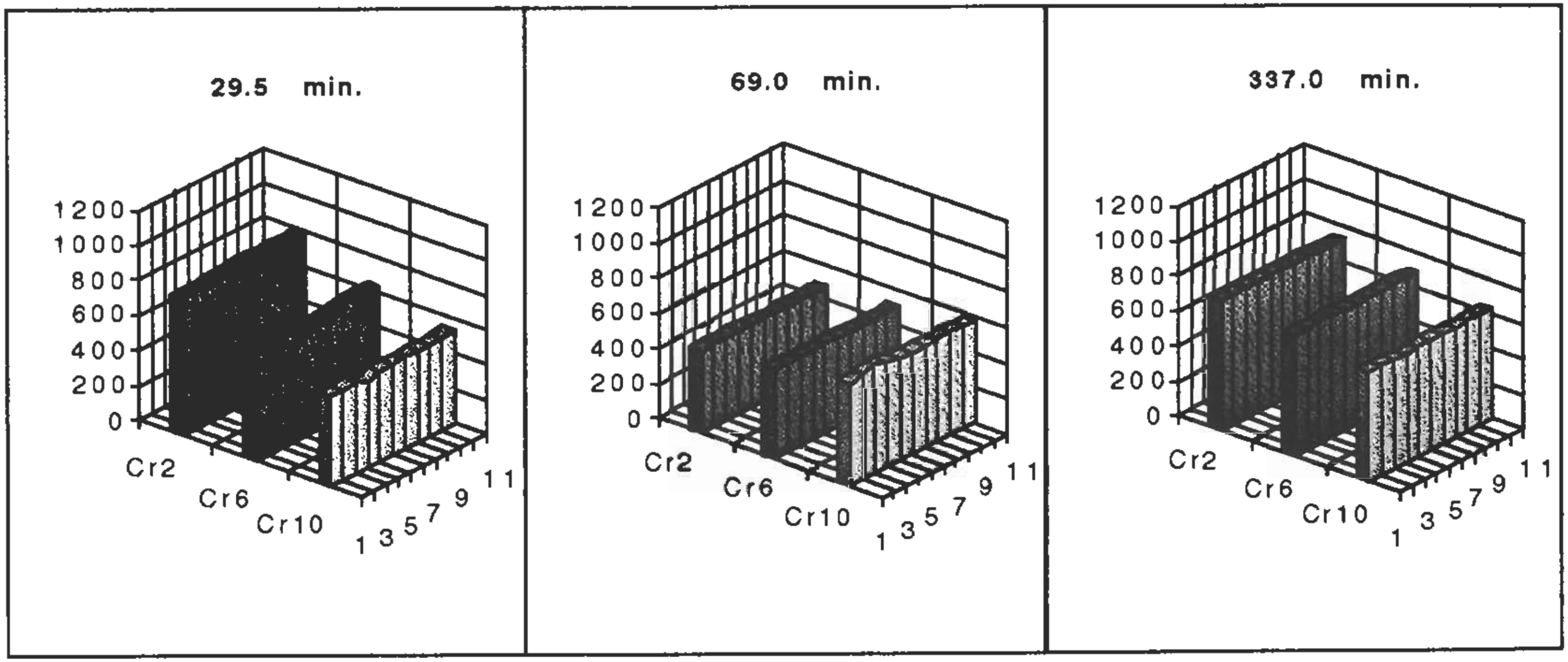


FIG. 39 TEST 6: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINES 2, 6 AND 10

T/c	Cr2	Cr6	Cr10
1			1260
2			1260
3			1260
4			1250
5			1260
6			1260
7			1260
8			1260
9			1260
10			1260
11			1260

Cr2	Cr6	Cr10
		564
		548
		556
		553
		563
		569
		555
		550
		570
		545
		553

Cr2	Cr6	Cr10
		241
		242
		242
		230
		234
		253
		240
		233
		229
		219
		226

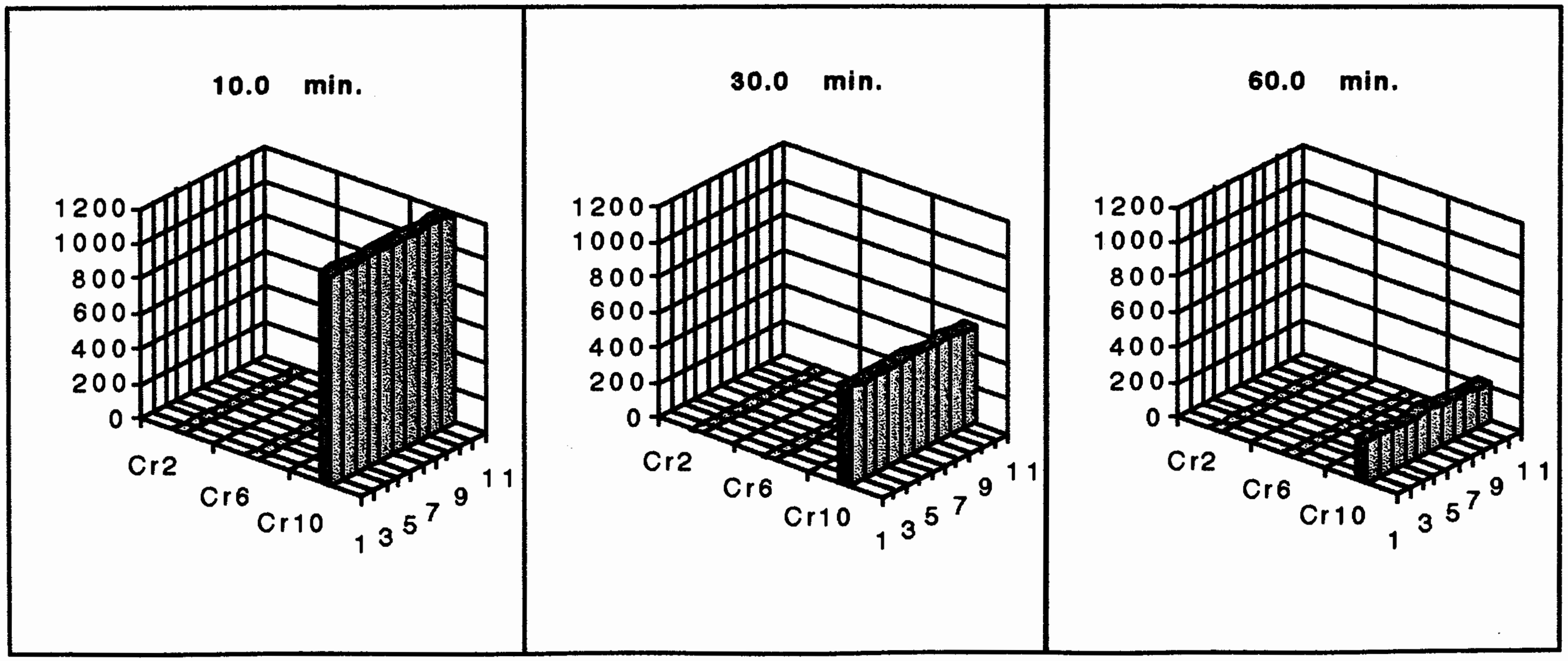


FIG. 40 TEST 7: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINE 10

T/c	Cr2	Cr6	Cr10
1	831	743	638
2	814	759	599
3	840	748	599
4	840	761	544
5	863	769	547
6	859	766	601
7	887	776	601
8	887	704	632
9	895	748	581
10	870	727	617
11	864	727	653

Cr2	Cr6	Cr10
548	713	943
556	698	946
559	729	955
567	712	958
568	730	982
562	728	995
555	714	990
550	746	1005
556	743	1019
547	733	1029
546	737	1007

Cr2	Cr6	Cr10
913	868	755
920	909	768
922	909	784
923	891	740
915	875	741
915	869	786
903	869	757
883	876	766
887	886	775
881	883	809
881	865	817

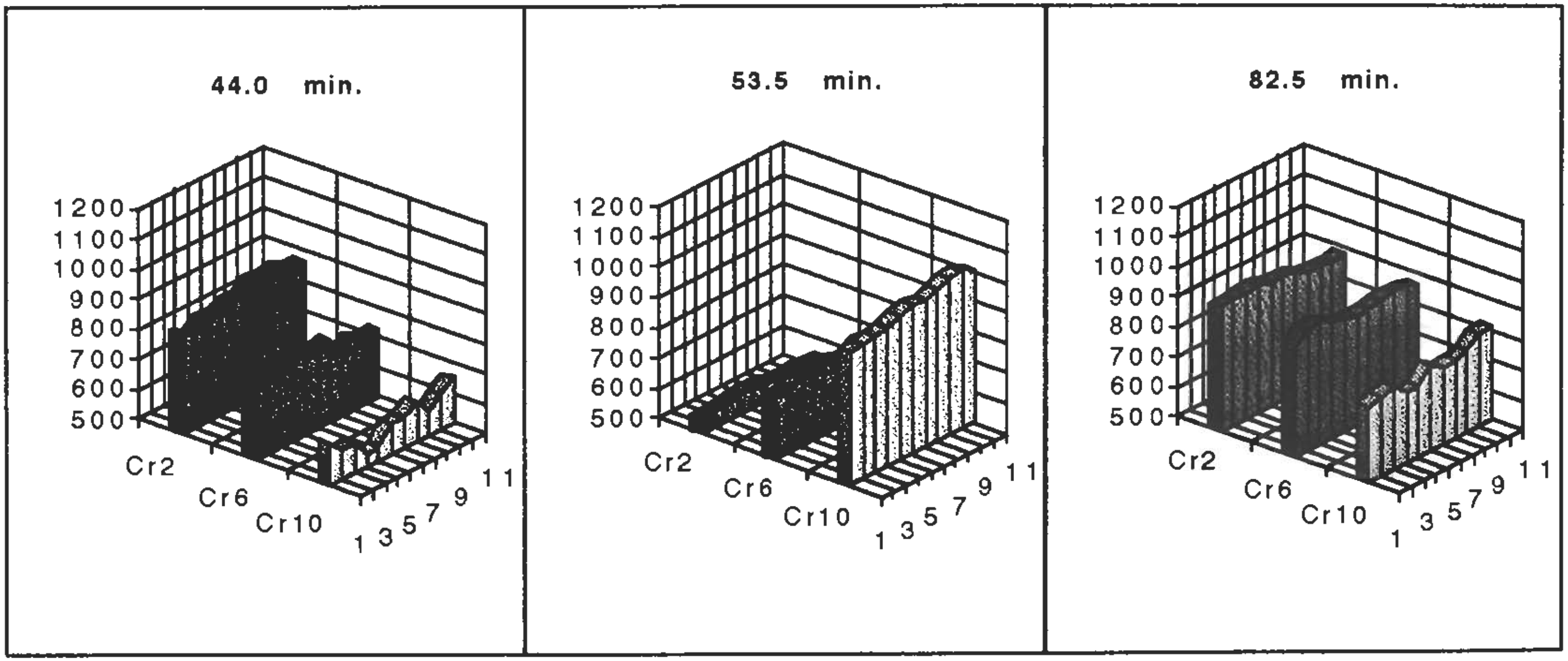


FIG. 41 TEST 8: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINES 2, 6 AND 10

T/c	Cr2	Cr6	Cr10
1	579	768	920
2	579	775	910
3	581	750	948
4	576	755	928
5	579	746	997
6	542	727	977
7	589	772	981
8	591	736	996
9	585	756	1006
10	584	748	1029
11	591	750	1027

Cr2	Cr6	Cr10
1197	942	742
1195	962	747
1195	974	760
1197	978	696
1205	979	765
1216	982	741
1201	980	735
1192	963	738
1189	962	744
1204	944	768
1200	930	755

Cr2	Cr6	Cr10
501	430	356
496	422	358
496	430	361
502	431	324
507	425	351
536	440	362
505	409	340
504	412	348
507	400	349
493	406	361
502	412	359

