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BS 476 : Part 21 Fire Resistance Tests

The Effect of Load Ratio on the Limiting Temperatures Observed During Tests Carried Out on Two 150 × 150 × 8 mm Cold Formed SHS Columns Protected With Spray Applied Vermiculite Cement

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SUMMARY

BS 476 : PART 21 FIRE RESISTANCE TESTS

THE EFFECT OF LOAD RATIO ON THE LIMITING TEMPERATURES OBSERVED DURING TESTS CARRIED OUT ON TWO 150 × 150 × 8 mm COLD FORMED SHS COLUMNS PROTECTED WITH SPRAY APPLIED VERMICULITE CEMENT

D.E. Wainman, M. Edwards

At the present time most structural steelwork is designed in the UK on a limit states basis to BS 5950:Part 1. This standard assumes the exclusive use of hot formed sections. Similarly fire resistant design of both protected and unprotected structural steelwork, using hot formed sections, can be undertaken using BS 5950:Part 8. However, cold formed sections are increasingly being used as compression members. Within Europe various codes and standards, (e.g. Eurocode 3, draft Part 1.2), are evolving which specifically include cold formed products within their scope. The methodologies involved in both room temperature design and fire design using the UK and European approaches are compared and discussed in the report.

The purpose of the present work was to establish whether the design rules given in BS 5950:Part 8, which were derived from tests carried out exclusively on hot formed open section beams and columns, were equally applicable to cold formed SHS products. More particularly, the work sought to determine whether the relationships given in the standard between load ratio and temperature at 'failure' could be applied to cold formed SHS members.

Accordingly, two standard fire resistance tests were carried out to BS 476:Part 21 on a pair of 150 × 150 × 8 mm CF SHS columns at significantly different levels of loading. Each column was protected with a nominally 17 mm thick coating of Mandolite CP2, a spray applied vermiculite / cement product from Mandoval Coatings Ltd. The tests were performed at the Loss Prevention Council, Borehamwood, during February 1993. This report contains a detailed description of each test together with all the measured data.

Four possible ultimate limit states room temperature design resistances were calculated, all in broad accordance with BS 5950 Part 1 and / or Eurocode 3.1, (ENV 1993-1-1), each time making an appropriate rational allowance for the use of cold formed material. Test loads were then fixed by applying the Fire Design Load Factors given in Table 2 of BS 5950:Part 8 to the highest calculated design resistance. This gave resulting notional test load ratios of 0.722 and 0.579.

From Table 5 of BS 5950:Part 8, limiting steel temperatures of 504°C and 548°C were initially estimated for the two respective load cases. Mean steelwork temperatures of 516°C and 560°C were recorded at the failure of each respective test column. The two tests described in this report therefore demonstrate that UK fire design procedures based on the fire performance of hot formed material can be used to predict the performance of cold formed sections with the same accuracy, since the failure temperatures of the two specimens were within 12°C of those predicted by the most optimistic design assessment.

KEYWORDS

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Fire Resistance	Fire Protection	+BS 6363
+BS 476	Sections(Hollow	Sections Cold Formed
Columns	+BS 5950	Lab Reports

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BS 476 : PART 21 FIRE RESISTANCE TESTS

THE EFFECT OF LOAD RATIO ON THE LIMITING TEMPERATURES OBSERVED DURING TESTS CARRIED OUT ON TWO 150 × 150 × 8 mm COLD FORMED SHS COLUMNS PROTECTED WITH SPRAY APPLIED VERMICULITE CEMENT

1. INTRODUCTION

The load bearing steel members making up the framework of a building are required, by the UK Building Regulations, to possess specified levels of fire resistance, such as one, two, or more hours. For steel sections this property can either be measured in the standard fire resistance test, (BS 476:Parts 20/21:1987),[1,2] or may be calculated by methods described in BS 5950:Part 8:1990[3]. One of the calculation procedures outlined therein is referred to as the limiting temperature method. This is based on a study of the behaviour of the critical element, which is defined as being that part of the section which will attain the highest temperature in fire conditions. In the standard fire resistance test the critical element of a column is usually considered to be located at the mid-height of the test member. The limiting temperature is the temperature attained by this element of the column at 'failure'. It therefore follows that the time taken for the critical element to heat up to its limiting temperature is a measure of the fire resistance rating of the section under test. Furthermore, the extent to which the test member is loaded clearly influences the time taken for it to reach failure, as defined by the standard. Consequently, the limiting temperature recorded for a lightly loaded steel section will be greater than for the same member subjected to a higher level of loading.

BS 5950:Part 8 provides a table, (Table 5 in the standard), of limiting temperatures, as a function of load ratio, for various categories of steel members including columns. It is important to appreciate that this table is largely based on data obtained during the fire resistance testing of unprotected hot rolled open section steel beams and columns and that no data relating to structural hollow sections were included. It is therefore important to ensure that the tabulated data are equally valid for this group of products.

Structural hollow sections may be produced by both hot and cold forming process routes. In the case of the latter the resulting products usually exhibit enhanced mechanical properties as a direct consequence of the cold working operations. Eurocode 3:Part 1[4] gives details of the methods by which the capacities of SHS members may be calculated. For cold formed sections two alternative methods are described in which either nominal strength properties for the basic material are assumed or average enhanced material properties may be determined depending on the type of forming and subsequent process route. This report includes a consideration of the two alternative methods of assessing capacity.

The present report gives details concerning the measurement of the limiting temperature at two different values of load ratio for 150 × 150 × 8 mm cold formed structural hollow section columns. It was considered necessary to apply fire protection material in order to reduce the rate at which the steel temperature increased to a more modest level than would otherwise be the case.

2. DETAILS OF THE TEST ASSEMBLIES

The size of square hollow section selected for this study was 150 × 150 mm with a wall thickness of 8 mm. This size was chosen after taking into account the following factors:-

(a) the section had to be large enough to withstand the applied loads without giving rise to premature failure.

(b) the section had to be small enough, for a given effective length, to ensure that when failure occurred it did so by buckling and not by squashing which would tend to occur with larger section sizes.

The cold formed section was sourced via British Tubes Stockholding Ltd. The product supplied was actually of American origin, having been manufactured by the Bull Moose Tube Company of St. Louis, Missouri.

The steel quality conformed to BS 6363:1983[5], Grade 43/36.

It should be noted that in terms of its wall thickness this particular section is just outside the size range covered by BS 6363, (maximum wall thickness = 6.3 mm). However, for the purposes of this work it has been assumed that the specifications given in the standard are applicable to the 8 mm thick material used.

The two test assemblies were fire protected over their entire lengths with a spray applied, 17 mm thick coating of Mandolite CP2, a cementitious vermiculite material manufactured by Mandoval Coatings Ltd. The coating thickness was derived from a consideration of the nominal Hp/A value for the section, (135 m^{-1}), and the required level of protection which was a minimum of 60 minutes.

Each assembly was instrumented such that a vertical temperature profile in the steel section could be recorded throughout the test.

The column ultimate load capacities were calculated in accordance with BS 5950:Part 1[6], but due allowance was made for the use of cold formed material. The applied test load levels were fixed by reference to BS 5950:Part 8. Loads of 1060 kN and 850 kN were applied to the first, (LPC 83064), and second, (LPC 83065), test assemblies respectively. These gave corresponding load ratio values of 0.722 and 0.579. The critical temperatures corresponding to these load levels were 504°C and 548°C, (see Section 4).

More detailed descriptions concerning the following topics are contained in Appendix 1.

1. Steel supply / analysis / properties / dimensions.
2. Test piece construction / fabrication.
3. Instrumentation.
4. Application and testing of the fire protection material.
5. Assembly / loading / applied loads.
6. Failure criteria.

3. EXPERIMENTAL RESULTS

The test assemblies achieved the following fire resistance ratings:-

LPC 83064 - 73 minutes
LPC 83065 - 84 minutes

At 'failure' the mean temperature of the steel section in the area of greatest deformation was:-

LPC 83064 - 516°C
LPC 83065 - 560°C

Detailed descriptions of the actual tests are contained in Appendices 2 and 3.

3.1 Residual Load Bearing Capacity Tests

The full test load appropriate to each column was reapplied approximately 24 hours after the completion of each test. In both cases the column supported the applied load. The requirements of the residual load bearing capacity test were therefore considered to have been satisfied.

4. DISCUSSION

Figure 1 shows a plot of limiting temperature, as a function of load ratio, for members in compression with a slenderness ratio less than or equal to 70. The data points are taken from Table 5 of BS 5950:Part 8:1990 which is reproduced here as Table 1.

A non-linear curve fitting programme, (using Marquart's method), was used to establish the equation of the best fit line through these data. An equation of the general form:-

$$y = Ax^2 + Bx + C$$

where y is the limiting temperature, °C
and x is the applied load ratio

was found to give a satisfactory solution.

The coefficients of the equation had the following values:-

A = 223.214
B = -595.179
C = 817.786

The RMS error was 4.561. The variation in y explained, which is indicative of the 'goodness of fit', was 99.8483%.

The polynomial function therefore satisfactorily described the data set. The main objection to its use however, is that with any parabolic function there is an associated turning point. For this reason it is important to appreciate that the function fitted to the data is strictly only valid within the limits of the data. Attempts to extrapolate the data should therefore be resisted since any data so obtained may contain serious errors. Since the applied load ratio values already span a range which is greater than any situation which is likely to arise in normal practice, there should be no necessity for any further extrapolation of the data.

The line joining the data points in Fig. 1 has been drawn using the polynomial function. Using this equation, the limiting temperatures at the test load ratios of 0.722 and 0.579 were calculated to be 504°C and 548°C respectively. The two experimental points, measured in the present work, have been superimposed on the graph. The values may be seen to be 12°C greater in both cases than those predicted by BS 5950:Part 8.

5. SUMMARY AND CONCLUSIONS

BS 476:Part 21 standard fire resistance tests have been carried out on two 150 × 150 × 8 mm square hollow section columns which were protected with nominally 17 mm of Mandolite CP2, a spray applied cementitious vermiculite product from Mandoval Coatings Ltd. The steel columns were cold formed products conforming to BS 6363:1983 Grade 43/36.

The relevant data for each test are summarised in the following table.

	83064	83065
Applied Load, kN	1060	850
Load Ratio	0.722	0.579
Critical Temperature, °C (Predicted)	504	548
Critical Temperature, °C (Measured)	516	560
Time to Failure, min	73	84

It may be seen that there is very good agreement between the experimentally derived values for critical temperature and those obtained by reference to the design standard. Based on only these two results it appears that the data given in BS 5950:Part 8 may be very slightly conservative for SHS columns tested under these conditions.

The following conclusions may be drawn from the present work.

1. The BS 5950 Part 8 Table 5 method for assessing column failure appears to be equally applicable to SHS columns as it is to rolled I sections. (It should be noted that rolled I sections were used to generate the bulk of the data given in BS 5950:Part 8.)

2. The use of this strain level appears equally valid as a criterion of failure for hot formed and cold formed structural hollow sections when used as columns.

3. Testing appears to initially validate the use of Buckling Curves 'C' (EC3 and 5950) for cold formed SHS columns in fire, together with the gross cross sectional mechanical properties as determined by squash tests.

6. FURTHER WORK

The present work has shown that the information given in BS 5950:Part 8 concerning the relationship between the temperature at failure and the applied load level, (load ratio), is realistic for cold formed structural hollow sections.

So far as is known there is very little, if any, other data available concerning CF SHS products. Consideration should therefore be given to obtaining further verification of the present results by way of additional fire resistance tests on a range of carefully chosen products. This could prove to be an expensive course to pursue and there is currently no intention to embark on such a programme. Therefore, apart from any further analyses of the present data, the current investigation should be considered to be complete.

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REFERENCES

1. BS 476:Part 20:1987: Fire Tests on Building Materials and Structures, - Methods for Determination of the Fire Resistance of Elements of Construction, (General Principles).

2. BS 476:Part 21:1987: Fire Tests on Building Materials and Structures, - Methods for Determination of the Fire Resistance of Load Bearing Elements of Construction.

3. BS 5950:Part 8:1990: Structural Use of Steelwork in Building, - Code of Practice for Fire Resistant Design.

4. Eurocode No. 3: Design of Steel Structures, Commission of the European Communities, Brussels.

5. BS 6363:1983: Welded Cold Formed Steel Structural Hollow Sections.

6. BS 5950:Part 1:1990 Structural Use of Steelwork in Building, - Code of Practice for Design in Simple and Continuous Construction: Hot Rolled Sections.

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TABLE 1

BS 5950:PART 8:1990 TABLE 5

Table 5. Limiting temperatures for design of protected and unprotected hot finished members

Description of Member	Limiting Temperature, °C at a Load Ratio of:					
	0.7	0.6	0.5	0.4	0.3	0.2
Members in compression, for a slenderness λ (see note)						
≤70	510	540	580	615	655	710
>70 but ≤180	460	510	545	590	635	635
Members in bending supporting concrete slabs or composite slabs:						
unprotected members, or protected members complying with item (a) or (b) of 2.3	590	620	650	680	725	780
other protected members	540	585	625	655	700	745
Members in bending not supporting concrete slabs:						
unprotected members, or protected members complying with item (a) or (b) of 2.3	520	555	585	620	660	715
other protected members	460	510	545	590	635	690
Members in tension:						
all cases	460	510	545	590	635	690

Note. λ is the slenderness, i.e. the effective length divided by the radius of gyration

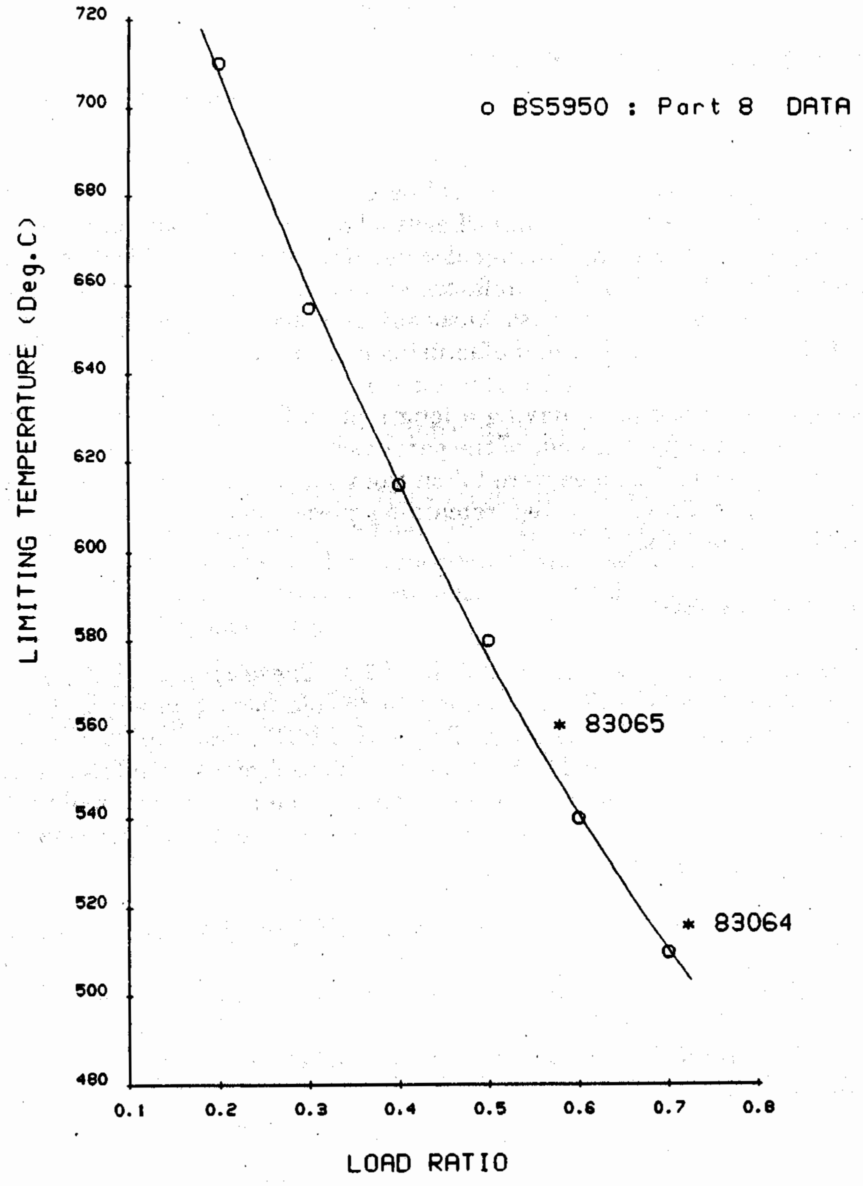

FIG. 1 LIMITING TEMPERATURE AS A FUNCTION OF LOAD RATIO FOR MEMBERS IN COMPRESSION WITH A SLENDERNESS RATIO NOT GREATER THAN 70

(BS 5950 : PART 8, TABLE 5)

APPENDIX 1

DETAILS OF THE TEST ASSEMBLIES

A1.1 STEEL SUPPLY AND TESTING

A1.1.1 General

The 150 × 150 × 8 mm cold formed SHS material used in the construction of both test assemblies was obtained from British Tubes Stockholding Ltd., Leeds. They, in turn, had obtained it from Natural Gas Tubes based at Tredegar, South Wales, although documentation still attached to the section at the time of its delivery suggested that the original manufacturer was the Bull Moose Tube Company of St. Louis, Missouri, USA. Enquiries revealed that both Natural Gas Tubes and the Bull Moose Tube Company are part of the Caparo Tube Group which has manufacturing plant in the UK, Canada and USA.

The material was supplied in one piece having a length of 10.1 m. For each test a 3400 mm length was required, these being cut from opposite ends of the parent section. The balance of approximately 3300 mm was cut into three equal pieces. Samples were taken from one of these for chemical analysis, mechanical testing and a dimensional survey. The two remaining pieces were retained at Swinden Laboratories pending any further investigations.

A1.1.2 Chemical Analysis

The results of the chemical analysis are given in Table A1.1. These confirm that the composition satisfied the requirements given in BS 6363:1983 for a Grade 43/36 cold formed product. It is interesting to note that the test certificate provided by Natural Gas Tubes, (via BTS), describes the product as a cold formed structural hollow section made from steel to BS 4360 and to the dimensional tolerances given in BS 4848, even though those standards relate to hot formed products. It should also be noted that the test certificate quoted the silicon content to be 0.010% whilst the confirmed value obtained by Swinden Laboratories was 0.19%.

Reference to the NGT brochure reveals that their range of cold formed hollow sections are:

> "Manufactured from hot rolled strip conforming to BS 4360 Grades 43C or 50C so that in terms of material analysis and weldability they have the same characteristics as the hot formed SHS products and meet the same mechanical property requirements that those specifications demand".

Furthermore it is stated that:

> "the overall dimensions of NGT cold formed sections are generally within the requirements of BS 4848 and are thus interchangeable with hot formed sections. The corner radius of cold formed sections is, however, not as tight as that for the hot formed section and is generally about 2 t compared with 1.5 t for hot formed, where t is the wall thickness".

It is also stated that:

> "NGT square and rectangular hollow sections also meet the requirements of BS 6363, (Specification for welded Cold Formed Steel Structural Hollow Sections), and thus conform to the requirements of BS 5950:Part 5, (Code of Practice for Design in Cold Formed Sections)".

A1.1.3 Dimensional Survey

Figure A1.1 depicts, at full size, the cross section of the as-received steel product. Figure A1.2 shows the positions at which measurements of the section profile were obtained. These are in line with the schematic arrangement outlined in BS 6363:1983. The results of the dimensional survey are given in Table A1.2.

A1.1.4 Hardness Survey

A hardness survey was carried out on a section of the as-received material. All measurements were made at the mid-wall thickness position at the locations indicated in Fig. A1.3. The results are given in Table A1.3.

A1.1.5 Mechanical Properties

Eurocode 3:Part 1 outlines methods by which the resistance of cold formed structural hollow sections may be calculated. These methods require a knowledge of either the actual gross cross sectional mechanical properties of the product or those of the parent plate material from which the product was formed. In the present work it was clearly impossible to obtain samples of the parent plate. However, an attempt was made to gain some indication of what the plate properties might have been by subjecting samples taken from the section to two different heat treatments. These were:-

(a) Treatment 1 - Heat to 600°C, hold at temperature for 30 minutes then air cool.

(b) Treatment 2 - Heat to 900°C, hold at temperature for 60 minutes then air cool.

The first treatment was intended to remove only the stresses introduced during the cold forming operation whilst the second would, it was anticipated, remove not only these stresses but also any present in the parent material. The difference between the properties of the material following the two treatments would, it was hoped, be small, indicating that any enhancement in the properties of the cold formed section was due principally to the forming operation.

Four samples were taken from each of the three plain faces of the section, (the face containing the weld bead was excluded). The samples were approximately 220 mm long × 50 mm wide and were situated about the mid-width position of each face. The samples were identified as follows:-

Position	Identification 2M86D + Sub-Code 1-12
Face between corners:	
C1 and C2	No samples - welded face
C2 and C3	Samples 1, 2, 3, 4
C3 and C4	Samples 5, 6, 7, 8
C4 and C1	Samples 9, 10, 11, 12

Samples 1, 5 and 9 received no heat treatment.

Samples 2, 6 and 10 were subjected to heat treatment No. 1 (600°C/30 min).

Samples 3, 7 and 11 were subjected to heat treatment No. 2 (900°C/60 min).

The remaining samples were retained pending any further investigations.

Standard NFT2 tensile specimens were machined from the nine samples.

The results of the room temperature tensile tests are given in Table A1.4, (as-received material), and Table A1.5, (heat treated material). These tests were carried out in accordance with the requirements of BS EN 10002-1:1990.

A1.1.6 Full Section Squash Test

In order to obtain the gross cross sectional mechanical properties of the complete section a squash test was carried out on a short, (165 mm), length of the as-received product. Figure A1.4 is a plot of the load / displacement data recorded during the test. The maximum value of the applied load was 2095.5 kN.

Based on the dimensional data given in Table A1.2 the cross sectional area of the steel was calculated to be 4472 mm^2. Hence, the maximum squash strength of the product may be calculated as:-

$$(2095.5 \text{ kN}/4472 \text{ mm}^2) \times 1000 \text{ N/mm}^2$$

i.e. 468.6 N/mm^2

Using the information contained in Fig. A1.4 the overall 0.2% proof stress value for the complete section may be calculated as:-

$$(1770 \text{ kN}/4472 \text{ mm}^2) \times 1000 \text{ N/mm}^2$$

i.e. 395.8 N/mm^2

A1.2 TEST PIECE CONSTRUCTION DETAILS

A1.2.1 Fabrication

Fabrication details for both test pieces were identical, and were as follows:-

(a) A 35 mm diameter hole to accommodate the thermocouple leads was drilled in one face of the SHS at a distance of approximately 80 mm from one end. This face and end were then defined to be 'East facing' and 'bottom' with respect to their eventual positions within the test furnace.

(b) The steelwork thermocouples were placed in position, (see Section A1.2.2.1).

(c) Steel bearing plates, having the dimensions shown in Fig. A1.5 were attached to both ends of each test piece using 90 × 90 mm × 12 mm thick angle cleats welded to the plate and section. The arrangement is shown in Fig. A1.6.

A1.2.2 Instrumentation

A1.2.2.1 Temperature Measurement

A total of twelve 'K' type thermocouples, formed from glass fibre covered Ni-Cr/Ni-Al conductors, were used to monitor the temperature of the steel section during each test. The thermocouples were located at the positions indicated in Fig. A1.7 and were at the mid-thickness of the section wall. In order to leave the faces of the section free for the application of the fire protection material it was necessary for the thermocouple cables to pass down the cavity of the section and exit through the 35 mm diameter hole provided. Fitting of the thermocouples was carried out by LPC personnel.

After the test assembly had been located within the furnace a further seven thermocouples were installed in order to monitor the furnace atmosphere temperature surrounding the column at positions along its height. These were 3 mm diameter mineral insulated 'K' type couples, each with insulated hot junctions and Inconel sheaths. They were located adjacent to the thermocouples installed by the LPC for monitoring and controlling the furnace atmosphere temperature and, like the LPC couples, were set with their hot junctions 100 mm from the steel surface.

They were identified as ATM1 to ATM7 and were positioned as follows:

ATM1	North Furnace Shell	Top
ATM2	North Furnace Shell	Centre
ATM3	North Furnace Shell	Bottom
ATM4	South Furnace Shell	Top
ATM5	South Furnace Shell	Centre
ATM6	South Furnace Shell	Bottom
ATM7	Between North and South Furnace Shells on East Side	Centre

A1.2.2.2 Column Extension

The longitudinal extension of the column was monitored throughout each test, by LPC personnel, using a linear displacement transducer situated below the centre of the crosshead transmitting the load from the hydraulic jacks to the column.

A1.2.3 Application of the Fire Protection

Both column assemblies were protected with Mandolite CP2, a cementitious vermiculite product manufactured and supplied by Mandoval Coatings Ltd. The material was applied in the form of a wet spray to a nominal thickness of 17 mm by Mandoval Technical Centre personnel during the period 9th/10th December 1992. The coating thickness was selected in conjunction with Mandoval staff and was based on the requirement to provide a minimum of one hour's fire protection to the steelwork. The declared nominal Hp/A ratio for the steel section was 135 m^{-1}.

Prior to its application the steelwork surfaces were degreased and any paint or other extraneous matter was removed. The two columns set up ready for spraying are shown in Fig. A1.8. The CP2 material was applied directly onto the prepared steel surfaces without any intermediate primer or pick-up coat. The full coating thickness was applied in several passes over the two day period. Installation was in accordance with the practices and procedures recommended by Mandoval Coatings Ltd. Thickness determinations were carried out by both Mandoval and LPC personnel after the coating had dried for approximately 48 hours. Details of these are included in Section A1.5.

Tray samples, nominally 300 × 300 mm square and approximately 17 mm thick were prepared at the time of spraying each column. These were for subsequent determinations of the densities and moisture contents. The sprayed columns were left to dry for about 10 weeks in a storage area, the air temperature in which was maintained at approximately 20°C. Regular weighing of the tray samples during the conditioning period indicated that the specimens had reached equilibrium with the atmosphere in the storage area prior to the fire tests being carried out.

A1.3 ASSEMBLY / LOADING

Each complete test assembly was positioned vertically between the upper and lower column furnace crossheads, to which they were attached by bolting through the holes in the welded on end plates. The orientation of each column was such that, using the convention adopted by the LPC, the thermocouple lead hole faced East, (see Fig. A1.9). Both ends of the column were protected by the application of a mineral fibre blanket material so that the length of column actually exposed to the heating conditions of the test was 3100 mm. Figure A1.10 shows one of the columns installed in the furnace prior to testing.

The load was applied to the column by means of two hydraulic jacks acting through the lower crosshead member. It was applied at least 15 minutes prior to the commencement of the heating period, and was kept constant throughout the test by allowing the column to expand against the applied load.

A1.4 LOADING CONDITIONS

A1.4.1 Loads Applied

This subject is covered in much greater detail in Appendix 4.

According to the design procedures outlined in Eurocode 3:Part 1, the columns had a buckling strength of 1467 kN, based on buckling curve 'C' and the measured gross material properties of the cross section, (partial safety factors set to unity). In the case of the first test, (LPC 83064), a load of 1060 kN was actually applied, resulting in a load ratio value of 0.722. According to the assessment procedures outlined in BS 5950:Part 8 the critical temperature corresponding to this load level is 504°C. In the case of the second test, (LPC 83065), the load was reduced sufficient to ensure that a significant increase in the critical temperature would result. The load actually applied was 850 kN, giving a load ratio value of 0.579 and a corresponding critical temperature of 548°C.

A1.4.2 Calculation Details

(a) Data Common to Both Tests

Steel Section

Designation: 150 × 150 × 8 mm CF SHS

Length, L	=	3400 mm
Effective Length, l_e	=	3400 mm × 0.7
	=	2380 mm

Note: An effective length factor of 0.7 was initially assumed. This was found to offer good agreement with the observed behaviour, e.g. see Figs. A2.5 and A3.5.

From BS 4848:Part 2:1991 (Page 16)

Least Radius of Gyration, r	=	5.78 cm
and therefore:		
Nominal Slenderness Ratio, l_e/r	=	2380/(5.78 × 10)
	=	41.18
Calculated Least Radius of Gyration, r_c	=	5.74 cm
and therefore:		
Actual Slenderness Ratio, l_e/r_c	=	2380/(5.74 × 10)
	=	41.46

From EC3:Part 1:1985

Buckling Strength of Column = 1467 kN

(Based on Buckling Curve 'C' and the measured gross material properties of the cross section as determined from the squash test.)