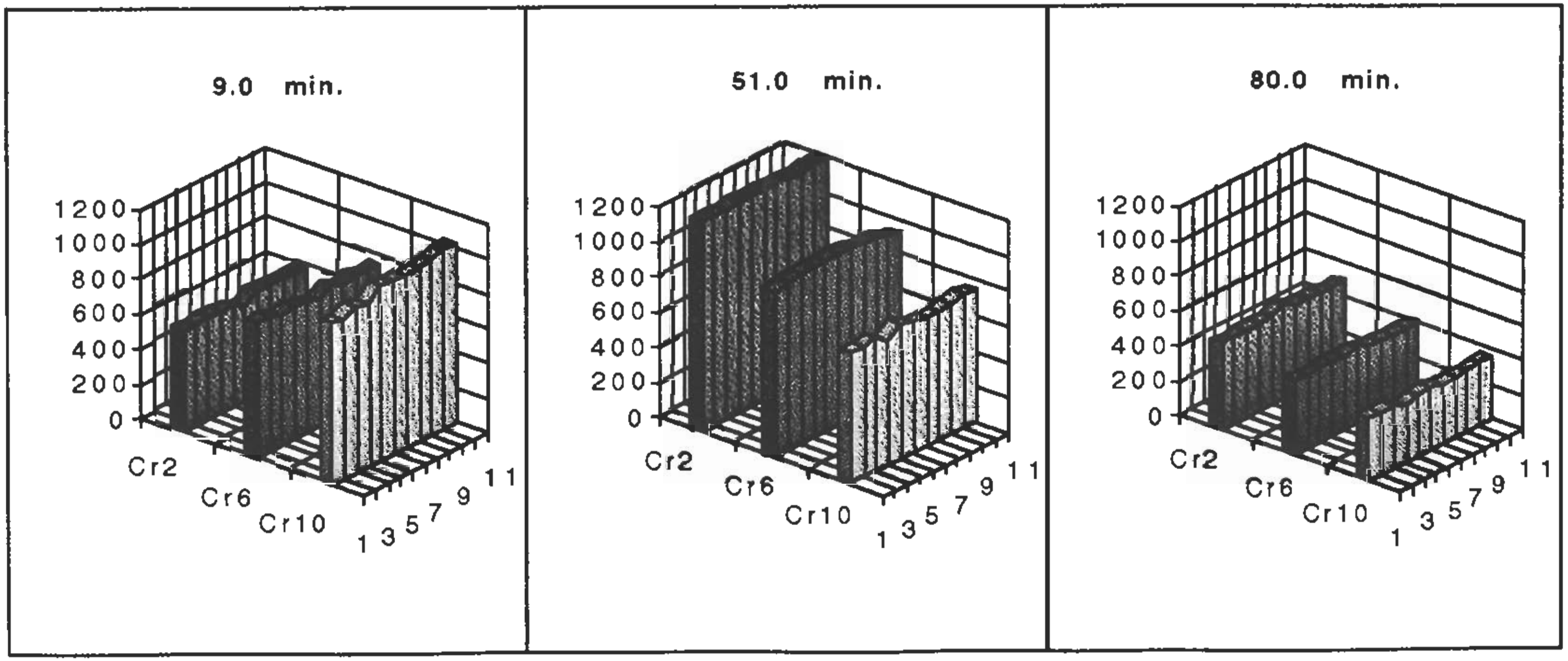


FIG. 42 TEST 9: HORIZONTAL TEMPERATURE PROFILES OF THE HOT GASES ON CRIB LINES 2, 6 AND 10

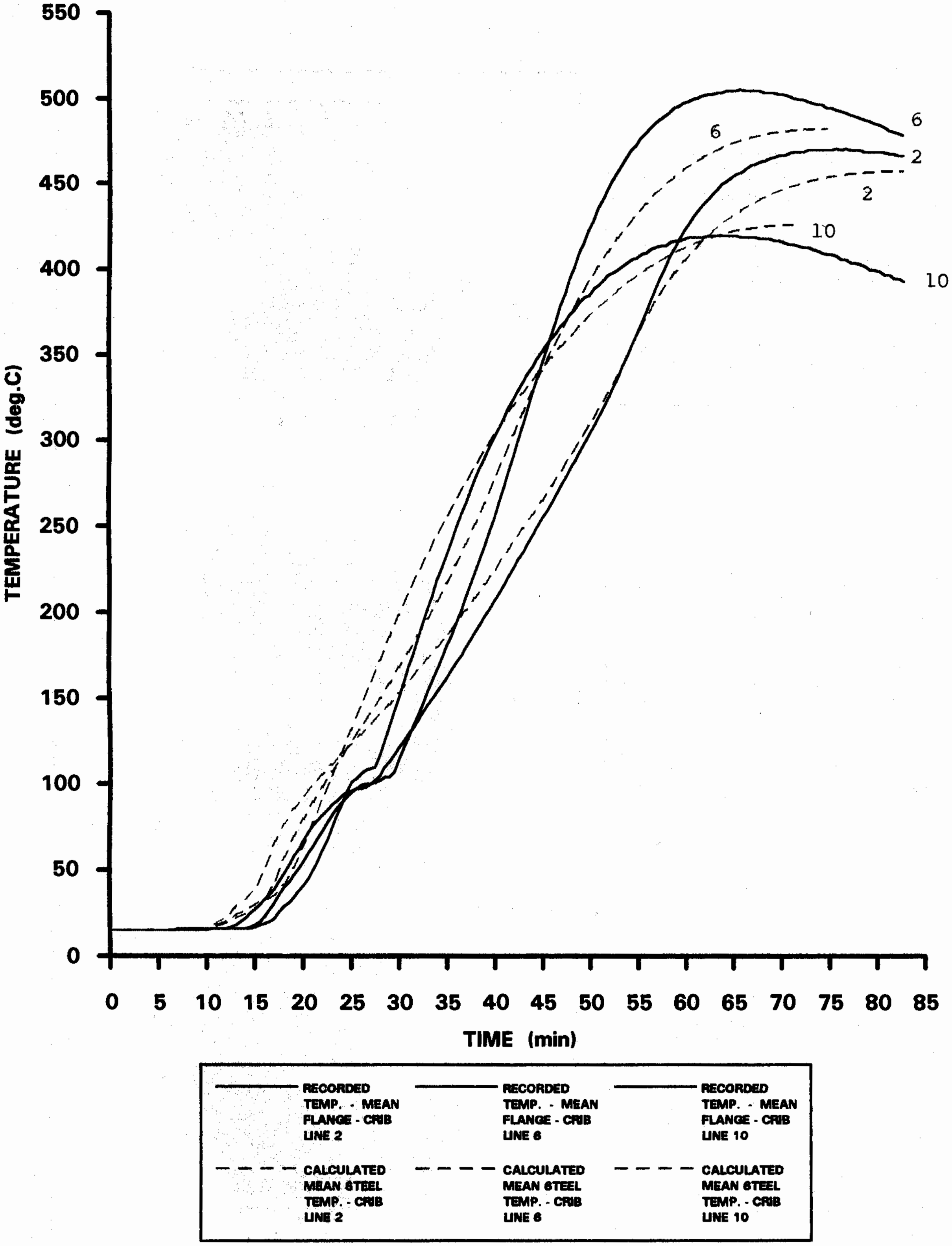


FIG. 43 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED BEAMS IN TEST 2

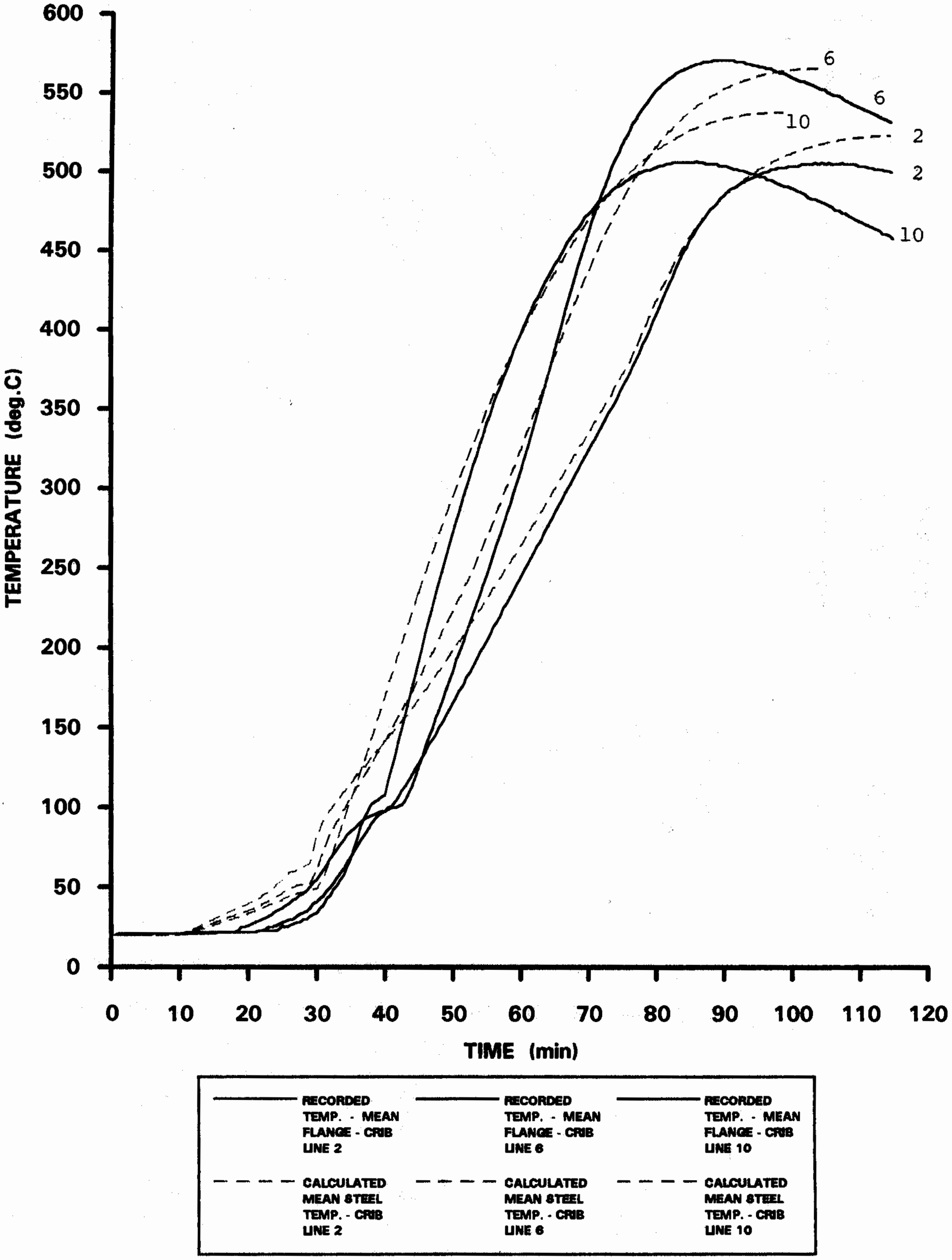


FIG. 44 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED BEAMS IN TEST 3

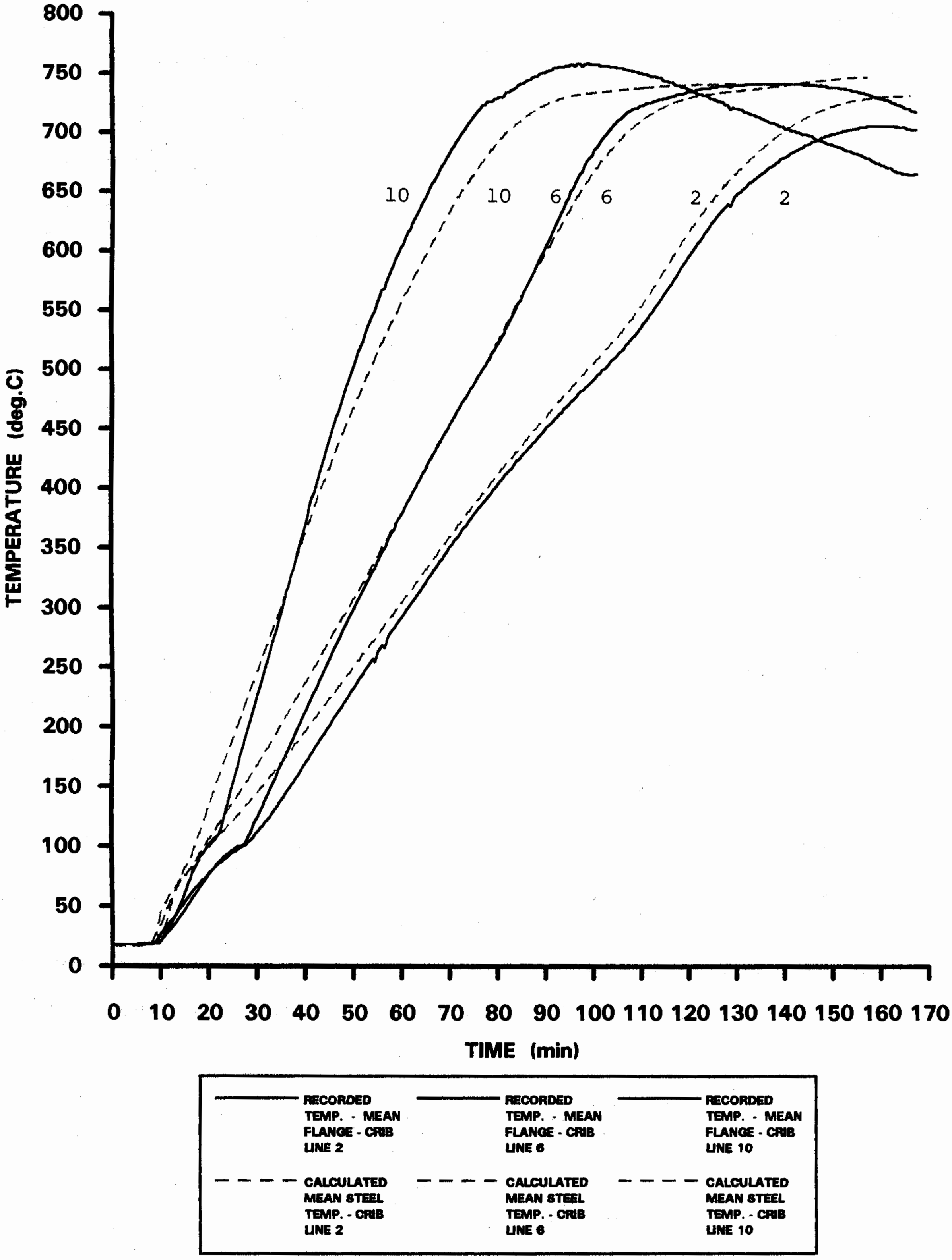


FIG. 45 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED BEAMS IN TEST 4