(b) Test No. LPC 83064

Load Applied = 1959 kN

$$\text{Load Ratio} = \frac{\text{Applied Load at Fire Limit State}}{\text{Load Capacity at 20°C (Buckling Strength)}}$$

$$= \frac{1060}{1467}$$

$$= \underline{0.722}$$

From BS 5950: Part 8*

Limiting Temperature at Load Ratio of 0.722 = 504°C

(c) **Test No. LPC 83065**

Load Applied = 850 kN

Load Ratio = $\frac{850}{1467}$

= 0.579

From BS 5950:Part 8*

Limiting Temperature at Load Ratio of 0.579 = 548°C.

A1.5 TESTS ON THE FIRE PROTECTION MATERIAL

The thickness of the applied coating was measured jointly by the LPC and Mandoval Coatings Ltd. The mean values reported by them are given in Table A1.6.

The moisture content and density of the coating material was determined by the LPC on the day(s) of the fire test(s) using the tray samples prepared at the time of spraying. The values reported by them are also given in Table A1.6.

Additional moisture content and density determinations were carried out by Mandoval Coatings Ltd. on small, (less than 15 g), samples of the coating removed from the base of each column on the day(s) of the test(s). The values reported by them are given in Table A1.7.

A1.6 FAILURE CRITERIA

The performance of the test assemblies was judged against the load bearing capacity criterion outlined in Section 6 of BS 476:Part 21:1987 and in accordance with the general principles embodied in BS 476:Part 20:1987.

The standards state that a column is regarded as having a fire resistance rating, (expressed in minutes), that is equal to the elapsed time, (in completed minutes), between the commencement of heating and the termination of heating or until failure to meet the load bearing capacity criterion occurs, whichever is the sooner.

It should, however, be noted that the principal purpose of carrying out these tests was to obtain confirmation, or otherwise, of the validity of the relationship given in BS 5950:Part 8 between the limiting temperature at 'failure' and the applied load ratio. Nevertheless, as a consequence of carrying out the test it was inevitable that a fire resistance rating for each assembly would be obtained.

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* Limiting Temperatures were calculated by reference to the polynomial function fitted to the BS 5950 data as described in the main section of this report.

TABLE A1.1
CHEMICAL COMPOSITION OF THE STEEL SECTION USED IN THE FIRE RESISTANCE TESTS

BS Code	Section and Test Details	Chemical Composition (Product Analysis, Wt. %)														
		C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	N	Nb	Sn	Ti	V
2M86D	150 × 150 × 8 mm thick wall Cold Formed Square Hollow Section	0.11 (0.11)	0.19 (0.010)	0.88 (0.88)	0.009 (0.009)	0.009 (0.011)	<0.02	<0.005	<0.02	0.056	<0.02	0.0056	0.022	<0.005	<0.005	<0.005
	Test Date: 16.02.93 Test I/D: LPC 83064 Test Date: 18.02.93 Test I/D: LPC 83065	Values in Parenthesis are those given on the test certificate from Natural Gas Tubes Ltd.														
	BS 6363:1983 Grade 43/36 Product Analysis	0.23 Max.	0.45 Max.	1.30 Max.	0.055 Max.	0.055 Max.										
	BS 4360:1990 Grade 43C Product Analysis	0.24 Max.	0.55 Max.	1.40 Max.	0.06 Max.	0.06 Max.										

TABLE A1.2
DIMENSIONAL DATA FOR THE STEEL SECTION USED IN THE FIRE RESISTANCE TESTS
(REFER TO FIG. A1.2 FOR DIMENSION POSITIONS)

Nominal Dimensions

Depth	:	150 mm
Breadth	:	150 mm
Wall Thickness	:	8 mm
Section Factor	:	135 m^{-1}

Actual Dimensions (2M86D)

Depth, mm at Position

D1 = 150.02		
D2 = 150.00		
D3 = 150.09	Mean = 149.96 mm	
D4 = 149.84		
D5 = 149.83		

Breadth, mm at Position

B1 = 150.29	
B2 = 150.06	
B3 = 149.71	Mean = 149.97 mm
B4 = 149.65	
B5 = 150.16	

Wall Thickness, mm at Position

t_1 = 8.51	t_{11} = 8.50	
t_2 = 7.87	t_{12} = 7.87	
t_3 = WELD	t_{13} = 7.90	Mean (t_1-t_5) = 8.24 mm
t_4 = 7.80	t_{14} = 7.90	Mean (t_6-t_{10}) = 8.12 mm
t_5 = 8.77	t_{15} = 8.70	Mean (t_{11}-t_{15}) = 8.17 mm
t_6 = 8.49	t_{16} = 8.53	Mean (t_{16}-t_{20}) = 8.15 mm
t_7 = 7.90	t_{17} = 7.90	Mean (t_1-t_{20}) = 8.17 mm
t_8 = 7.89	t_{18} = 7.93	
t_9 = 7.86	t_{19} = 7.90	
t_{10} = 8.47	t_{20} = 8.48	

Corner Dimensions, mm

	t_c	Ri	Ro	x	y
At Corner 1	8.15	8	16	12.14	14.32
2	8.09	8	16	13.78	13.97
3	8.18	8	16	16.47	12.97
4	8.26	8	16	16.91	13.29
Mean Values	8.17	8	16	14.83	13.64

TABLE A1.3
HARDNESS SURVEY RESULTS

Measurement Position Number (Fig. A1.3)	Equivalent Dimension Measurement Position (Fig. A1.2)	Vickers Hardness Number HV30	Approximate Equivalent Tensile Strength N/mm²
1	Corner 1	185	584
2	D2	161	511
3	D3/t3	197	637 (Weld)
4	D4	138	461
5	Corner 2	173	542
6	B2	157	500
7	B3/t13	151	488
8	B4	138	461
9	Corner 3	160	508
10	D4	164	518
11	D3/t18	154	494
12	D2	147	479
13	Corner 4	189	608
14	B4	172	539
15	B3/t8	154	494
16	B2	140	464

TABLE A1.4
TENSILE TEST RESULTS FROM THE STEEL SECTION USED IN THE FIRE RESISTANCE TESTS (TESTED IN THE AS-RECEIVED CONDITION)

BS Code	Section and Test Details	Sub-Code	0.2% PS N/mm²	0.5% TES N/mm²	Tensile Strength N/mm²	Elongation $L_o = 5.65\sqrt{S_o}$ %	Yield Strength N/mm²
2M86D	150 × 150 × 8 mm thick wall Cold Formed Square Hollow Section Test Date: 16.02.93 Test I/D: LPC 83064 Test Date: 18.02.93 Test I/D: LPC 83065	1 5 9	366.00 361.40 345.07	372.10 376.41 356.24	474.79 482.53 472.95	37.60 34.60 38.60	
		Mean	357.49	368.25	476.76	36.93	
		Natural Gas Tubes Test Certificate No. 30079			505	29	407
	BS 6363:1983 Grade 43/36 Specification				430 (min)	10 (min)	360 (min)
	BS 4360:1990 Grade 43C Specification				430/580	22 (min)	275 (min)

TABLE A1.5
TENSILE TEST RESULTS FROM THE STEEL SECTION USED IN THE FIRE RESISTANCE TESTS (TESTED IN THE HEAT TREATED CONDITION)

BS Code	Heat Treatment	Sub-Code	0.2% PS N/mm^2	0.5% TES N/mm^2	Tensile Strength N/mm^2	Elongation $L_o = 5.65 \sqrt{S_o}$ %
2M86D	600°C for 30 min	2	408.47	407.46	484.11	34.0
		6	425.89	423.90	488.73	36.0
		10	408.02	408.02	480.26	36.0
		Mean	414.13	413.13	484.37	35.3
	900°C for 60 min	3	317.19	317.19	431.41	44.0
		7	300.85	311.99	428.48	42.4
		11	312.31	312.31	423.19	45.0
		Mean	310.12	313.83	427.69	43.8

TABLE A1.6
RESULTS OF TESTS CARRIED OUT ON THE FIRE PROTECTION MATERIAL - LPC DATA

LPC Test No.	83064	83065
Date Column Sprayed	9/10 Dec. '92	9/10 Dec. '92
Coating Thickness (Nominal), mm	17	17
Coating Thickness Measured	12 Dec. '92	11 Dec. '92
Mean Coating Thickness, mm	17.25	17.8
Date Column Tested	16 Feb. '93	18 Feb. '93
Age at Test Date, days	68	70
Coating Density, kg/m^3	421	473
Coating Moisture Content, % w/w (*)	6.8	7.0
Coating Dry Density, kg/m^3	394	440

(*) By weight loss after drying at 105°C

TABLE A1.7
RESULTS OF TESTS CARRIED OUT ON THE FIRE PROTECTION MATERIAL - MANDOVAL COATINGS DATA

LPC Test No.	83064	83065
Sample Removed from Test Column	16 Feb. '93	18 Feb. '93
Mandoval Reference No.	5501 B	5501 A
Sample Weight, g	11.34	12.01
Weight Loss		
- Ambient → 50°C, %	3.09	4.16
- Ambient → 105°C, %	5.82	6.66
Dry Density, kg/m^3	350 (*)	370 (*)

(*) These values are only very approximate due to the small sample weight

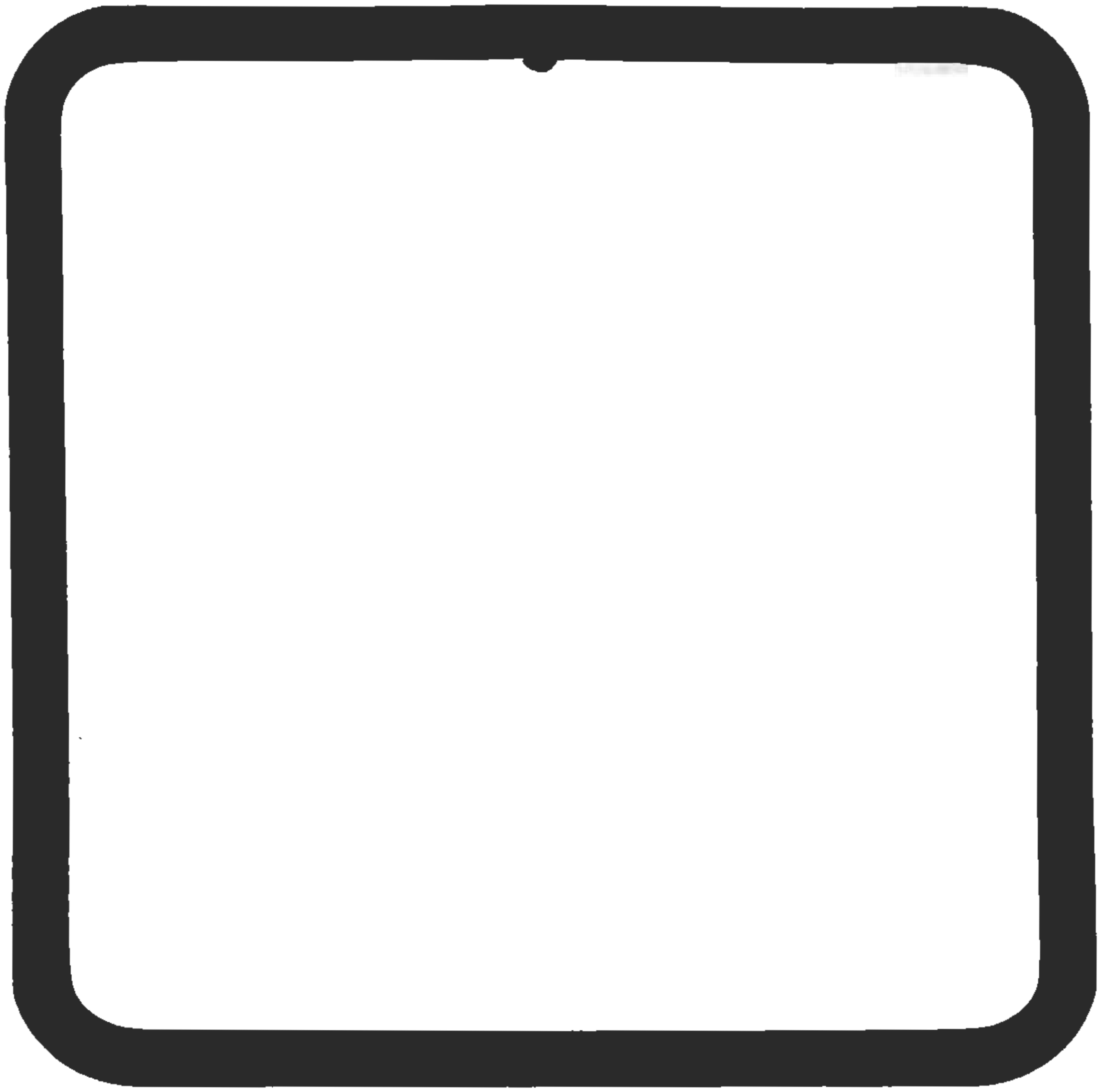
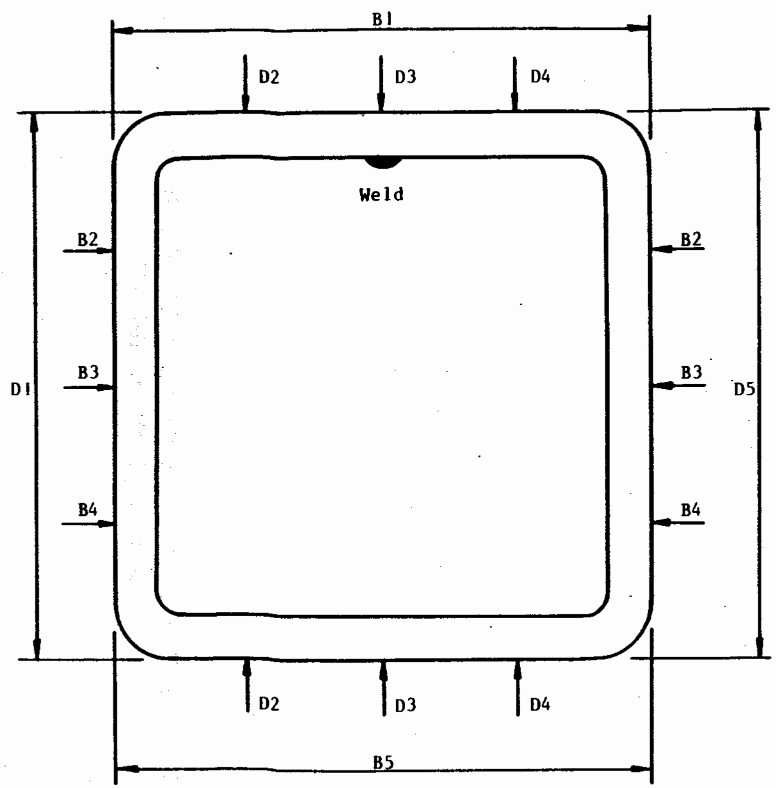


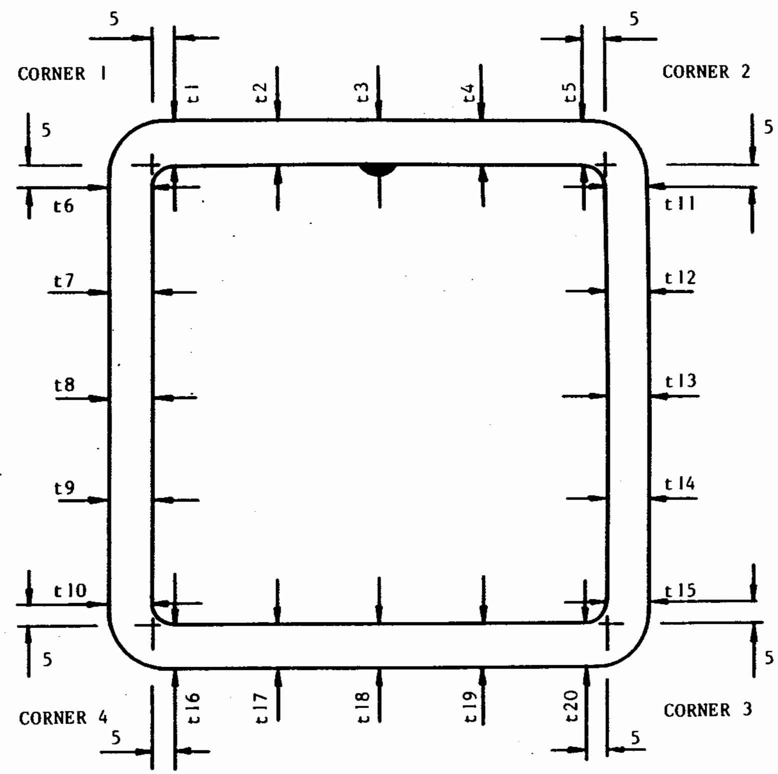
FIG. A1.1 FULL SIZE SECTION PROFILE

(a) Overall Depth and Breadth



D1, D2, D3, D4 and D5 are equidistant as are B1, B2, B3, B4 and B5

(b) Wall Thickness

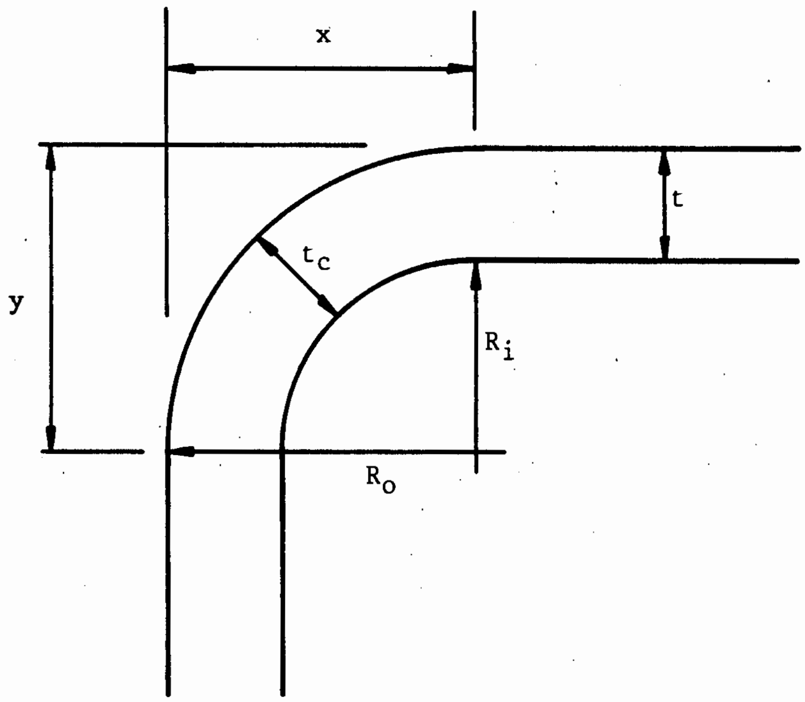


All measurement positions along each side are equidistant

All Dimensions in mm.

FIG. A1.2a-b (cont ...) **POSITIONS OF THE MEASUREMENT POINTS USED IN THE DIMENSIONAL SURVEY** **(R4/1603)**

(c) Corner Details



BS6363:1983 Specification

External Corner Radii, R_o = 2.5 x t

Internal Corner Radii, R_i = 1.5 x t

FIG. A1.2c POSITIONS OF THE MEASUREMENT POINTS USED IN THE DIMENSIONAL SURVEY (R4/1604)

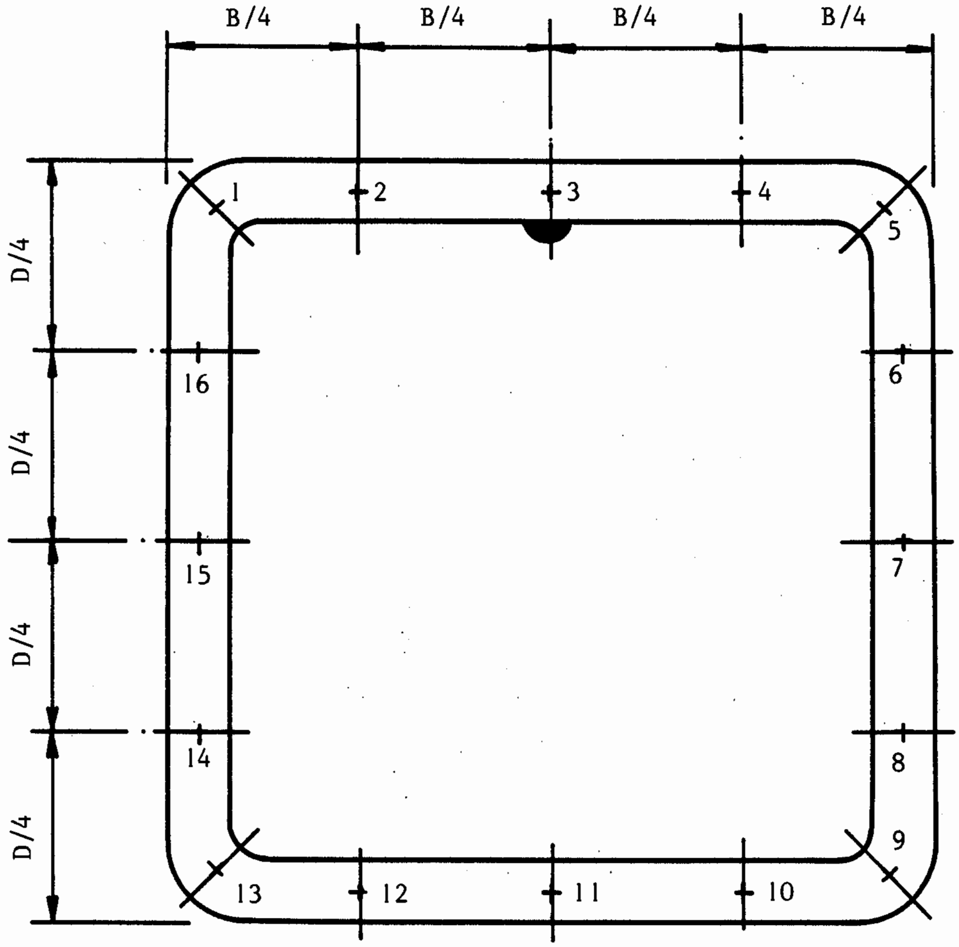


FIG. A1.3 **HARDNESS SURVEY MEASUREMENT POSITIONS** **(R4/1604A)**

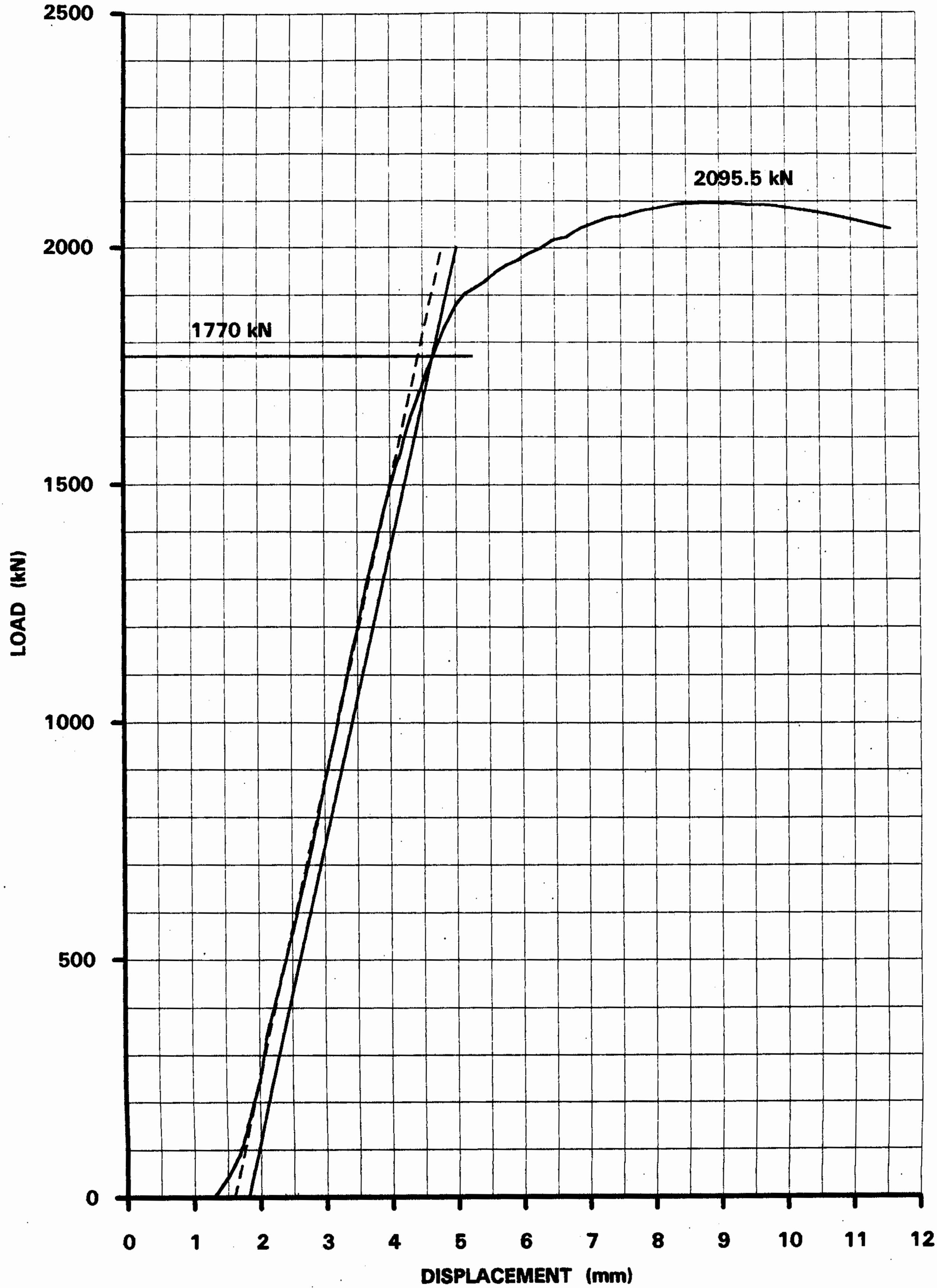


FIG. A1.4 LOAD / DISPLACEMENT CURVE FOR THE FULL SECTION SQUASH TEST

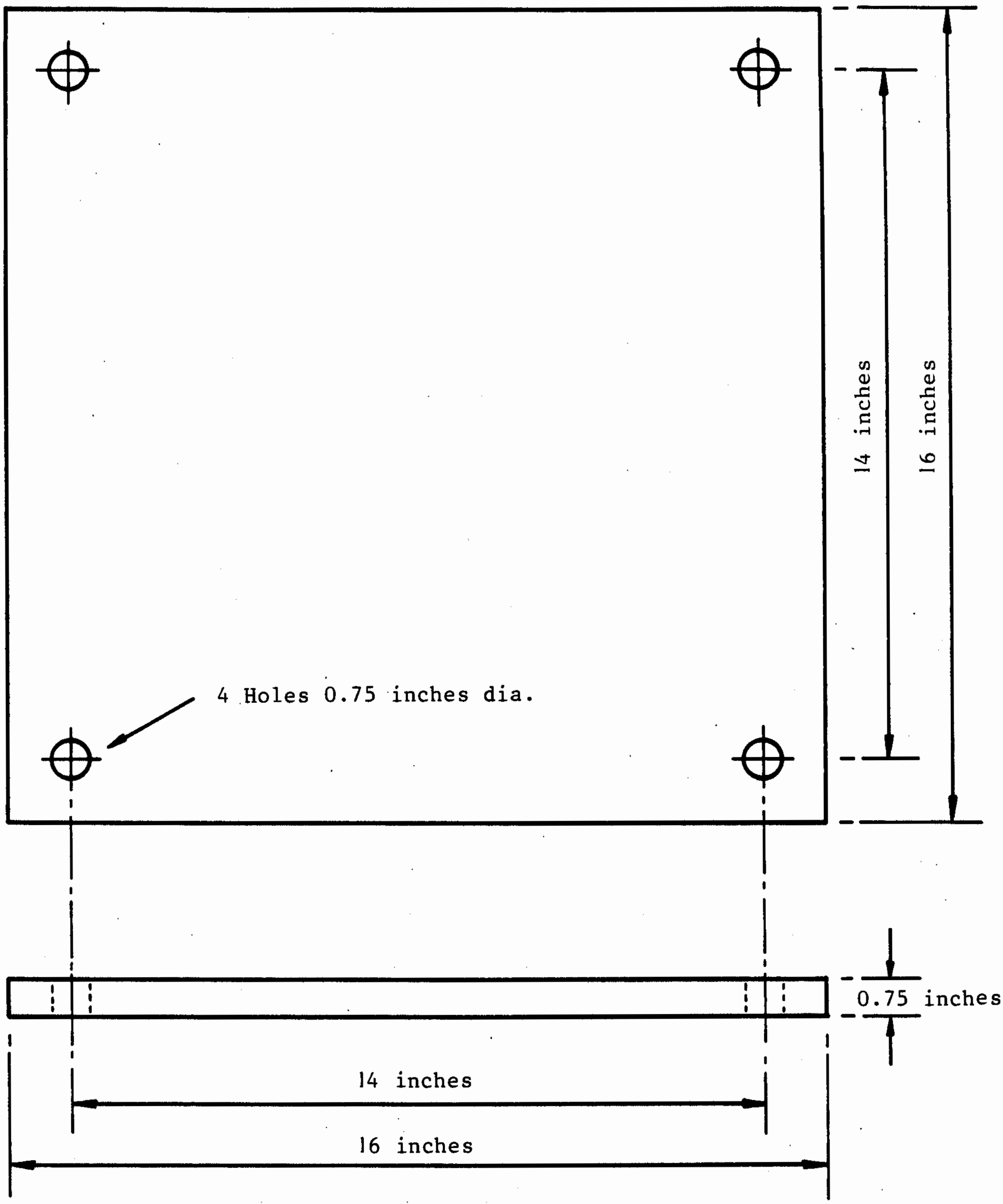


FIG. A1.5 DIMENSIONAL DETAILS OF THE TOP AND BOTTOM END PLATES (R3/94 14)