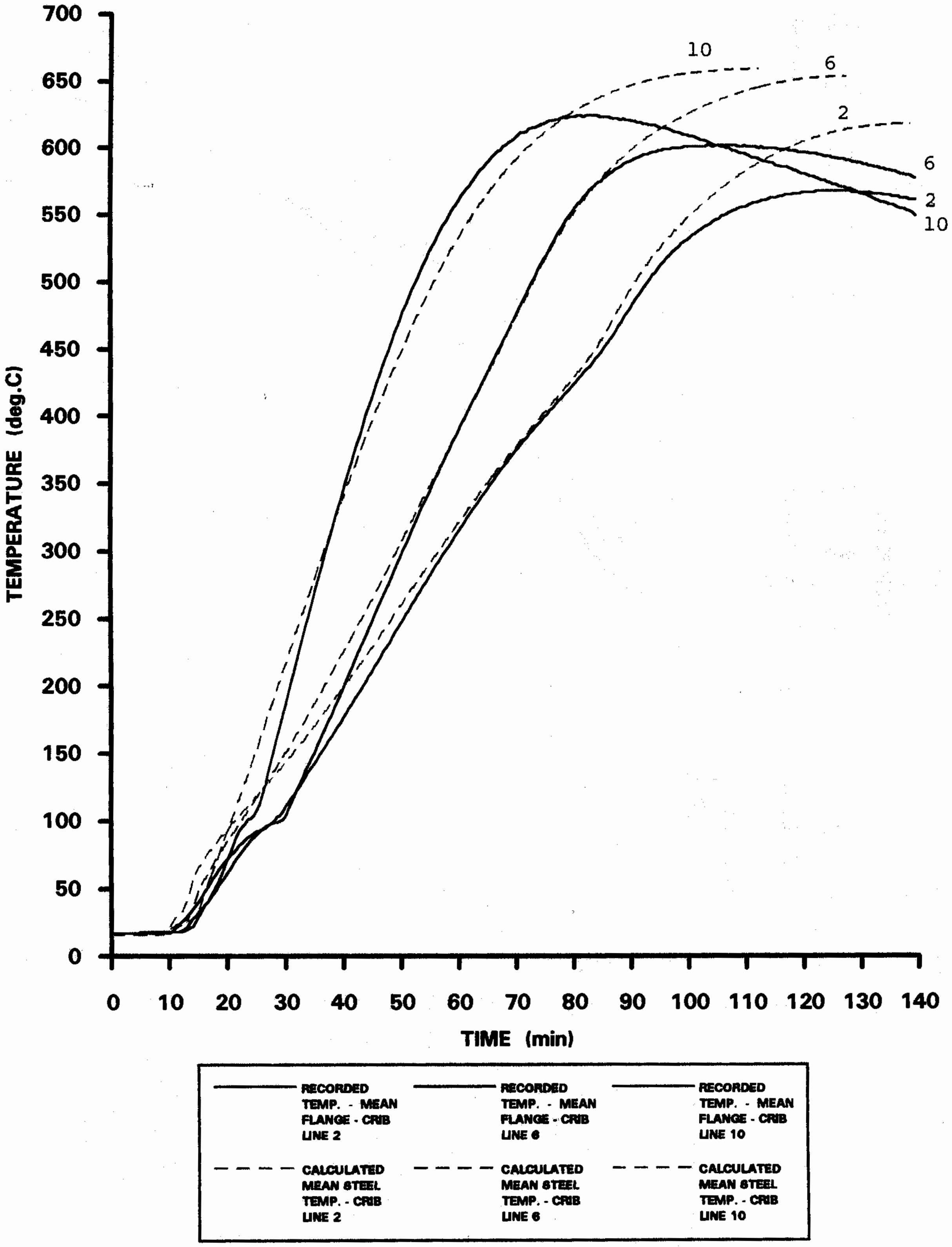


FIG. 46 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED BEAMS IN TEST 5

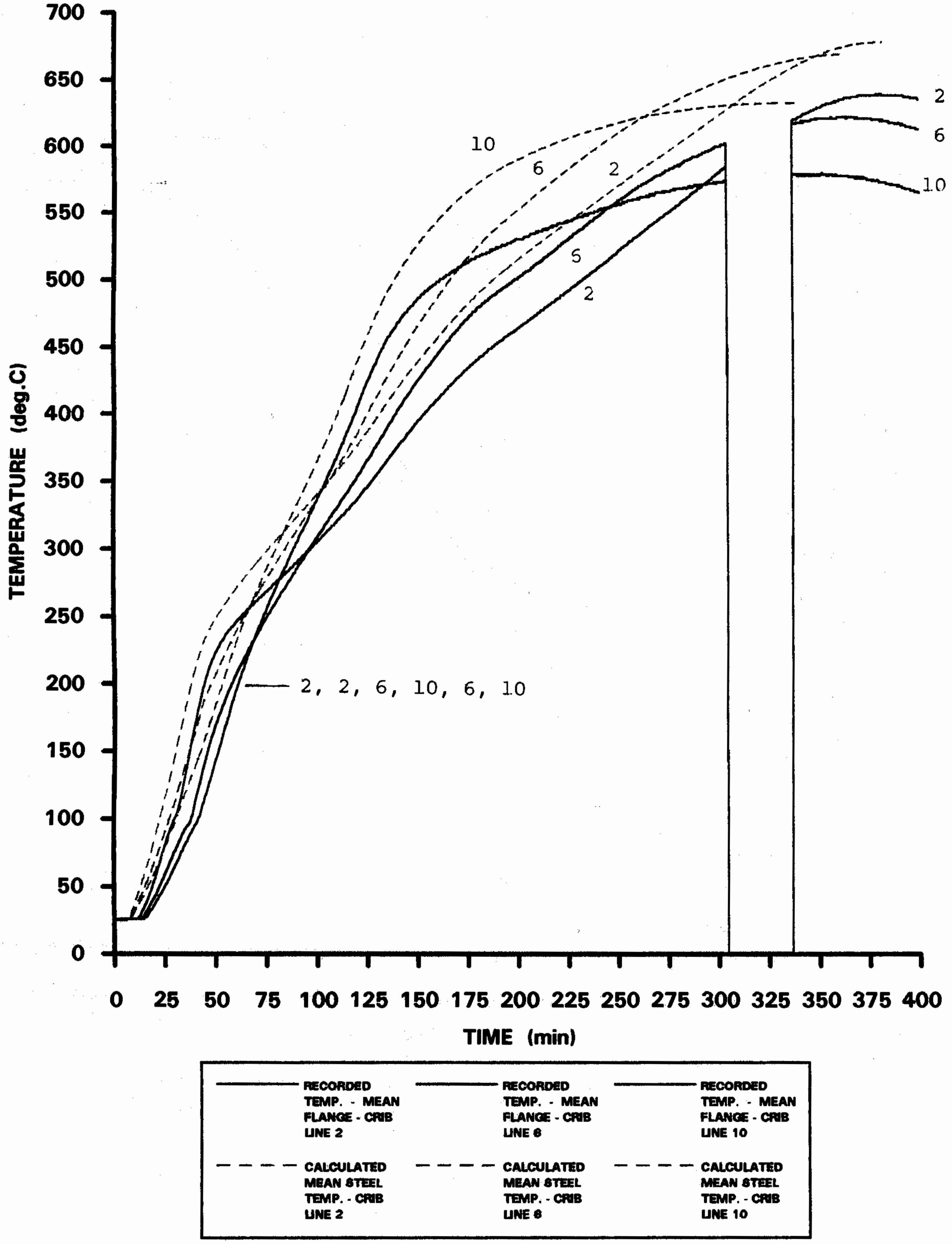


FIG. 47 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED BEAMS IN TEST 6

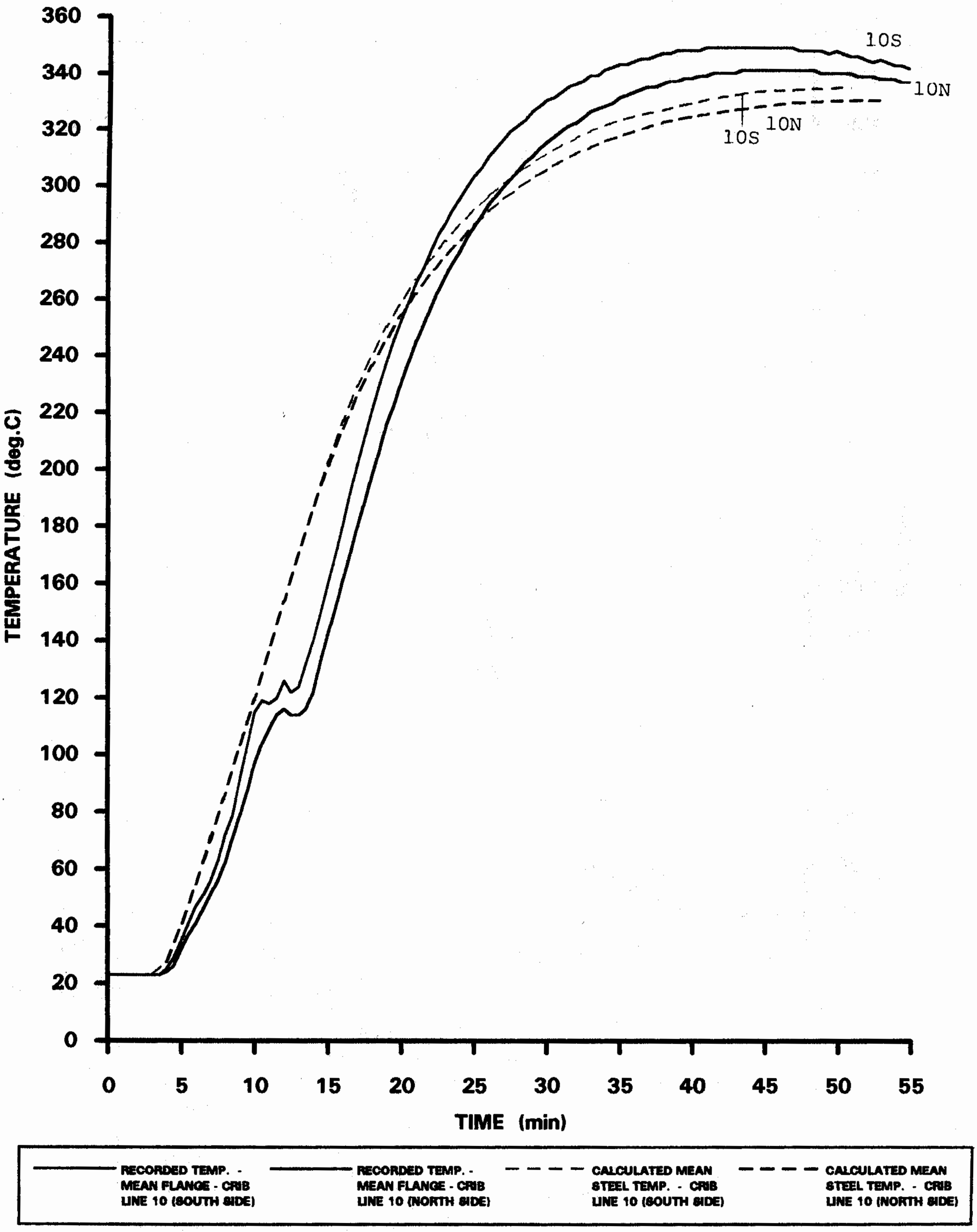


FIG. 48 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED BEAMS IN TEST 7

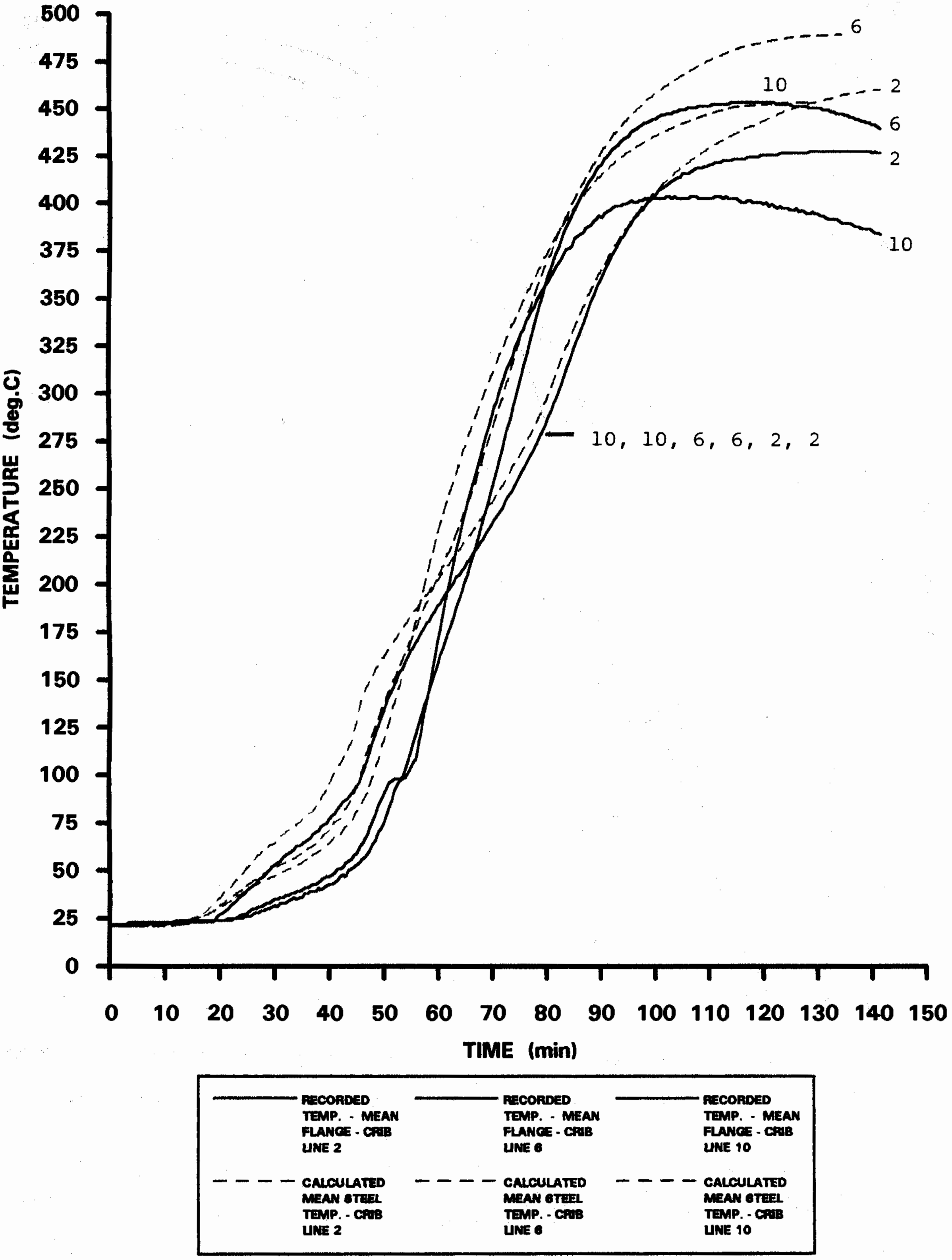


FIG. 49 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED BEAMS IN TEST 8

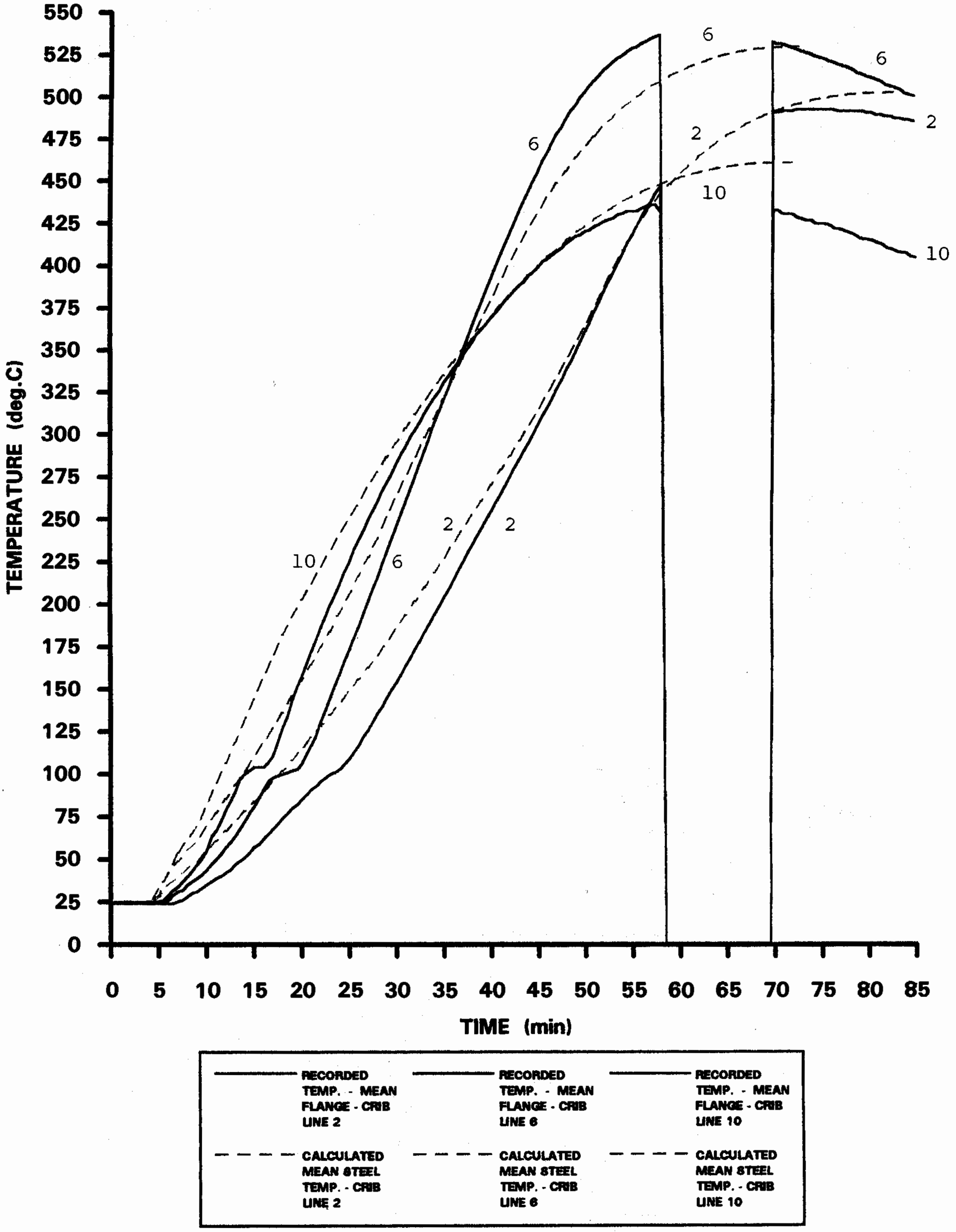