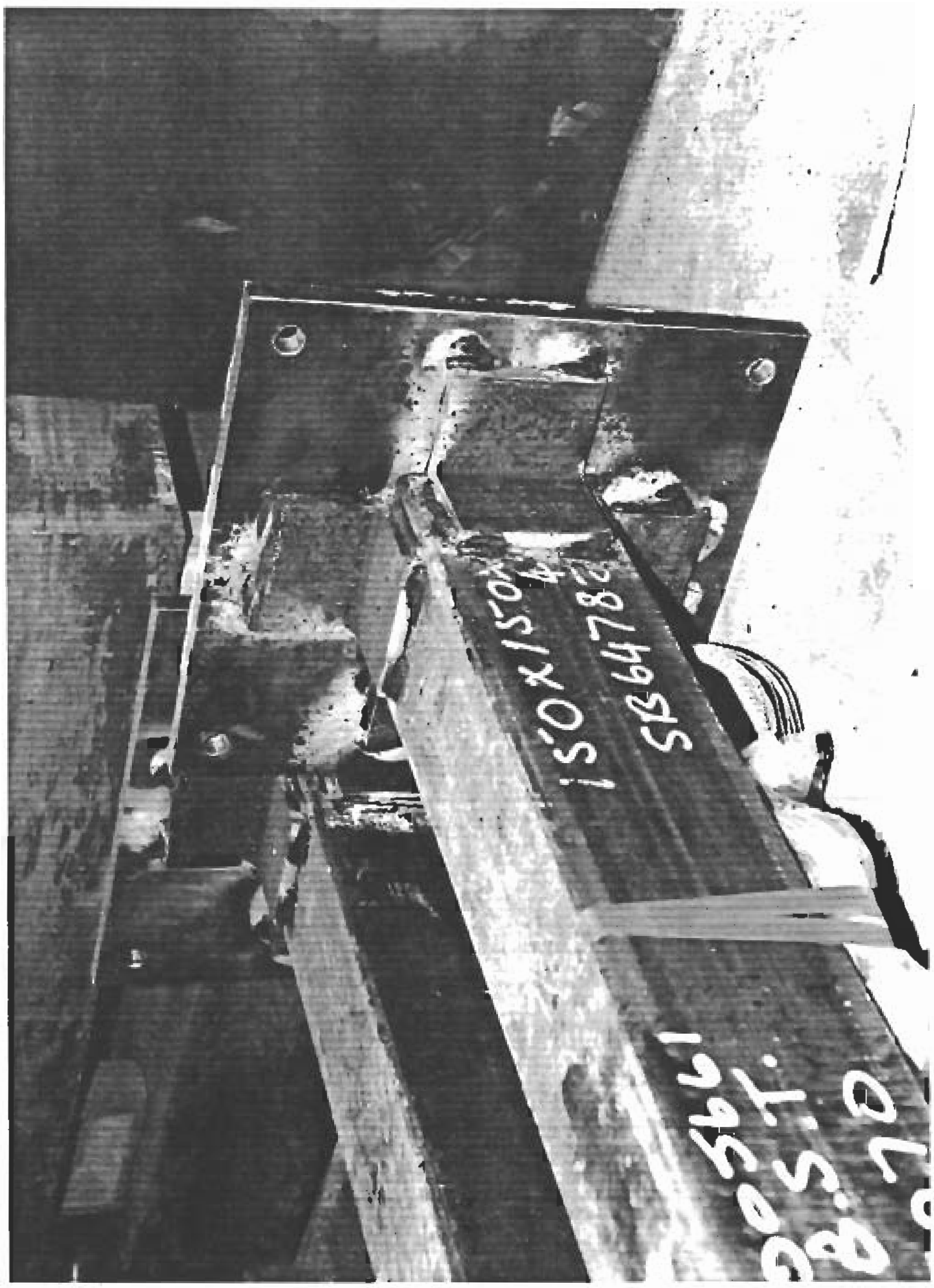


FIG. A1.6 ARRANGEMENT FOR ATTACHING BEARING PLATES AT ENDS OF TEST COLUMNS

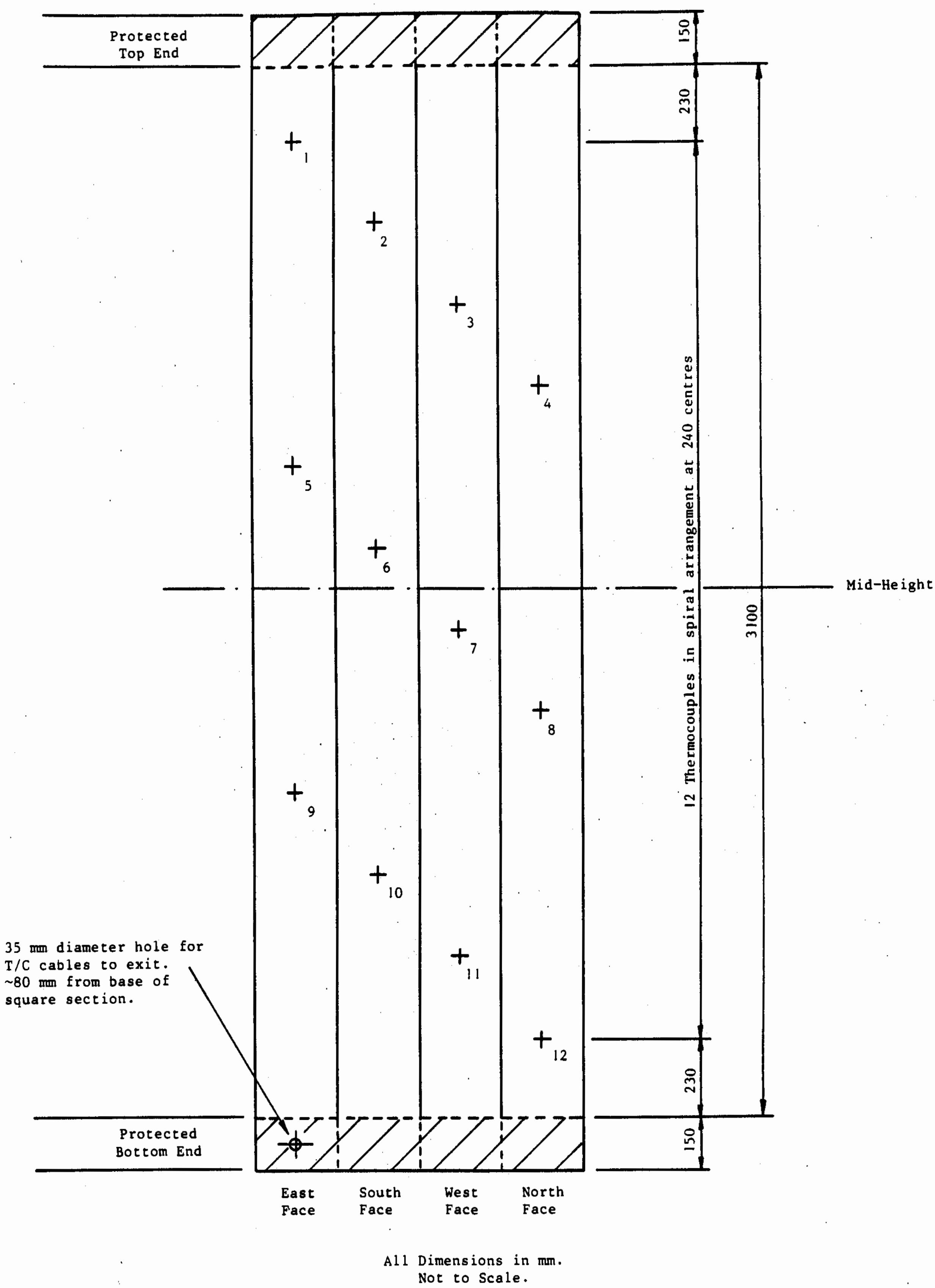


FIG. A1.7 **THERMOCOUPLE POSITIONS ON 150 × 150 × 8 mm COLD FORMED SHS COLUMNS** **(R4/1605)**

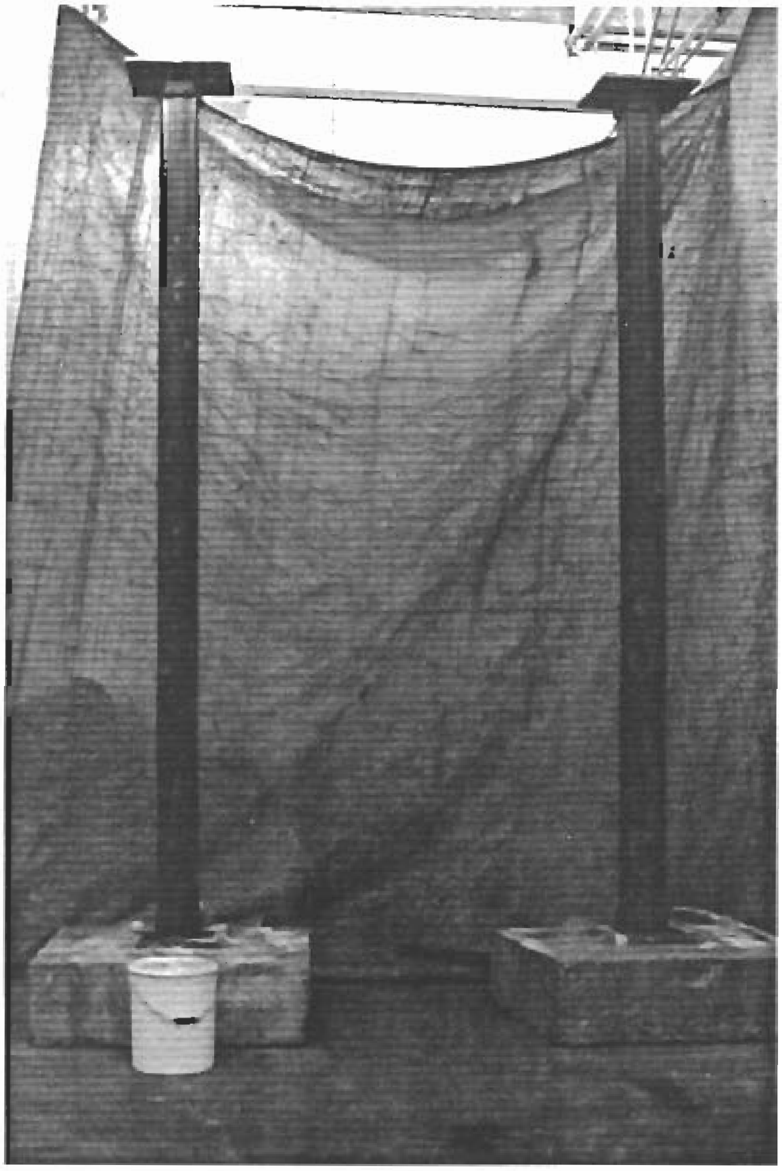
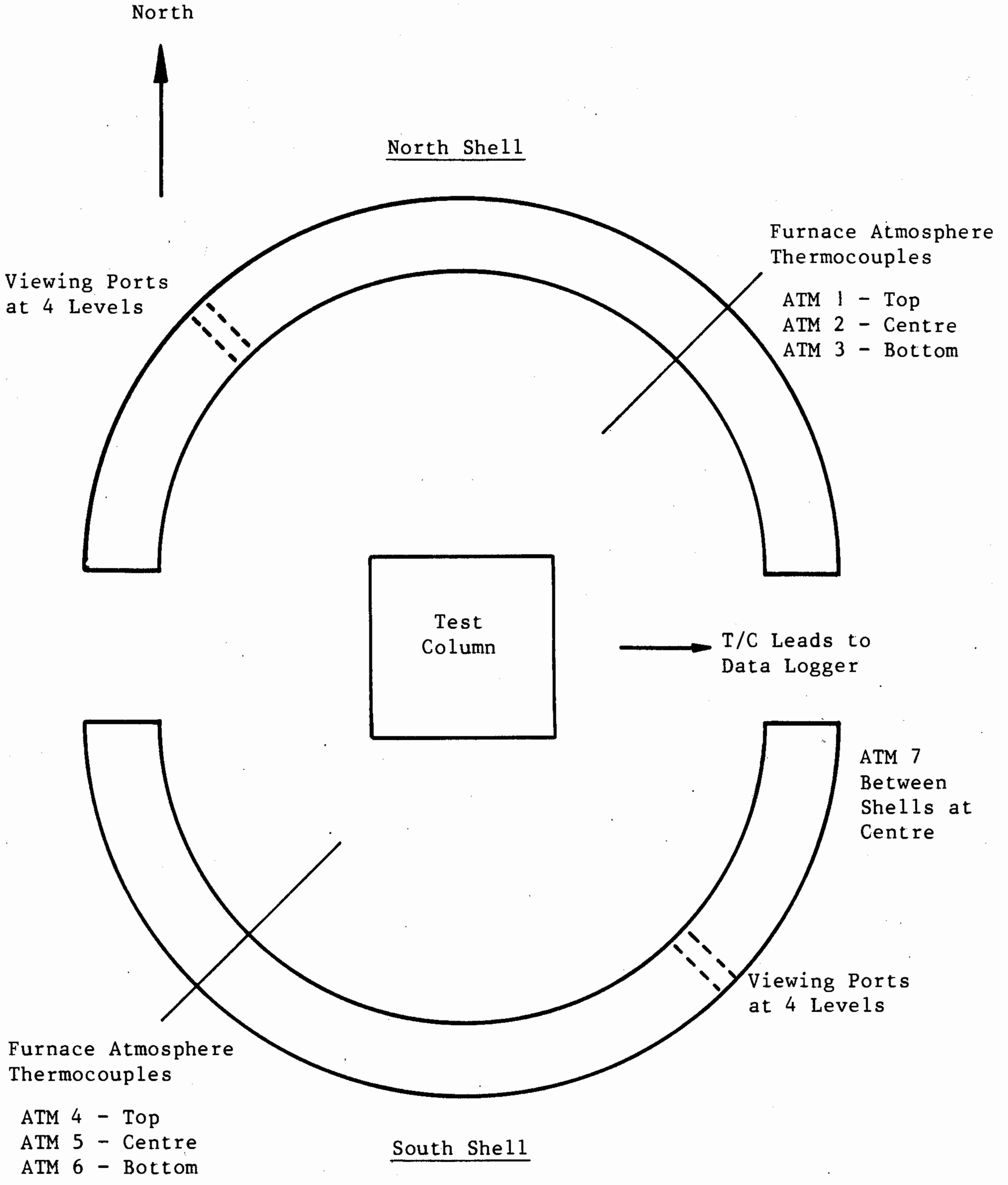


FIG. A1.8 COLUMNS SET UP READY FOR THE APPLICATION OF THE FIRE PROTECTION MATERIAL

(PHOTOGRAPH COURTESY OF MANDOVAL COATINGS LTD.)



Furnace Shells Shown Separated.

FIG. A1.9 LPC COLUMN TEST FURNACE - POSITION AND ORIENTATION OF MAJOR COMPONENTS (R3/9417)

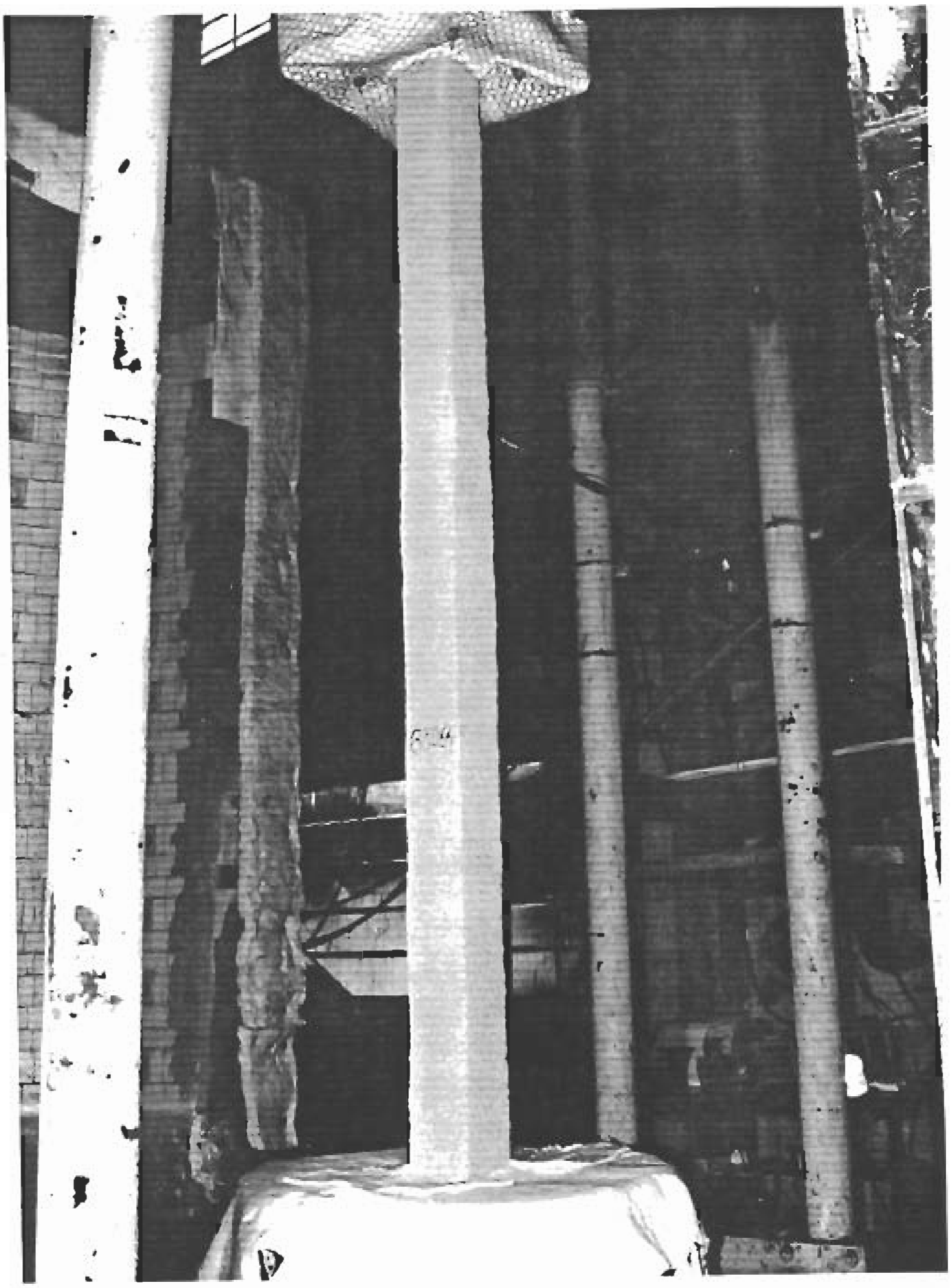


FIG. A1.10 COLUMN INSTALLED IN THE FURNACE PRIOR TO TESTING

APPENDIX 2

DETAILED EXPERIMENTAL RESULTS - 1ST COLUMN TEST

A2.1 TEST NO. LPC 83064

The test was carried out in accordance with Section 6 of BS 476:Part 21:1987 at the LPC, Borehamwood, on 16th February 1993.

The column supported the full test load of 1060 kN for a period of 73.5 minutes, at which time the load was reduced to a pinch value. The test was terminated after a total heating period of 76 minutes. In accordance with the provisions of BS 476:Part 21 the fire resistance rating of the test assembly was therefore 73 minutes.

A2.1.1 Temperature Measurements

A2.1.1.1 Atmosphere Data

The temperatures recorded by the seven thermocouples monitoring the furnace atmosphere are presented in Table A2.1. The table also gives the mean furnace atmosphere temperatures and the corresponding BS 476 standard heating curve values. The individual thermocouple data are shown plotted in Figs. A2.1(a) to A2.1(g) which also include the BS 476 standard heating curve. It may be seen that of the seven traces only two, (ATM4 and ATM5), show reasonably good agreement between the actual and aim values. In the case of ATM's 1, 2 and 7 the tendency is for the recorded values to exceed the aim values throughout most, if not all, of the test. Initially this is also the case with ATM3 although agreement with the aim values improves after about 50 minutes into the test. The trace for ATM6 shows very poor agreement with the aim values, the recorded temperatures being much lower throughout the entire test. These deviations from the standard curve were also evident in the temperature data recorded by the LPC and were brought to their attention by the British Steel personnel present at the time. The effect of such marked variations in temperature distribution within the furnace may well influence the temperature profile for the steelwork, (see Section A2.1.1.2).

In Fig. A2.2 the average furnace atmosphere temperature is compared with the BS 476 time / temperature curve. This plot gives a quite different impression of the accuracy to which the furnace temperature was controlled. Apart from a period between about 30 and 45 minutes during which the temperature rose slightly above the standard curve there appears to be very close agreement between the actual and aim values. However, all that the graph shows is that the higher than aim values recorded by ATM's 1, 2, 3 and 7 have been effectively cancelled out by the very low values recorded by ATM6.

A2.1.1.2 Steelwork Data

The temperature data from the twelve thermocouples embedded in the steelwork are presented in Table A2.2 and are shown graphically in Fig. A2.3. From this plot it may be seen that three of the thermocouples have given responses which do not follow the trends set by the other nine. These are T/C's 2, 7 and 8. In the case of T/C2 it appears to have performed satisfactorily during the first 48 minutes of the test but thereafter its output became erratic. The values recorded after this time should therefore be disregarded. Thermocouple 8 also appears to have performed satisfactorily during the first 30 minutes of the test but the values recorded thereafter are untypical and are not consistent with its position in the steel section. A possible explanation for this could be that the thermocouple became detached from the steelwork at this time and fell into the cavity of the section, where it continued to record the air temperature. Again the values recorded after 30 minutes should be disregarded. The graph also reveals an inflexion in the data which is similar to the normal moisture plateau but occurring at a lower temperature of around 86/87°C. Thermocouple 7 shows a totally untypical response and the values recorded by it should also be disregarded. The trace shows no evidence of a moisture plateau and this tends to suggest that the couple may not have been in contact with the steelwork. As with T/C8 it was probably located somewhere in the cavity of the section, but this is only speculative. The remaining nine thermocouples all show a similar type of response with a moisture plateau at around 100°C. The temperatures at the conclusion of the test generally reflect the thermocouple positions within the column with the hottest part being the upper middle quarter. Thermocouple 12, situated near the bottom end of the column, recorded the lowest final temperature of 428°C, (disregarding T/C's 2, 7 and 8). This was 49 Centigrade degrees cooler than the next highest value, (T/C11). To what extent this is a reflection of the low atmosphere temperature in this area, (ATM6), is difficult to assess.

At 'failure', (73 minutes), the mean temperature of the hottest portion of the steel section, derived from T/C's 3, 4, 5 and 6, was approximately 516°C. The highest individual value recorded at this time was 524°C by T/C3. The length of column containing measurement positions 3-6 was noted to be that over which deformation, (bowing), was concentrated, (see Section A2.1.3.2).

A2.1.2 Column Extension Data

The longitudinal extension of the column, as indicated by the linear displacement transducer, and logged by the LPC, is presented in Table A2.3. The data are shown plotted in Fig. A2.4. The maximum extension under load was 15.7 mm. This occurred 60 minutes from the commencement of the test and was maintained until the 63rd minute after which time the column began to contract. It regained its original length between 73.0 and 73.5 minutes.

A2.1.3 General Observations

A2.1.3.1 During the Test

The following observations were recorded during the conduct of the test.

Time min / seconds	Event / Observation
-24.00	- Load of 1060 kN applied to the column. - Displacement transducer set to zero.
00.00	- Test commenced.
10.00	- Column visible inside the furnace.
16.00	- Corners of fire protection beginning to glow dull red.
30.00	- Corners now glowing brightly.
45.00	- A number of dark spots are evident on the surface of the fire protection. Possibly associated with holes made by the depth gauge used to check the coating thickness.
54.00	- No evidence of any cracking in the fire protection. - All surfaces radiating brightly.
60.00	- Column extension reaches a maximum value of 15.7 mm.
63.30	- Column begins to contract.
73.00	- Difficult to maintain the load. - Column length almost at its original value.
73.30	- Column unable to support the load. - Column length less than its original value. - Load reduced to a pinch value.
74.00	- Load removed.
76.00	- Test terminated.

A2.1.3.2 Subsequent to the Test

The furnace was opened up within a few minutes of the test being terminated. At this time it was noted that the fire protection material was still intact over all four faces of the steel section. Some cracking of the coating surface had occurred but this was generally of a minor nature and was not unexpected. Figures A2.5 to A2.7 are general views of the column, after cooling, taken from the South, West and North West positions respectively. These give an overall indication of the extent to which the column deformed during the final few minutes of the test. It was noted that bowing had occurred principally in the East-West direction. Some deformation in the North-South direction had also taken place but, by comparison, was only slight. The actual extent of the deformation was not recorded. Figure A2.8 shows the column after removal from the test furnace and with the protection material removed from the deformed area. A portion of the fire protection containing a typical surface crack is shown in Fig. A2.9. A more detailed examination of the column indicated that deformation, (bowing), was concentrated in the region between approximately 1700 mm and 2600 mm from the true base of the section, i.e. in the portion covered by thermocouples T/C3-T/C6 inclusive. This is consistent with the recorded thermal data, (Section A2.1.1.2), which indicates that, at failure, this was the hottest part of the section.