FIG. 50 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED BEAMS IN TEST 9

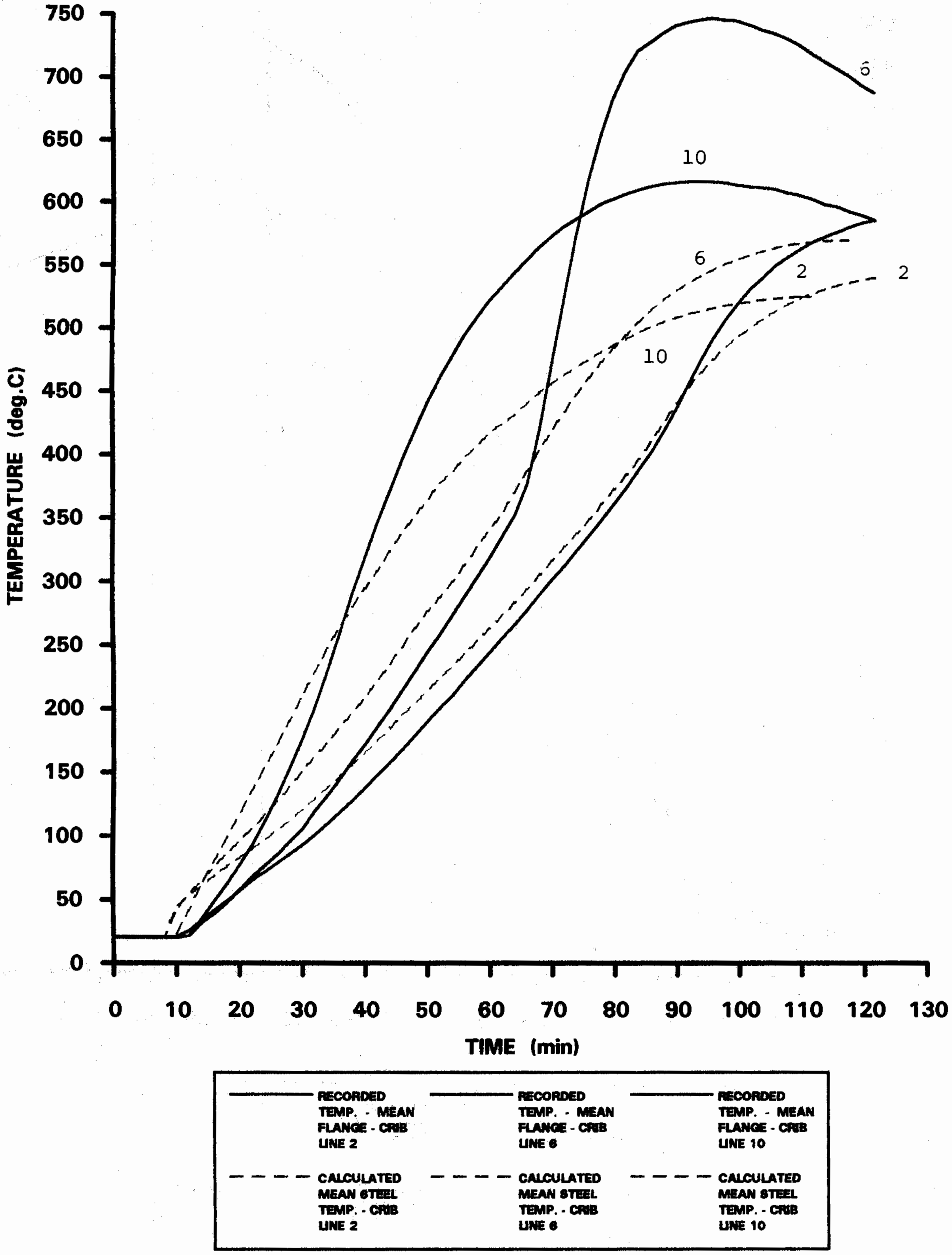


FIG. 51 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 1

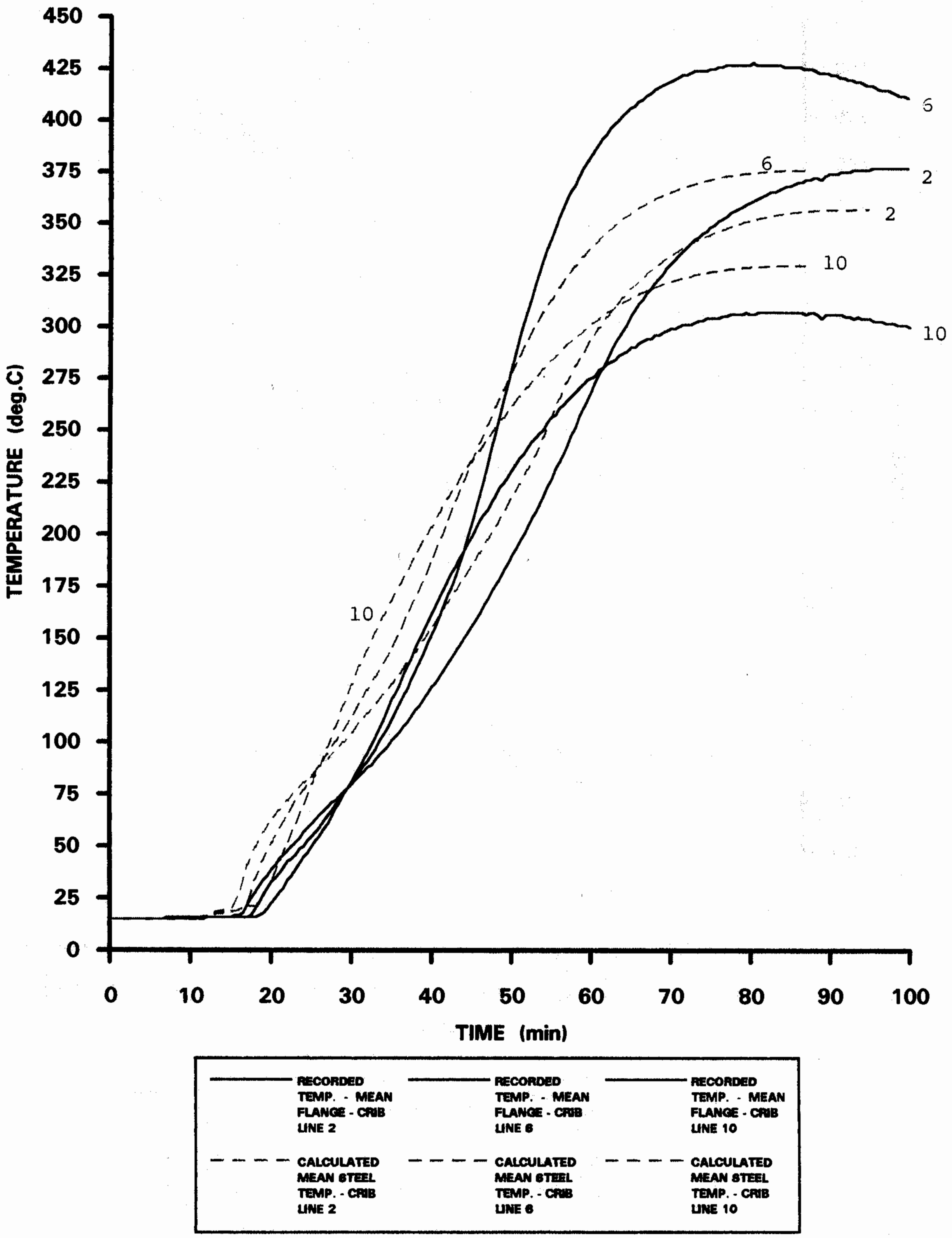


FIG. 52 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 2

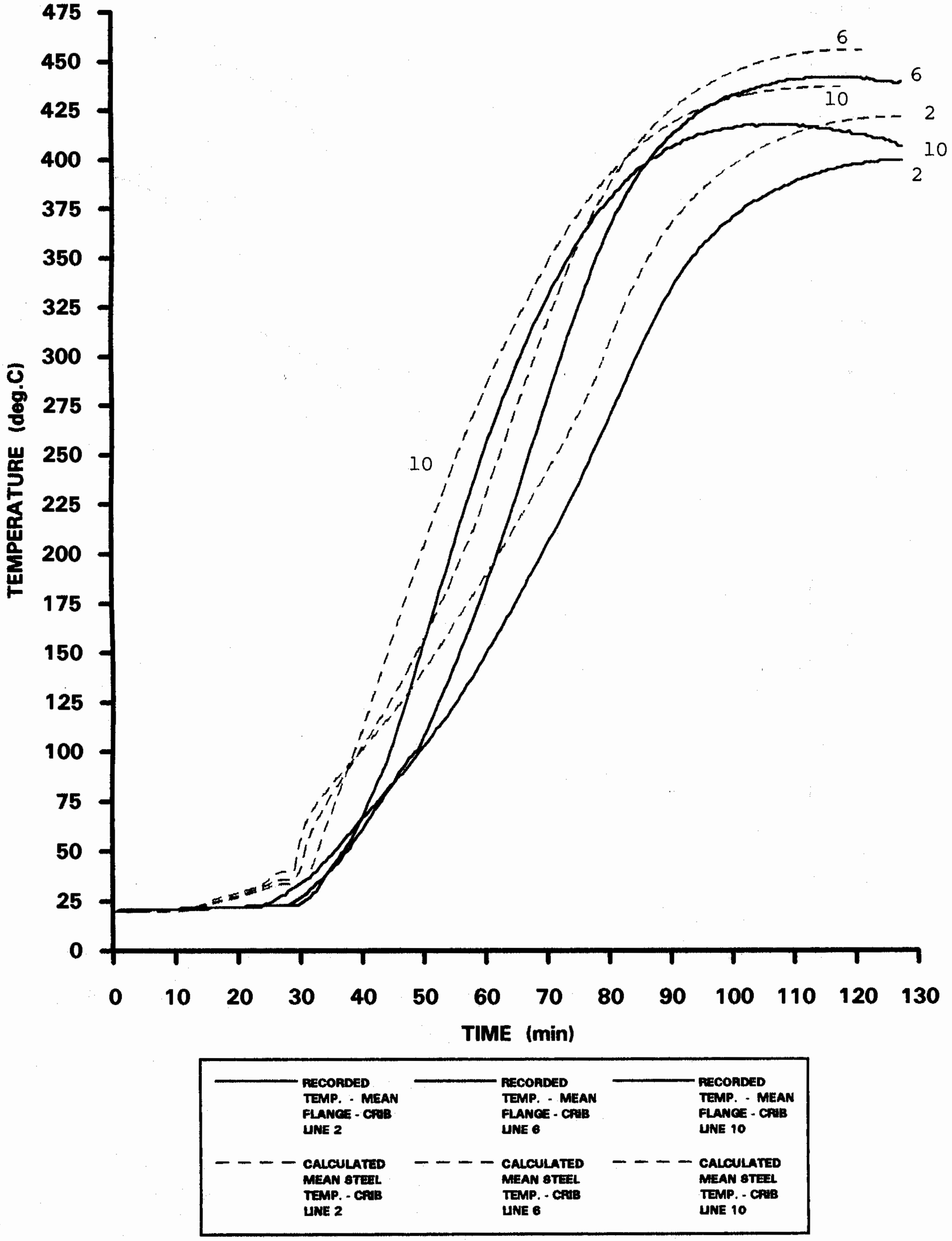


FIG. 53 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 3

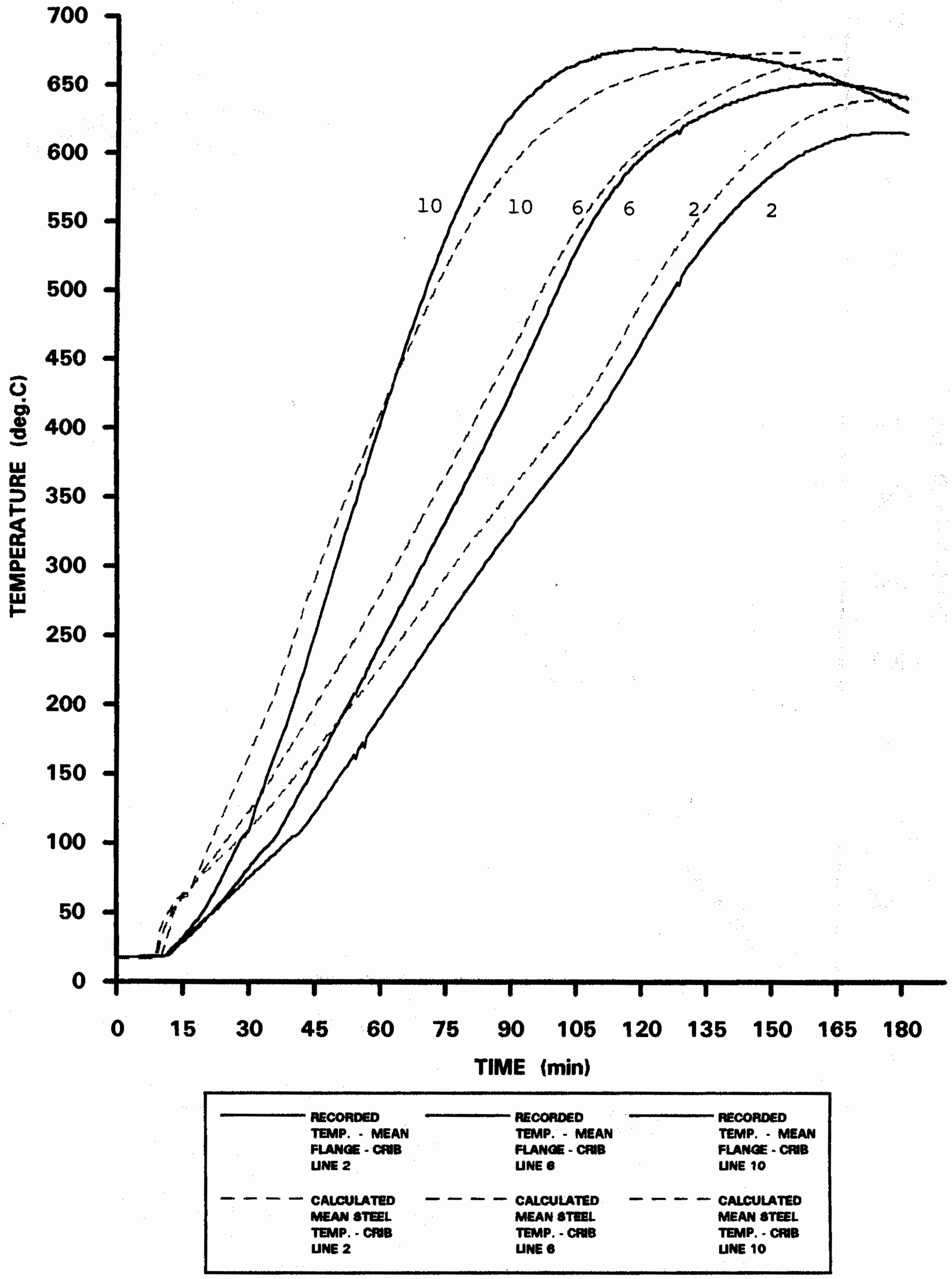


FIG. 54 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 4

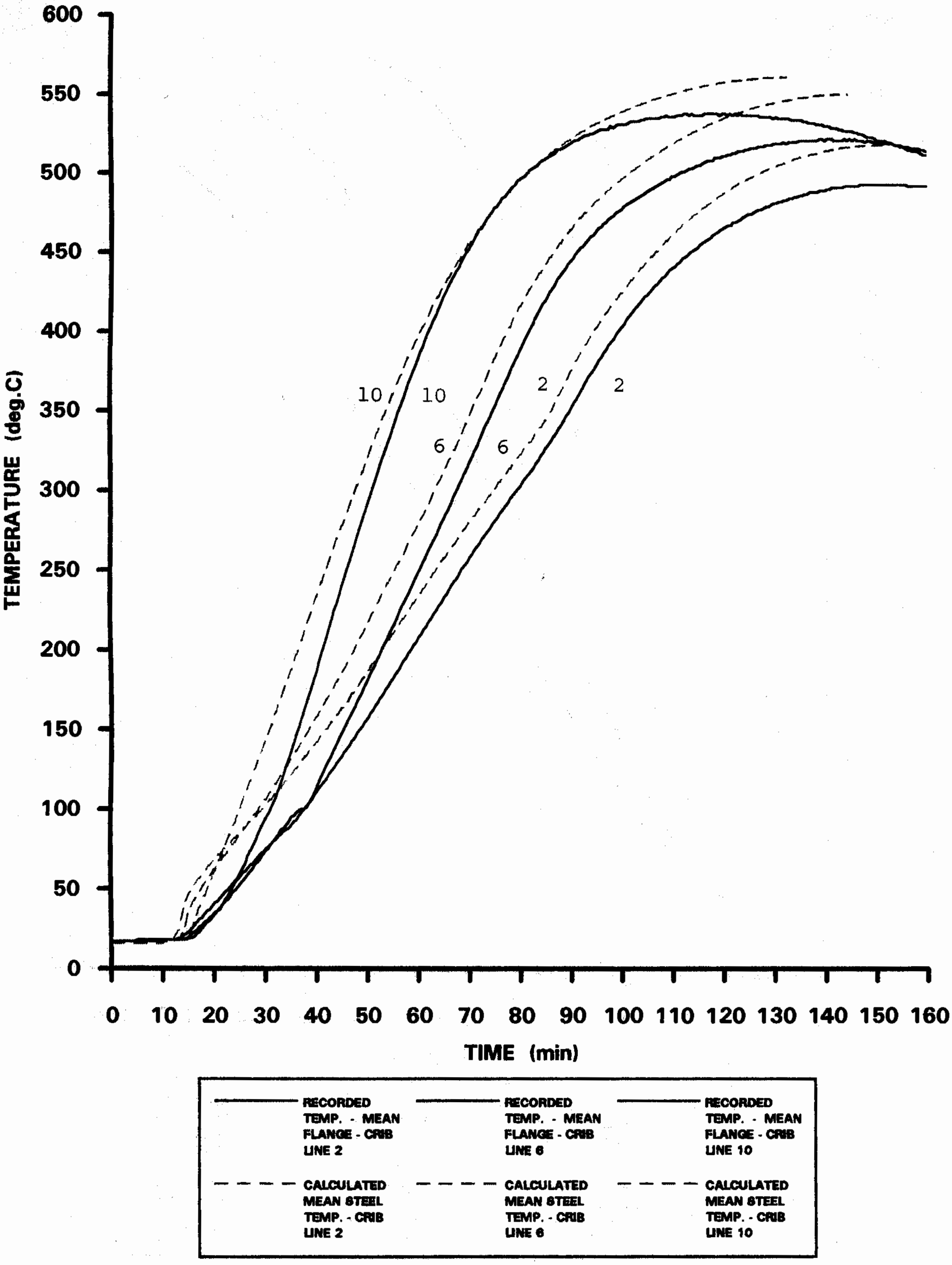