TABLE A2.1
FURNACE ATMOSPHERE TEMPERATURE DATA - LPC 83064

TIME MINS	ISO TEMP	ATM 1	ATM 2	ATM 3	ATM 4	ATM 5	ATM 6	ATM 7	ATM MEAN
0	20	59	58	62	57	33	14	30	45
1	349	326	313	284	296	291	191	306	287
2	445	451	454	452	394	427	325	441	421
3	502	506	499	508	446	475	387	479	471
4	544	573	608	585	545	564	420	549	549
5	576	594	632	602	586	588	442	572	574
6	603	617	653	665	600	611	494	593	605
7	626	627	662	672	614	619	503	607	615
8	645	659	684	706	631	653	543	624	643
9	663	686	702	712	651	686	571	648	665
10	678	686	702	725	669	688	590	659	674
11	693	716	701	729	689	675	602	687	686
12	705	764	760	760	722	745	610	753	731
13	717	766	753	765	731	732	610	754	730
14	728	774	757	768	737	740	625	760	737
15	739	778	762	771	743	743	628	770	742
16	748	784	768	778	747	748	634	771	747
17	757	799	780	783	757	757	643	787	758
18	766	806	787	791	771	783	647	799	769
19	774	813	794	795	773	789	654	804	775
20	781	818	794	801	784	786	661	813	780
21	789	826	807	817	792	799	687	821	793
22	796	834	815	823	797	805	687	828	798
23	802	838	820	827	805	813	695	834	805
24	809	844	826	834	808	814	702	835	809
25	815	850	827	837	813	818	714	845	815
26	820	857	833	842	819	827	717	850	821
27	826	859	836	846	825	827	731	854	825
28	832	864	841	847	829	836	730	859	829
29	837	867	845	852	833	837	738	864	834
30	842	876	866	873	842	849	761	867	848
31	847	889	883	886	850	869	772	874	860
32	851	894	889	891	858	873	781	879	866
33	856	899	892	891	862	875	785	883	870
34	860	903	896	896	867	881	792	889	875
35	865	906	897	903	873	879	802	894	879
36	869	911	905	900	876	892	801	900	884
37	873	914	909	910	880	896	808	902	888
38	877	920	911	912	885	895	809	907	891
39	881	921	913	906	887	896	806	907	891
40	885	923	914	906	890	902	808	910	893
41	888	927	920	909	895	901	813	911	897
42	892	928	919	911	899	906	817	913	899
43	896	929	917	905	900	904	810	916	897
44	899	933	920	910	903	906	809	920	900
45	902	934	922	912	905	909	815	920	902
46	906	938	923	911	907	910	821	923	905
47	909	940	927	918	912	914	821	923	908
48	912	944	930	915	915	918	827	928	911
49	915	945	930	920	916	922	827	931	913
50	918	950	935	922	920	922	833	932	916
51	921	951	936	919	923	925	830	936	917
52	924	954	939	926	923	927	831	937	920
53	927	955	939	927	927	928	840	941	922
54	930	958	942	931	929	930	839	941	924
55	932	960	947	932	932	935	841	943	927
56	935	963	946	932	934	936	848	947	929
57	938	964	948	934	935	937	848	949	931
58	940	966	952	938	942	944	852	950	935
59	943	969	953	941	946	943	859	954	938
60	945	973	960	941	949	945	858	957	940

(continued)

TABLE A2.1
(continued)

TIME MINS	ISO TEMP	ATM 1	ATM 2	ATM 3	ATM 4	ATM 5	ATM 6	ATM 7	ATM MEAN
61	948	978	965	952	954	947	865	959	946
62	950	982	967	954	957	950	871	965	949
63	953	984	970	957	958	954	868	967	951
64	955	987	975	959	964	962	875	974	957
65	957	991	982	963	967	965	879	974	960
66	960	993	984	970	970	971	877	978	963
67	962	997	984	965	973	969	881	980	964
68	964	998	985	970	975	971	887	982	967
69	966	999	986	973	976	973	886	987	969
70	968	1002	989	973	979	976	889	989	971
71	971	1004	990	974	981	976	889	990	972
72	973	1007	990	976	984	972	891	992	973
73	975	1009	987	981	986	984	894	996	977
74	977	1012	991	984	989	986	895	1000	980
75	979	1018	998	998	992	990	900	999	985
76	981	1020	1000	1000	994	996	900	1000	987

TABLE A2.2
TEMPERATURES RECORDED IN THE STEELWORK - LPC 83064

TIME MINS	T/C 01	T/C 02	T/C 03	T/C 04	T/C 05	T/C 06	T/C 07	T/C 08	T/C 09	T/C 10	T/C 11	T/C 12
0	10	10	10	10	10	10	10	10	10	9	9	9
1	10	10	10	10	10	10	10	10	10	9	9	9
2	10	10	10	10	10	10	10	10	10	9	9	9
3	12	11	11	10	10	10	10	10	10	9	9	9
4	16	14	14	12	13	13	10	11	14	11	10	10
5	20	19	18	15	16	16	11	14	18	16	13	13
6	26	24	23	20	21	21	13	19	23	21	17	17
7	32	30	28	25	26	27	16	23	28	26	22	22
8	38	36	34	31	32	33	19	28	34	31	27	27
9	45	42	40	36	37	38	21	33	40	36	32	32
10	52	49	46	42	43	44	25	40	46	41	37	37
11	59	56	53	49	49	50	28	45	51	47	43	42
12	66	63	59	55	56	56	32	50	58	53	49	47
13	73	70	66	61	62	63	35	56	64	59	55	52
14	81	78	74	68	70	70	39	62	71	65	61	58
15	88	85	81	75	76	77	43	65	78	71	67	63
16	94	92	89	82	84	84	48	72	84	77	73	69
17	98	97	95	89	90	91	52	77	90	83	79	75
18	100	99	98	95	96	96	55	82	94	89	85	81
19	104	101	100	98	99	99	58	86	97	93	91	86
20	111	108	104	100	100	100	60	87	99	96	95	90
21	118	116	112	101	104	102	64	87	104	98	98	94
22	127	124	120	108	110	110	68	90	111	99	99	97
23	135	133	128	116	118	118	73	97	118	104	102	98
24	143	142	137	125	127	127	77	103	126	111	107	101
25	152	152	146	134	135	136	82	109	134	119	114	108
26	160	161	155	143	144	145	87	118	142	127	121	115
27	169	170	164	152	153	154	92	123	150	135	129	122
28	177	179	174	161	162	163	97	129	158	143	137	129
29	186	188	183	170	171	172	102	138	166	151	145	136
30	195	197	192	180	180	181	108	144	175	160	153	143
31	203	206	201	189	189	190	113	148	183	168	161	151
32	211	215	210	198	198	199	119	155	191	176	170	158
33	220	225	220	208	207	207	125	161	200	185	178	165
34	228	234	229	217	216	216	131	166	208	193	186	173
35	237	243	238	226	225	225	138	172	217	202	195	180
36	245	252	247	235	234	234	144	178	226	210	203	188
37	253	261	257	245	243	243	151	182	235	219	212	195
38	261	270	266	254	252	252	158	187	243	227	220	202
39	269	279	275	263	261	261	165	195	252	236	228	210
40	277	287	284	272	270	270	172	201	260	244	237	217
41	285	296	292	281	279	278	179	207	269	253	245	225
42	293	304	301	290	288	287	186	212	277	261	253	232
43	300	313	310	298	296	295	193	218	286	269	261	239
44	307	321	319	307	305	304	200	222	294	278	269	246
45	315	329	327	316	313	312	207	227	302	285	277	253
46	322	337	335	324	322	320	213	231	310	293	285	260
47	329	345	344	332	330	328	220	236	318	301	292	266
48	336	353	352	341	338	336	227	241	326	309	299	273
49	343	348	360	349	346	344	234	246	334	316	307	280
50	350	355	368	357	354	352	240	251	341	324	314	286
51	356	374	376	365	362	360	247	255	349	332	321	292
52	363	330	383	372	370	368	253	260	356	339	328	298
53	369	322	391	380	377	375	260	264	364	346	335	304
54	375	304	398	388	385	383	266	268	371	353	343	311
55	382	300	406	395	392	390	272	272	378	360	349	317
56	388	306	413	403	400	397	278	276	385	368	356	323
57	394	317	420	410	407	404	283	280	392	374	363	328
58	399	317	427	417	414	412	289	284	399	381	369	334
59	405	317	434	424	421	419	295	288	406	388	376	340
60	411	321	441	431	428	425	301	293	413	395	382	346

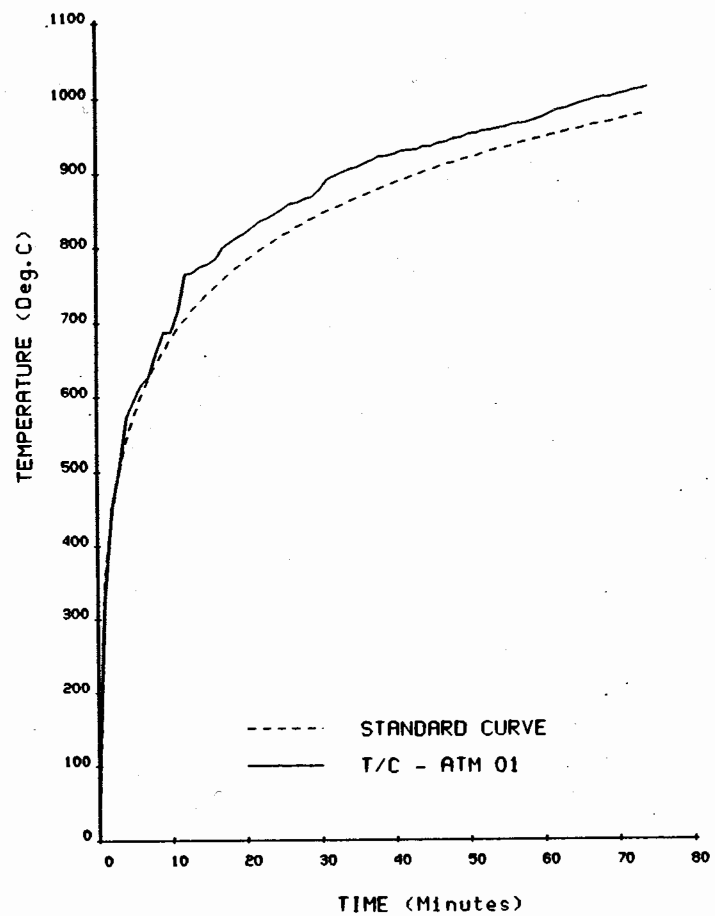
(continued)

TABLE A2.2
(continued)

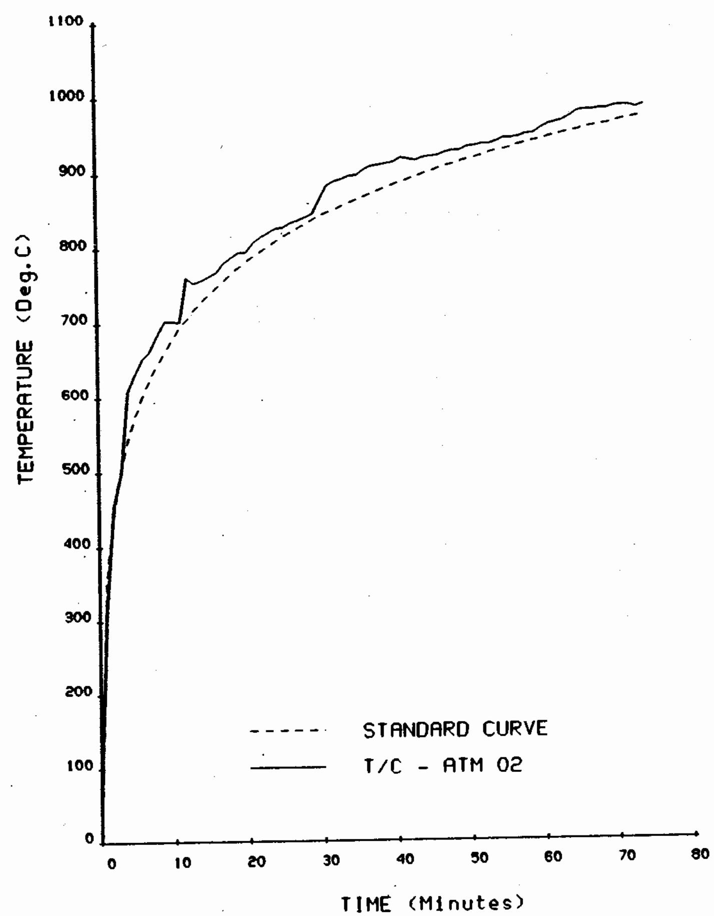
TIME MINS	T/C 01	T/C 02	T/C 03	T/C 04	T/C 05	T/C 06	T/C 07	T/C 08	T/C 09	T/C 10	T/C 11	T/C 12
61	417	328	448	438	435	432	306	297	420	402	389	351
62	422	332	455	445	442	439	312	301	426	408	395	357
63	428	336	461	452	449	446	318	305	433	414	401	362
64	433	348	468	459	455	453	323	310	439	421	408	368
65	439	358	474	465	462	459	329	314	446	428	414	373
66	444	369	481	472	469	466	335	318	452	434	420	378
67	450	402	487	478	475	472	341	323	459	440	426	383
68	455	409	494	485	482	479	346	329	465	447	432	389
69	460	418	500	491	488	485	352	335	471	453	438	394
70	465	419	506	498	494	491	357	342	478	459	444	399
71	470	437	512	504	501	498	362	349	484	465	449	404
72	475	402	518	510	507	504	368	358	490	471	455	409
73	480	391	524	516	513	510	377	349	495	477	461	414
74	485	390	529	522	518	516	379	350	501	482	466	419
75	489	392	535	527	524	521	383	354	507	488	471	423
76	494	396	541	533	530	527	388	358	512	494	477	428