FIG. 55 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 5

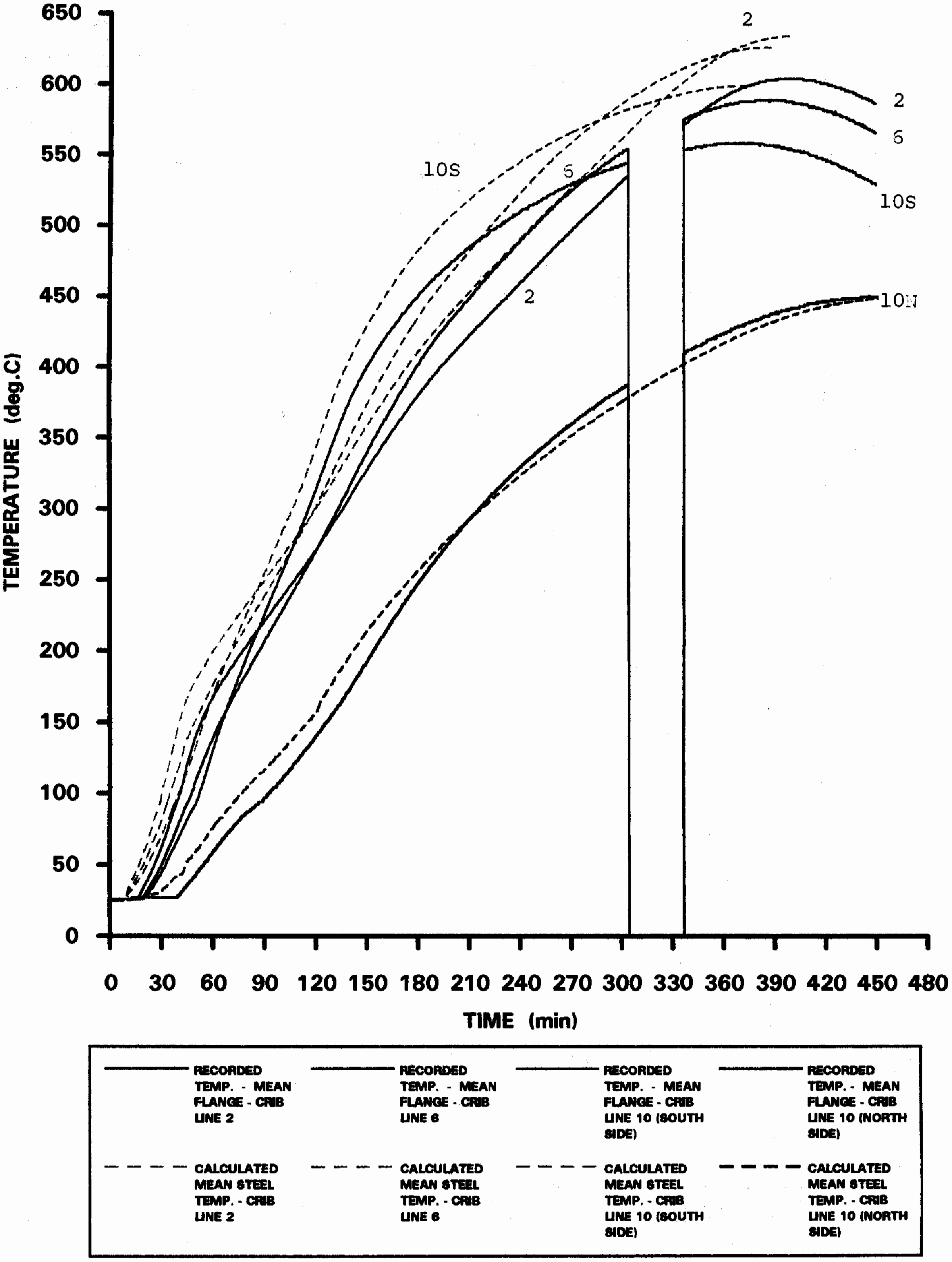


FIG. 56 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 6

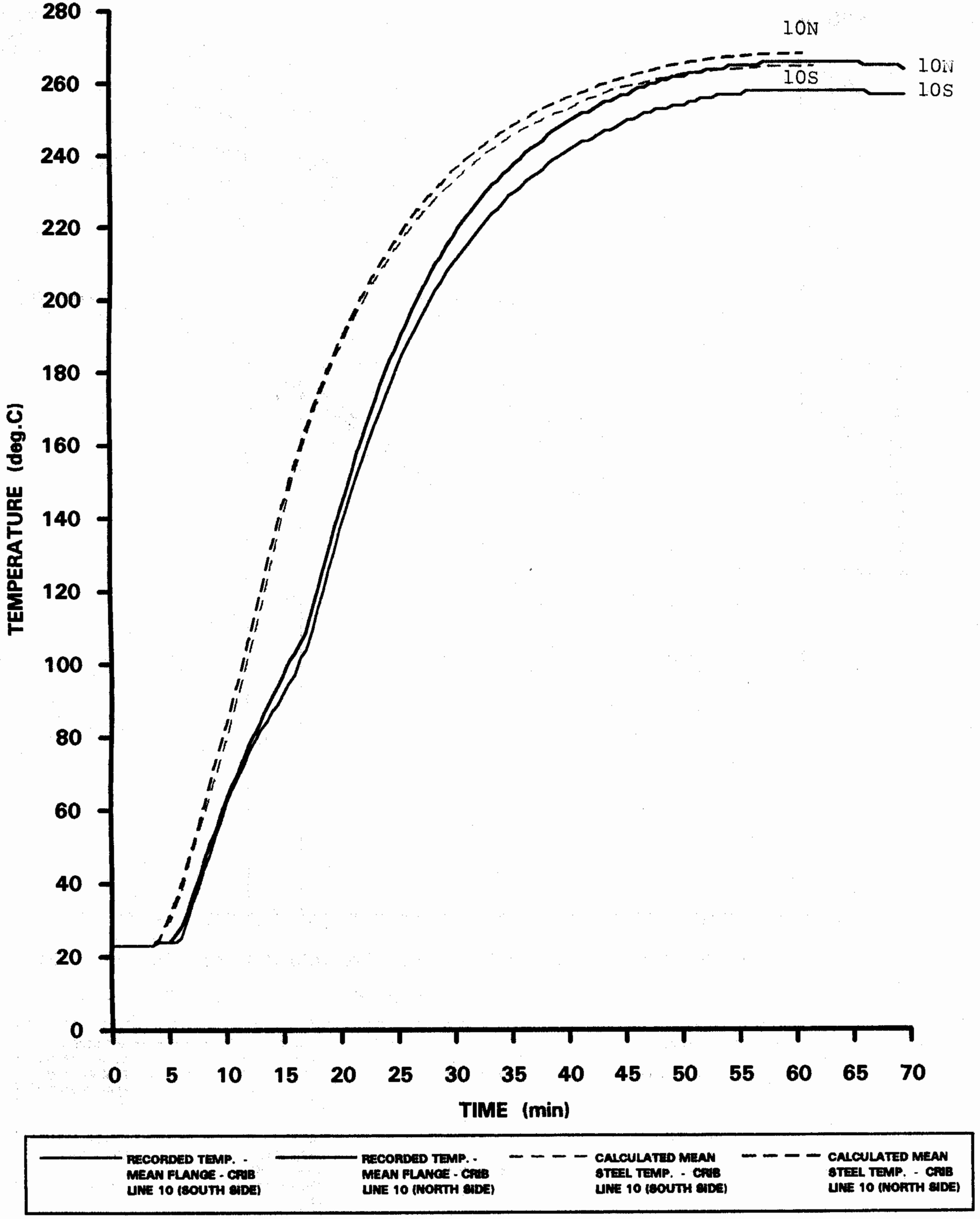


FIG. 57 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 7

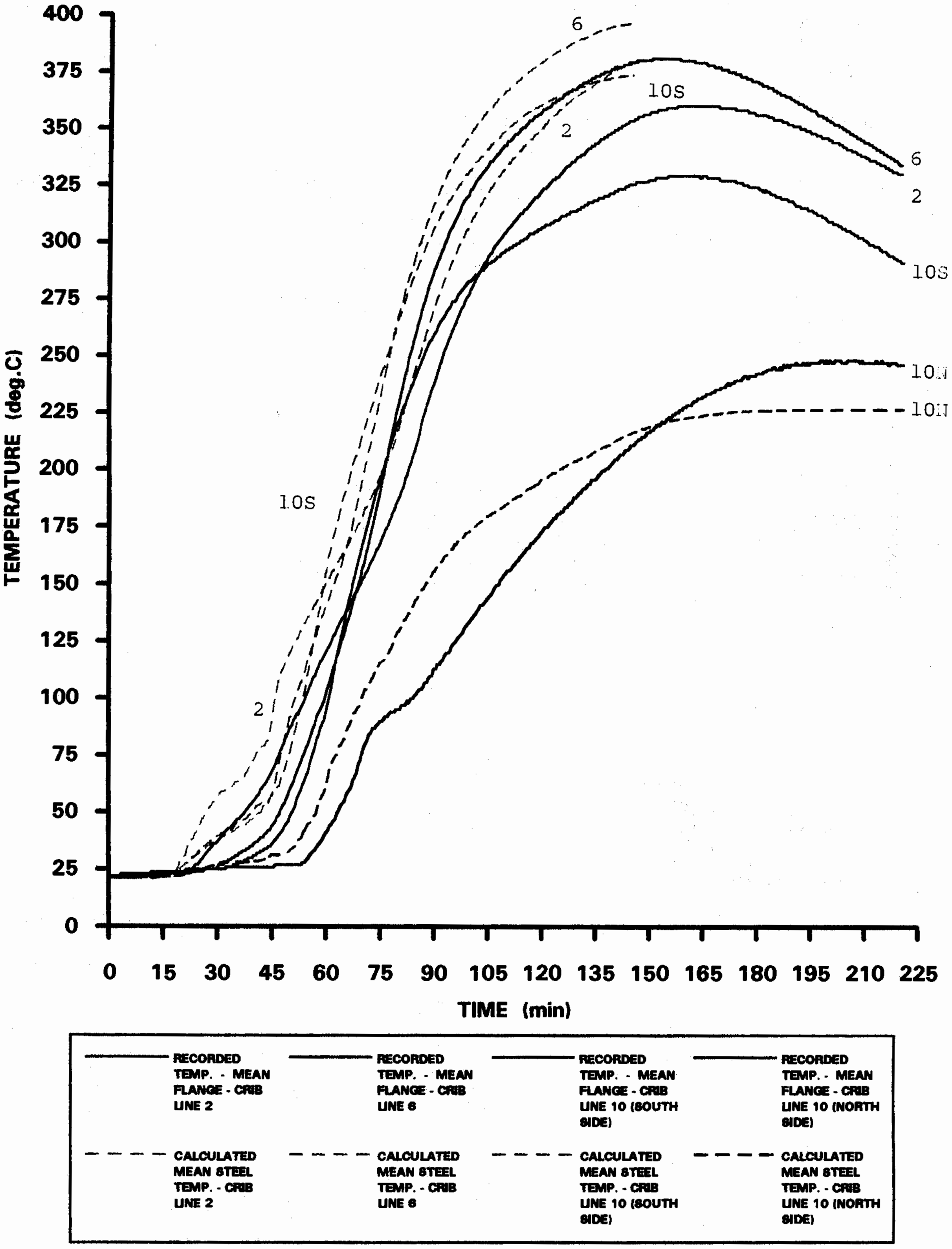


FIG. 58 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 8

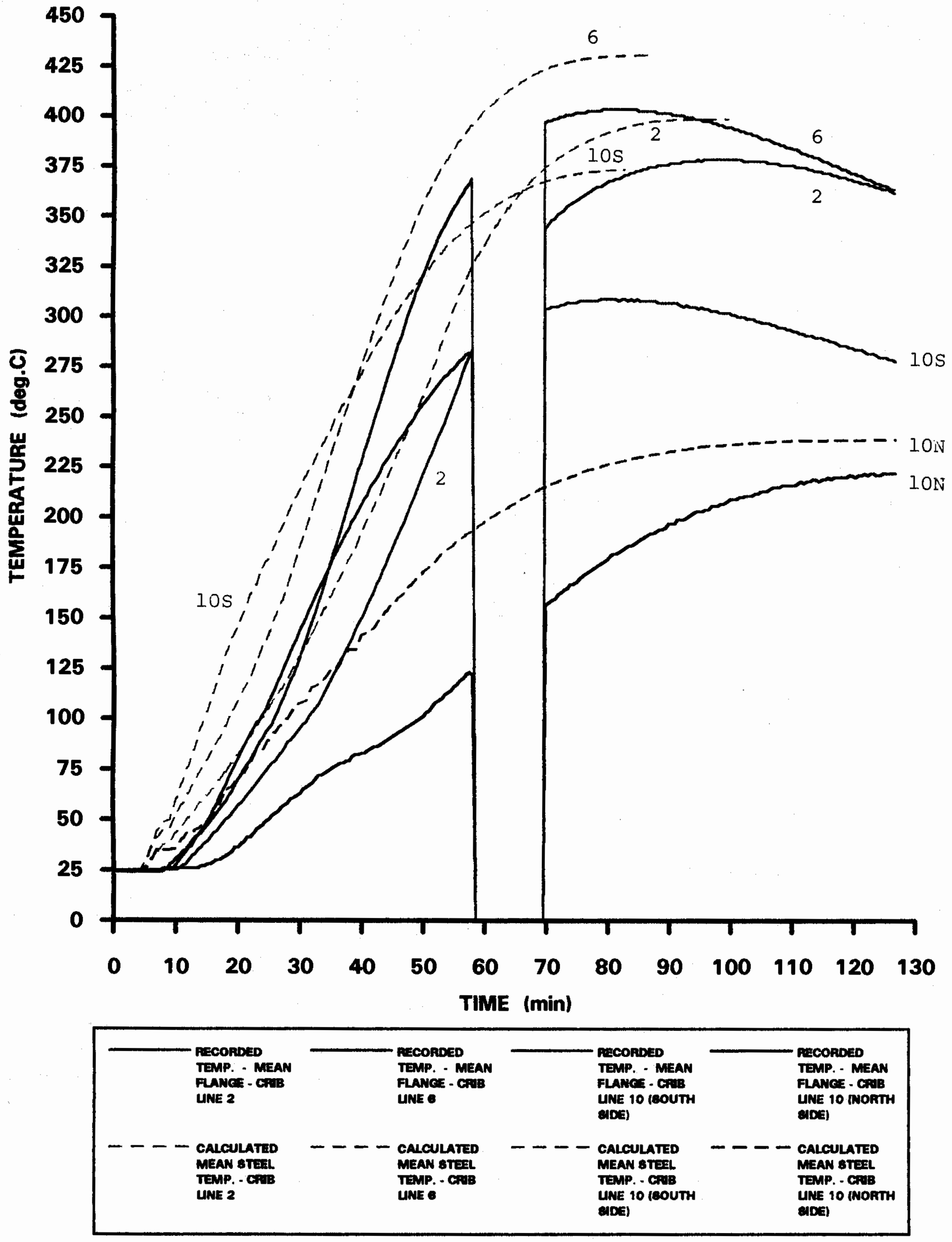


FIG. 59 COMPARISON BETWEEN THE RECORDED AND CALCULATED HEATING CURVES FOR THE PROTECTED COLUMNS IN TEST 9

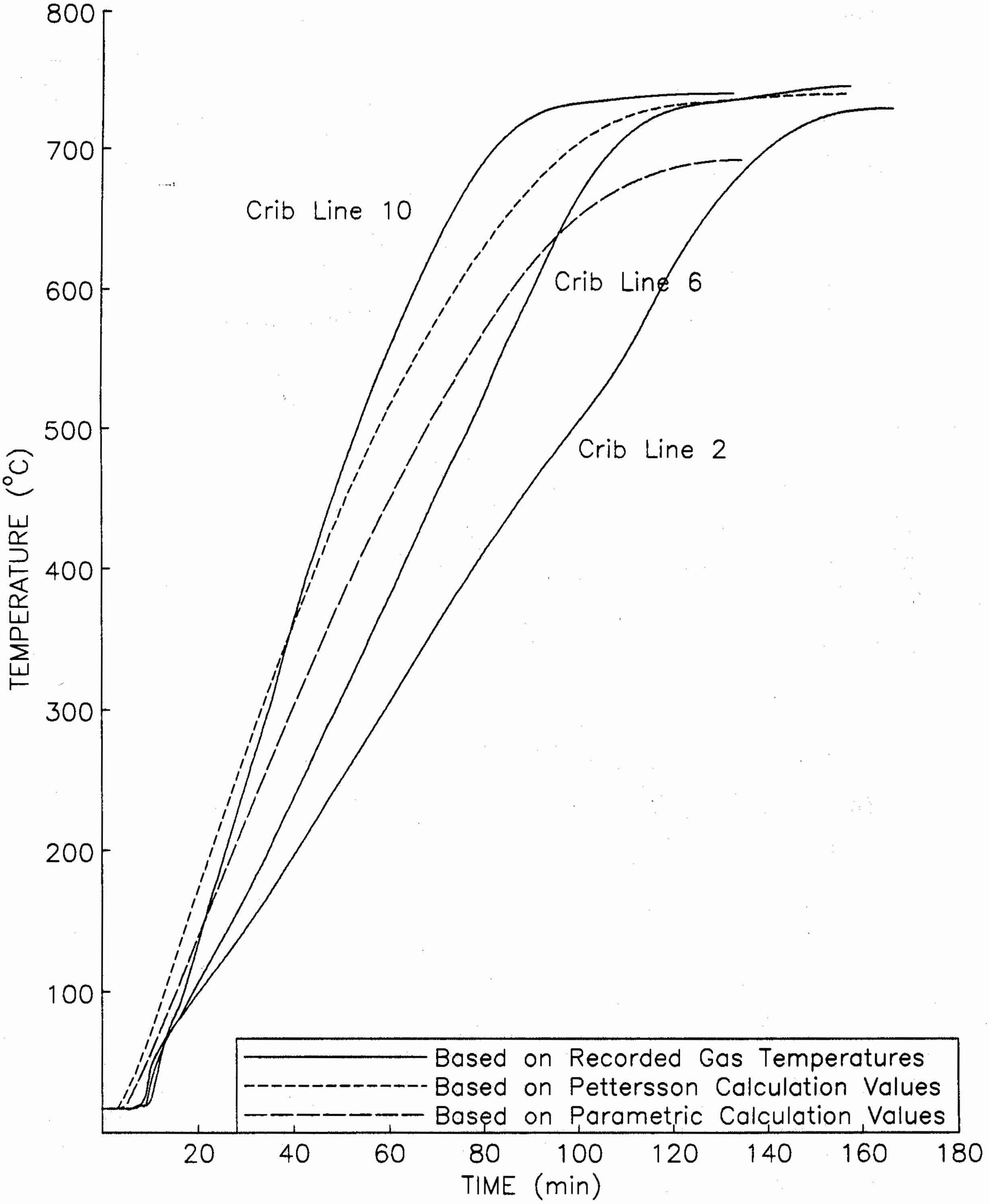


FIG. 60 CARDINGTON NATURAL FIRE TEST 4
TEMPERATURE CALCULATIONS FOR THE PROTECTED BEAMS

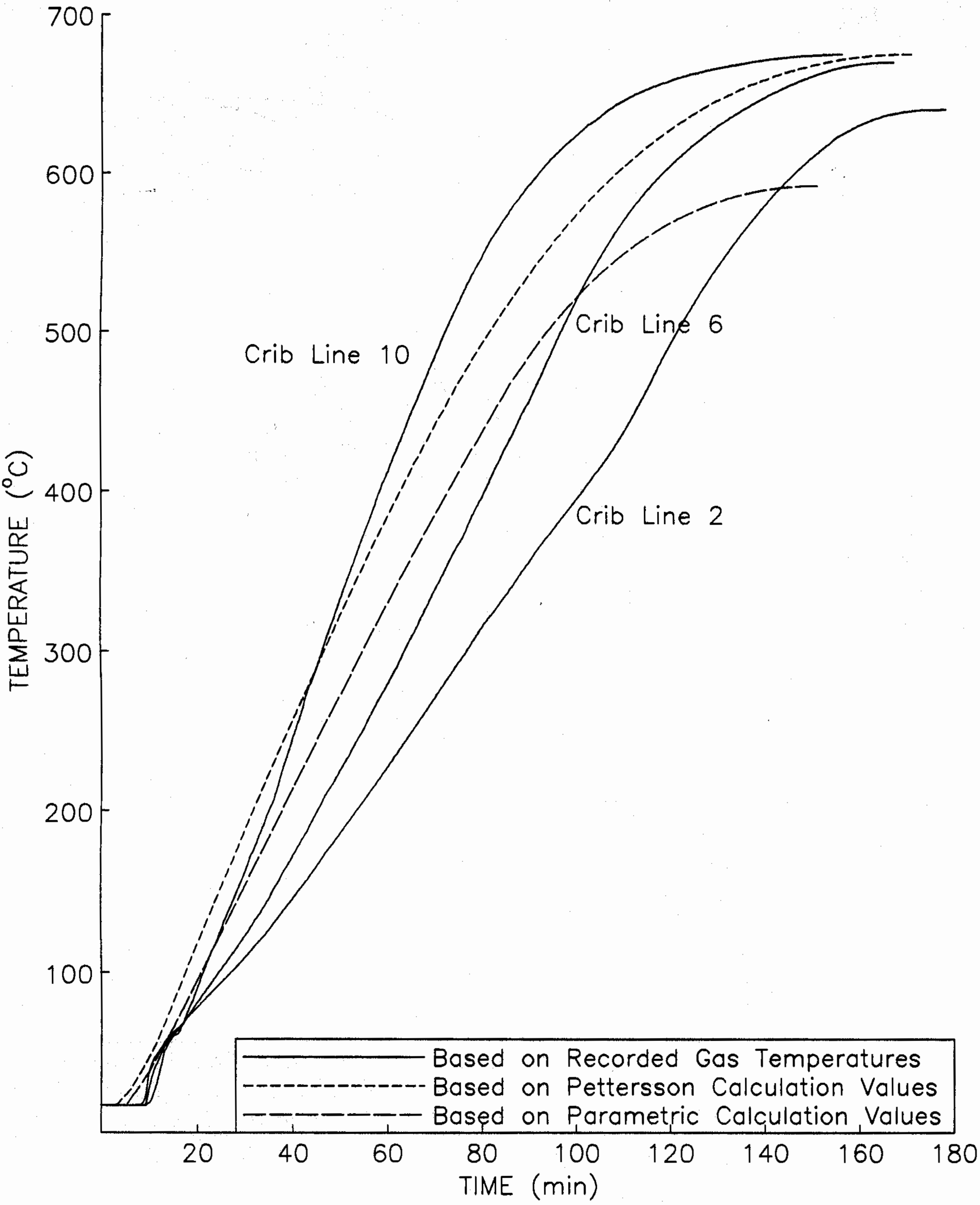


FIG. 61 CARDINGTON NATURAL FIRE TEST 4
TEMPERATURE CALCULATIONS FOR THE PROTECTED COLUMNS

APPENDIX 1
EQUIVALENT TIME OF FIRE EXPOSURE

A1.1 EC1: PART 10A: GENERAL PRINCIPLES AND NOMINAL THERMAL ACTIONS DRAFT DATED 17 SEPTEMBER 1992(4)

The equivalent time of fire exposure, excluding gamma factors is given as:-

$$t_{e,d} = q_{fd} \cdot c' \cdot w_f \qquad \text{(min)}$$

where $t_{e,d}$ = equivalent time of fire exposure (min), also called design value of equivalent duration (min)

q_{fd} = fire load density (MJ/m^2) = Q_K/A_f (see equation below)

c' = Conversion factor to take account of the thermal properties of the enclosure which may be taken as 0.06 where no details are available. Other values may be obtained from the CIB W14 'Design Guide Structural Fire Safety'(5) and DIN 18230:Part 1(12) although EC1:Part 10A does not say so.

In the CIB W14 Design Guide values of c′ can be determined from the table below:-

$b = \sqrt{\lambda \rho c_p}$ (W $h^{\frac{1}{2}}$/m^2 °K)	c' (min/(MJ/m^2))
>12	0.09
12 42	0.07
<42	0.05

where λ = thermal conductivity (W/m °C)
ρ = density (kg/m^3)
c_p = specific heat (J/kg °C)

w_f = ventilation factor calculated from:

$$w_f = (6.0/H)^{0.3}\,[0.62 + 90\,(0.4 - \alpha_v)^4 / (1 + b\,\alpha_h)] = >0.5$$

where α_v = A_v/A_f = ventilation area of vertical openings A_v/compartment floor area
α_h = A_h/A_f = ventilation area of horizontal openings A_h/compartment floor area

The fire load density, Q_k/A_f, can be determined using:

A_f = floor area (m^2)

$$Q_k = \Sigma\, M_{k,i} \cdot H_{ui} \cdot [m_i] \cdot [\psi_i]$$

where H_{ui} = net calorific value (MJ/kg)
$[m_i]$ = optional factor describing the combustion behaviour;
M_i = 1.0 for cellulosic masterials (conservative)
$[\psi_i]$ = optional factor for assessing protected fire loads. Fire loads in non-combustible containments with no specific fire design may be considered as follows:

The largest fire load, but at least [10]% of the protected fire loads are associated with $\psi_i = 1.0$

If only negligible amounts of unprotected fire loads surround the protected fire loads, then the remaining unprotected fire loads may be associated with $\psi_i = [0.0]$. Otherwise ψ_i values need to be assessed individually.

A1.2 EC1: PART 2.7: ACTIONS ON STRUCTURES EXPOSED TO FIRE, APRIL 1993(1) (with June amendments)

The equivalent time of fire exposure is defined as:

$$t_{e,d} = q_{f,d} \cdot k_b \cdot w_f \qquad \text{(min)}$$

$$= q_{t,d}\ k_b \cdot w_f$$

where q_d = design fire load density (MJ/m^2) as defined in Appendix A1.1

k_b = conversion factor as defined in Appendix A1.1 and is ascribed new values given in the table below:

$b = \sqrt{\lambda \rho\, c_p}$ (J/m^2 s$^{\frac{1}{2}}$ °K)	k_b [(min/(MJ/m^2)]
>2500	0.04
2500.........720	0.055
<720	0.07

λ, ρ, c_p are as defined in Appendix A1.1.

Where no detailed assessment of the thermal properties of the enclosure is made $k_b = 0.07$ may be adopted.

w_f = ventilation factor calculated as before in Appendix A1.1.

A1.3 WORKSHOP CIB W14(5)

The equivalent time of fire exposure is defined as:

$$t_e = q_f\ c\ w \qquad \text{(min)}$$

where q_f and c are as defined in A1.1.

w = ventilation factor is calculated from

$$w = w'\left(\frac{A_f}{A}\right)^{\frac{1}{2}}$$

and

$$w' = \left(\frac{A_f}{A_t\sqrt{h}}\right)^{\frac{1}{2}}$$

A_f = floor area (m^2)

A_t = total area of bounding surfaces (m^2)

A = ventilation area (m^2)

h = ventilation height (m)

A1.4 LAW(6)

The equivalent time of fire exposure is defined as:

$$t_e = k \frac{L}{(A_v A_t)^{\frac{1}{2}}} \qquad \text{(min)}$$

where L = fire load (kg of wood)
A_v = area of ventilation (m^2)
A_t = area of walls and roof but not including openings (m^2)
k = a constant, usually taken as unity for large scale experimental fires (min m^2/kg)

No account is made for the insulation properties of the compartment boundaries.

A1.5 PETTERSSON(7)

The equivalent time of fire exposure is defined as:

$$t_e = 0.067\, q_t \left(\frac{A\sqrt{h}}{A_t}\right)^{-\frac{1}{2}} \qquad \text{(min)}$$

where q_t = fire load density (MJ/m^2 of total boundary surfaces)
A = area of ventilation (m^2)
h = weighted mean ventilation height (m)
A_t = area of total boundary surfaces including the openings

To take account of the thermal properties of the compartment, based upon the opening factor

$$\left(\frac{A\sqrt{h}}{A_t}\right)$$

the fire load and ventilation factor are multiplied by the coefficient k_f which varies from 0.5 up to 3.0

$$q_{tf} = k_f\, q_t$$

$$\left(\frac{A\sqrt{h}}{A_t}\right)_f = k_f \left(\frac{A\sqrt{h}}{A_t}\right)$$

A1.6 HARMATHY(8)

The equivalent time of fire exposure is based upon the normalised heat load H ($s^{\frac{1}{2}}$ °K) defined as:

$$H = \frac{1}{\sqrt{\lambda \rho c_p}} \int_0^{\tau} q\, dt$$

where q = the heat flux that penetrates the building element (W/m^2)
t = time (s)
τ = fire duration (s)

The normalised heat load of a real fire H′ is derived from the approximate relationship for cellulosic fires:

$$H' = \frac{10^6\,(11.0\,\delta + 1.6)\,A_F\,L}{(A_t - A_v)\,.\,(\lambda \rho\, c_p)^{\frac{1}{2}} + 935\,(\phi\, A_F\, L)^{\frac{1}{2}}}$$

where $$\delta = \begin{cases} 0.79\ (h_c^3/\phi)^{\frac{1}{2}} & \\ 1 & \text{whichever is less} \end{cases}$$

and ϕ = ventilation parameter

$= \rho_a\, A_v\, (g\, h_v)^{\frac{1}{2}}$ (kg/s)

in which ρ_a = density of air entering the compartment (kg/m^3)
g = gravitational constant (m/s^2)
A_v = area of ventilation (m^2)

from H′, t_e is obtained by setting

$$t_e = \tau = 0.11 + 0.16 \times 10^{-4}\, H' + 0.13 \times 10^{-9}\, (H')^2 \qquad \text{(hour)}$$

The key parameters used in calculating the various time equivalent relationships of CIB W14, Law, Pettersson and Harmathy for each set of fire conditions are given in Table A1.1.

TABLE A1.1
KEY PARAMETERS USED IN CALCULATING TIME EQUIVALENT BASED UPON CIB W14(5), LAW(6), PETTERSSON(7) AND HARMATHY(8)

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Floor Area A_f (m^2)	127.87	127.87	127.87	127.87	127.87	127.87	31.304	120.80	127.87
Area of Bounding Surfaces A_t (m^2)	412.22	412.22	412.22	412.22	412.22	412.22	124.15	389.36	412.22
Area of Walls and Ceiling - Ventilation A_t (m^2) Law	268.96	268.96	276.71	276.71	280.65	282.40	89.08	254.99	270.09
Ventilation Height h (m)	2.750	2.750	1.470	1.470	1.730	0.375	2.750	2.680	2.750
Ventilation Area A_v (m^2)	15.386	15.386	7.637	7.637	3.701	1.948	3.768	13.574	14.286
Opening Factor: w (CIB W14)	1.247	1.247	2.070	2.070	2.855	5.766	1.124	1.299	1.294
$\frac{A_v \sqrt{h}}{A_t}$ ($m^{\frac{1}{2}}$) (Pettersson)	0.062	0.062	0.0225	0.0225	0.0118	0.0029	0.050	0.057	0.058
Fire Load L (kg)	5115	2558	2558	5115	2558	2558	626	2558/ 3225	2558
Fire Load Density: q_f (MJ/m^2 of floor) (CIB)	759.9	380.1	380.1	759.9	380.1	380.1	380.1	402.3/ 507.2	380.1
q_t (MJ/m^2 of total surfaces) (Pettersson)	235.7	117.9	117.9	235.7	117.9	117.9	95.8	124.8/ 157.4	117.9
Insulation Factor: $b = \sqrt{\lambda \rho c_p}$ (CIB W14) (W h/m^2 °K) (<12, 12-42, >42)	<12	<12	<12	<12	<12	<12	<12	<12	<12
c (CIB W14)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
k_f (Pettersson)	3	3	3	3	3	3	3	~2.5	3
ϕ (kg/s) (Harmathy)	96.65	96.65	35.09	35.09	18.45	4.52	23.78	84.22	89.04
δ (Harmathy)	0.3664	0.3664	0.6082	0.6082	0.8387	1.695	0.740	0.3777	0.3817
H' ($10^4 s^{\frac{1}{2}}$ °K)(Harmathy)	3.221	2.053	4.118	6.720	6.335	15.50	3.391	2.228/ 2.599	2.174

CALCULATED TIME EQUIVALENT - MINUTES

CIB W14	85.3	42.7	70.8	141.6	97.7	197.3	38.5	47.0/ 59.3	44.3
Law	79.5	39.8	55.7	111.3	79.4	109.1	34.2	43.5/ 54.8	41.2
Pettersson	109.9	55.0	91.2	182.4	126.0	254.1	49.7	55.4/ 69.8	56.8
Harmathy	45.6	29.6	59.4	106.3	98.8	342.8	48.2	31.9/ 36.8	31.2

APPENDIX 2

HEAT TRANSFER CALCULATION METHOD - PROTECTED MEMBERS
EC3: PART 1.2(9)

The temperature rise $\Delta\theta_{a(t)}$ of an insulated member can be calculated from:

$$\Delta\theta_{a(t)} = \frac{\lambda_p/d_p}{c_a\rho_a}\,\frac{A_p}{V}\left[\frac{1}{1+\phi/3}\right](\theta_t-\theta_a)\Delta t-(e^{\phi/10}-1)\,\Delta\theta_{(t)} \quad \text{but} \quad \Delta\theta_{(t)} \geq 0$$

in which:

$$\phi = \frac{c_p\rho_p}{c_a\rho_a}\,d_p\,\frac{A_p}{V}$$

where A_p/V is the section factor for steel members insulated by fire protection material

A_p is the area of the inner surface of the fire protection material per unit length of the member

V is the volume of the member per unit length

c_a is the specific heat of steel (J/kg °C)

c_p is the specific heat of the fire protection material (J/kg °C)

d_p is the thickness of the fire protection material (m)

Δt is the time interval (seconds)

$\theta_{(t)}$ is the ambient gas temperature at time t

$\theta_{a(t)}$ is the steel temperature at time t

$\Delta\theta_{(t)}$ is the increase of the ambient temperature during the time interval Δt

λ_p is the thermal conductivity of the fire protection material (W/m °C)

ρ_a is the unit mass of steel = 7850 kg/m^3

and ρ_p is the unit mass of the fire protection material (kg/m^3)

APPENDIX 3

PARAMETRIC TIME TEMPERATURES CURVES
EC1: PART 2.7

The time temperature curve of a natural fire can be calculated using the following expression for the heating phase:

$$\Theta_g = 1325\,(1 - 0.325\,\exp^{-0.2t^*} - 0.204\,\exp^{-1.7t^*} - 0.472\,\exp^{-19t^*})$$

where Θ_g = temperature in the fire compartment (°C)
t^* = $t \cdot \Gamma$ with

t = time (h)
Γ = $[O/b]^2 / (0.04/1160)^2$

where b = $\sqrt{(\rho c \lambda)}$ should observe the limits:

$1000 \leq b \leq 2000$ (J/m² $s^{1/2}$ K)

O = opening factor: $A_v \sqrt{h}/A_t$ with the following limits:

$0.02 \leq O \leq 0.20$ ($m^{1/2}$)

A_v = area of vertical openings (m²)
h = height of vertical openings (m)
A_t = total area of enclosure, walls, ceiling and floor (including openings) (m²)
ρ = density of boundary of enclosure (kg/m³)
c = specific heat of boundary of enclosure (J/kg K)
λ = thermal conductivity of boundary of enclosure (W/m K)

To account for enclosures with different layers of material $b = \sqrt{(\rho c \lambda)}$ should be introduced as:

$$b = \sqrt{(\Sigma s_i c_i \lambda_i)} \,/\, \sqrt{\Sigma(s_i c_i \lambda_i / b_i^{\,2})}$$

where s_i = the thickness of layer i
c_i = the specific heat of layer i
λ_i = the thermal conductivity of layer i
b_i = $\sqrt{(\rho_i c_i \lambda_i)}$

To account for different materials in walls, ceiling and floor $b = \sqrt{(\rho c \lambda)}$
b = $\Sigma b_j A_{tj} / \Sigma A_{tj}$

where A_{tj} = the area of enclosure with the thermal property b_j

The temperature-time curves in the cooling phase are given by:

$\Theta_g = \Theta_{max} - 625\,(t^* - t_d^*)$ for $t_d^* \leq 0.5$ h
$\Theta_g = \Theta_{max} - 250\,(3 - t_d^*)\,(t^* - t_d^*)$ for $0.5\text{ h} \leq t_d^* \leq 2$ h
$\Theta_g = \Theta_{max} - 250\,(t^* - t_d^*)$ for $t_d^* \geq 2$ h

where Θ_{max} = maximum temperature in the heating phase (°C)
t_d^* = $0.13 \,.\, 10^{-3}\, q_{t,d} / (O\Gamma)$
$q_{t,d}$ = fire load density related to the surface area of the enclosure A_t (MJ/m²)

whereby $q_{t,d}$ = $q_{fd} \,.\, A_f / A_t$; the following limits should be observed:

$100 \leq q_{t,d} \leq 1000$ (MJ/m²)