TABLE A2.3
DEFLECTION DATA RECORDED DURING EACH OF THE FIRE TESTS

TIME MINS	DEFLECTION (mm) 83064	83065
0.0	0.00	0.00
0.5	0.00	0.00
1.0	0.00	0.00
1.5	0.00	0.00
2.0	0.10	0.00
2.5	0.10	0.00
3.0	0.10	0.10
3.5	0.10	0.10
4.0	0.30	0.10
4.5	0.30	0.20
5.0	0.40	0.30
5.5	0.40	0.40
6.0	0.60	0.60
6.5	0.70	0.70
7.0	0.80	0.70
7.5	1.00	0.80
8.0	1.10	0.80
8.5	1.10	0.90
9.0	1.20	1.00
9.5	1.30	1.20
10.0	1.40	1.30
10.5	1.50	1.40
11.0	1.60	1.50
11.5	1.70	1.60
12.0	1.80	1.70
12.5	2.00	1.80
13.0	2.10	1.90
13.5	2.20	2.10
14.0	2.40	2.20
14.5	2.50	2.40
15.0	2.60	2.50
15.5	2.70	2.70
16.0	2.80	2.80
16.5	3.00	2.90
17.0	3.10	3.00
17.5	3.20	3.10
18.0	3.30	3.20
18.5	3.40	3.30
19.0	3.50	3.30
19.5	3.50	3.40
20.0	3.60	3.50
20.5	3.60	3.50
21.0	3.70	3.60
21.5	3.80	3.70
22.0	3.80	3.80
22.5	3.90	4.00
23.0	4.10	4.20
23.5	4.20	4.30
24.0	4.40	4.50
24.5	4.50	4.70
25.0	4.70	4.90
25.5	4.80	5.00
26.0	5.00	5.20
26.5	5.10	5.30
27.0	5.50	5.50
27.5	5.70	5.60
28.0	5.80	5.90
28.5	6.00	6.00
29.0	6.20	6.20
29.5	6.30	6.40
30.0	6.50	6.60
30.5	6.60	6.80
31.0	6.80	7.00
31.5	6.90	7.10
32.0	7.20	7.30
32.5	7.50	7.50
33.0	7.60	7.70
33.5	7.80	7.80
34.0	8.00	7.90
34.5	8.20	8.20
35.0	8.30	8.50
35.5	8.50	8.60
36.0	8.70	8.80
36.5	8.80	9.00
37.0	9.00	9.20
37.5	9.20	9.30
38.0	9.50	9.50
38.5	9.70	9.70
39.0	9.90	9.90
39.5	10.10	10.00
40.0	10.30	10.20
40.5	10.40	10.40
41.0	10.60	10.60
41.5	10.70	10.80
42.0	11.00	11.00
42.5	11.20	11.10
43.0	11.40	11.30
43.5	11.60	11.50
44.0	11.70	11.60
44.5	11.90	11.80
45.0	12.00	12.10
45.5	12.10	12.30
46.0	12.30	12.50
46.5	12.60	12.50
47.0	12.80	12.60
47.5	12.90	12.70
48.0	13.10	12.90
48.5	13.20	13.10
49.0	13.40	13.30
49.5	13.50	13.50
50.0	13.60	13.60
50.5	13.80	13.80
51.0	13.90	13.90
51.5	14.10	14.00
52.0	14.20	14.20
52.5	14.40	14.30
53.0	14.50	14.40
53.5	14.60	14.60
54.0	14.70	14.70
54.5	14.80	14.80
55.0	14.90	15.00
55.5	15.00	15.10
56.0	15.10	15.20
56.5	15.20	15.30
57.0	15.30	15.50
57.5	15.40	15.60
58.0	15.50	15.70
58.5	15.40	15.90
59.0	15.50	16.00
59.5	15.60	16.10
60.0	15.70	16.20
60.5	15.70	16.30
61.0	15.70	16.40
61.5	15.70	16.40
62.0	15.70	16.50
62.5	15.70	16.60
63.0	15.70	16.60
63.5	15.60	16.70
64.0	15.60	16.70
64.5	15.50	16.80
65.0	15.50	16.90
65.5	15.40	17.00
66.0	15.30	17.00
66.5	15.10	17.10
67.0	15.00	17.10
67.5	14.80	17.20
68.0	14.60	17.20
68.5	14.40	17.20
69.0	14.00	17.30
69.5	13.60	17.30
70.0	13.20	17.30
70.5	12.60	17.30
71.0	11.80	17.30
71.5	10.70	17.30
72.0	9.20	17.30
72.5	6.80	17.30
73.0	3.10	17.30
73.5	-1.60	17.20
74.0		17.20
74.5		17.10
75.0		17.00
75.5		16.80
76.0		16.70
76.5		16.60
77.0		16.40
77.5		16.20
78.0		16.00
78.5		15.80
79.0		15.60
79.5		15.20
80.0		14.70
80.5		14.30
81.0		13.80
81.5		13.20
82.0		12.40
82.5		11.20
83.0		9.70
83.5		7.50
84.0		3.00
84.5		1.50



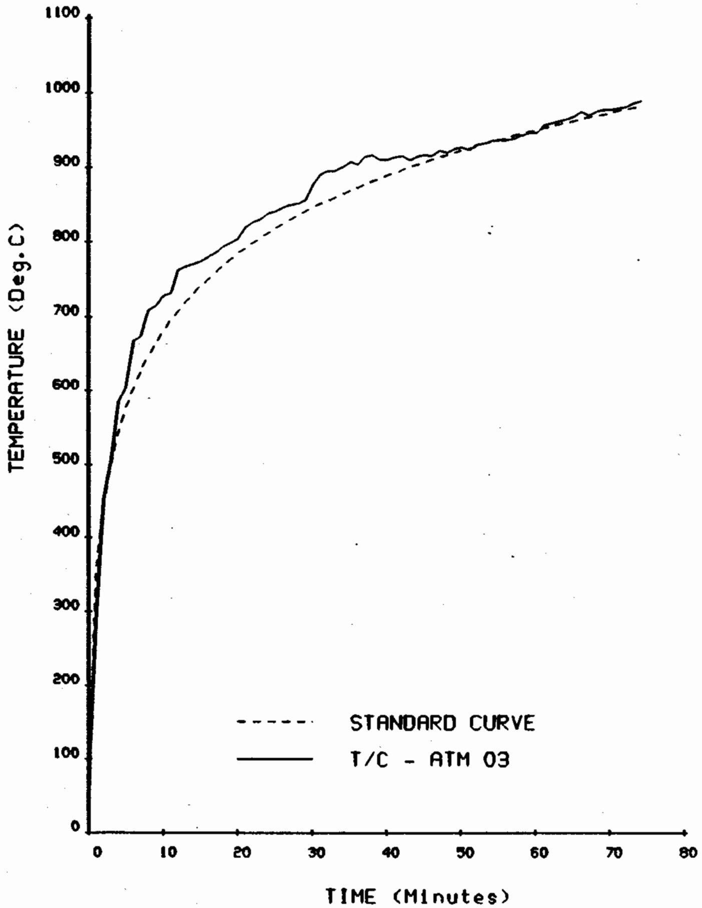
(a) North Shell - Top



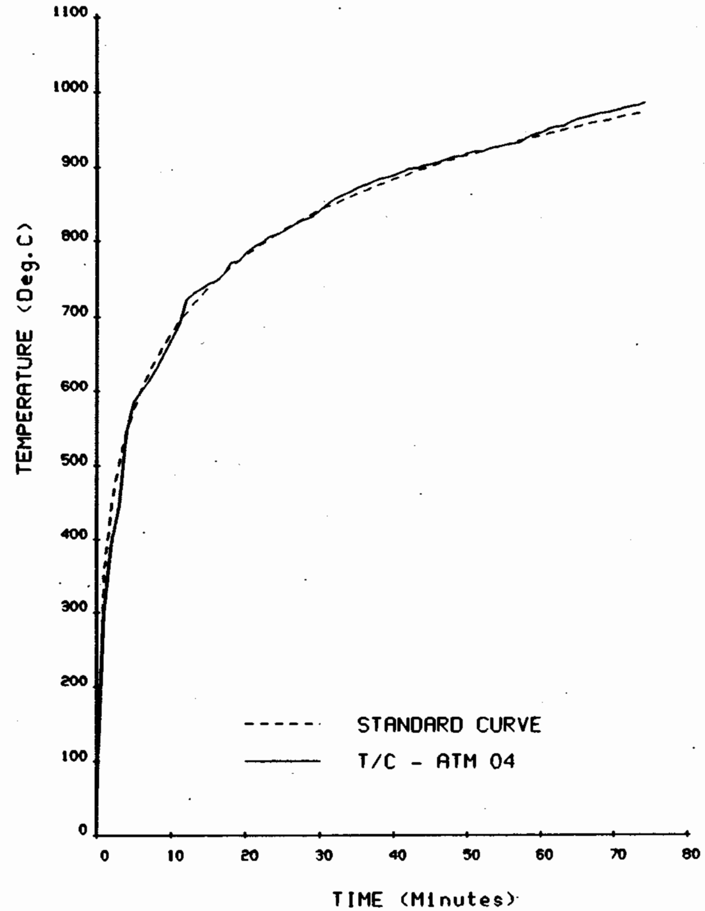
(b) North Shell - Centre

FIG. A2.1a-b COMPARISONS OF INDIVIDUAL FURNACE ATMOSPHERE TEMPERATURES AND THE STANDARD TEMPERATURE / TIME CURVE

TEST NO. LPC 83064



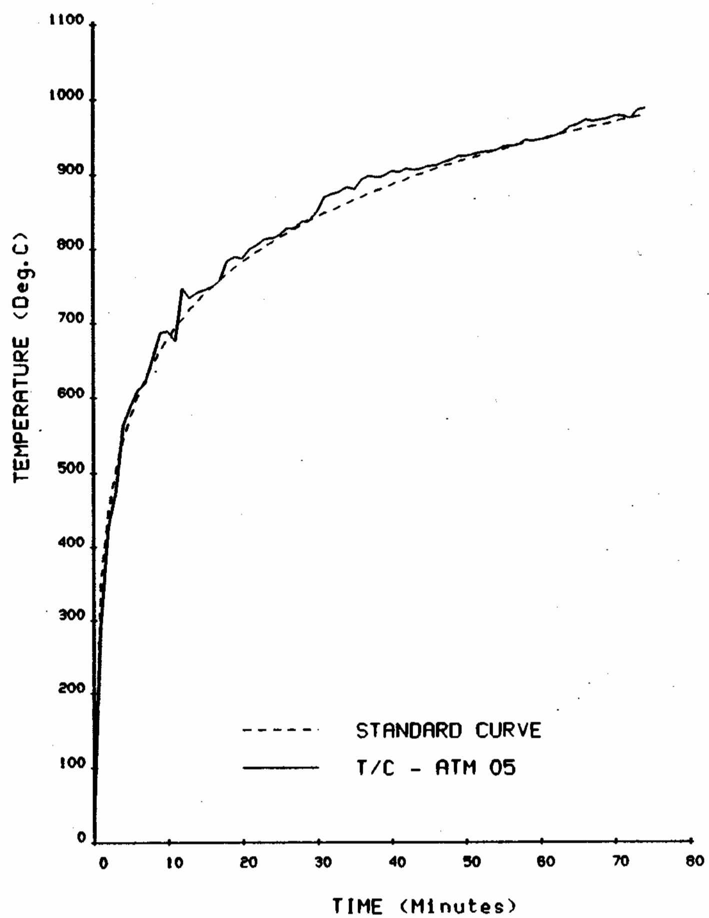
(c) North Shell - Bottom



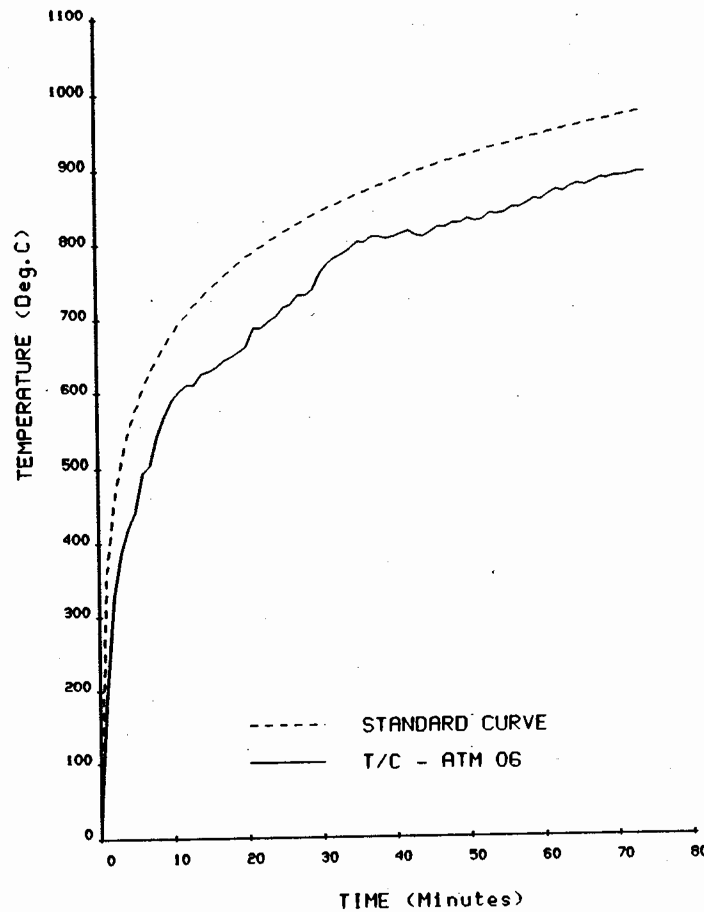
(d) South Shell - Top

FIG. A2.1c-d COMPARISONS OF INDIVIDUAL FURNACE ATMOSPHERE TEMPERATURES AND THE STANDARD TEMPERATURE/TIME CURVE

TEST NO. LPC 83064



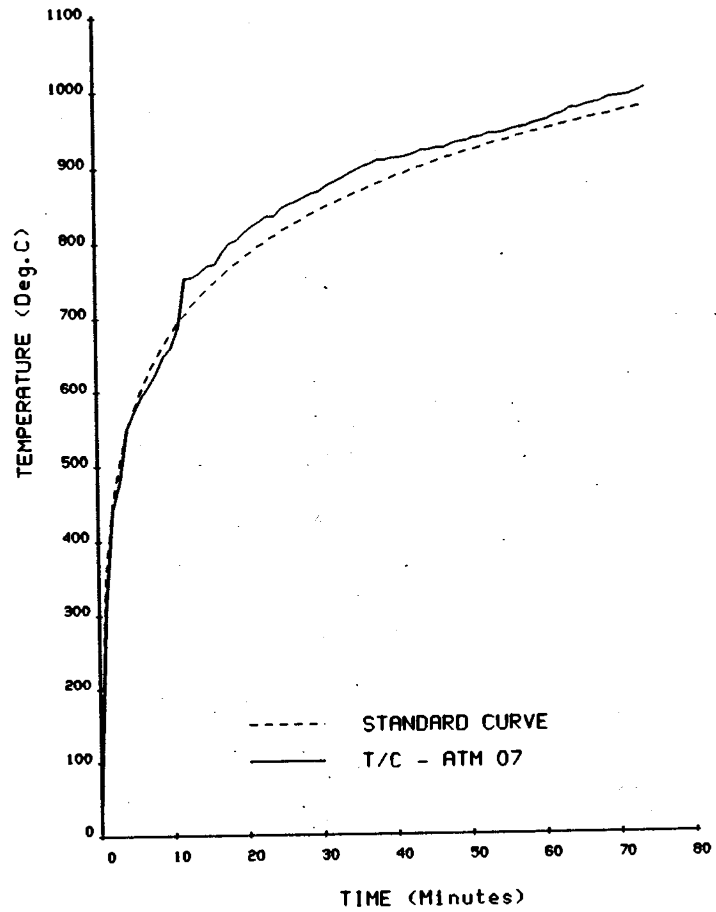
(e) South Shell - Centre



(f) South Shell - Bottom

FIG. A2.1e-f COMPARISONS OF INDIVIDUAL FURNACE ATMOSPHERE TEMPERATURES AND THE STANDARD TEMPERATURE / TIME CURVE

TEST NO. LPC 83064



(g) Between Shells - Centre

FIG. A2.1g **COMPARISONS OF INDIVIDUAL FURNACE ATMOSPHERE TEMPERATURES AND THE STANDARD TEMPERATURE / TIME CURVE**

TEST NO. LPC 83064

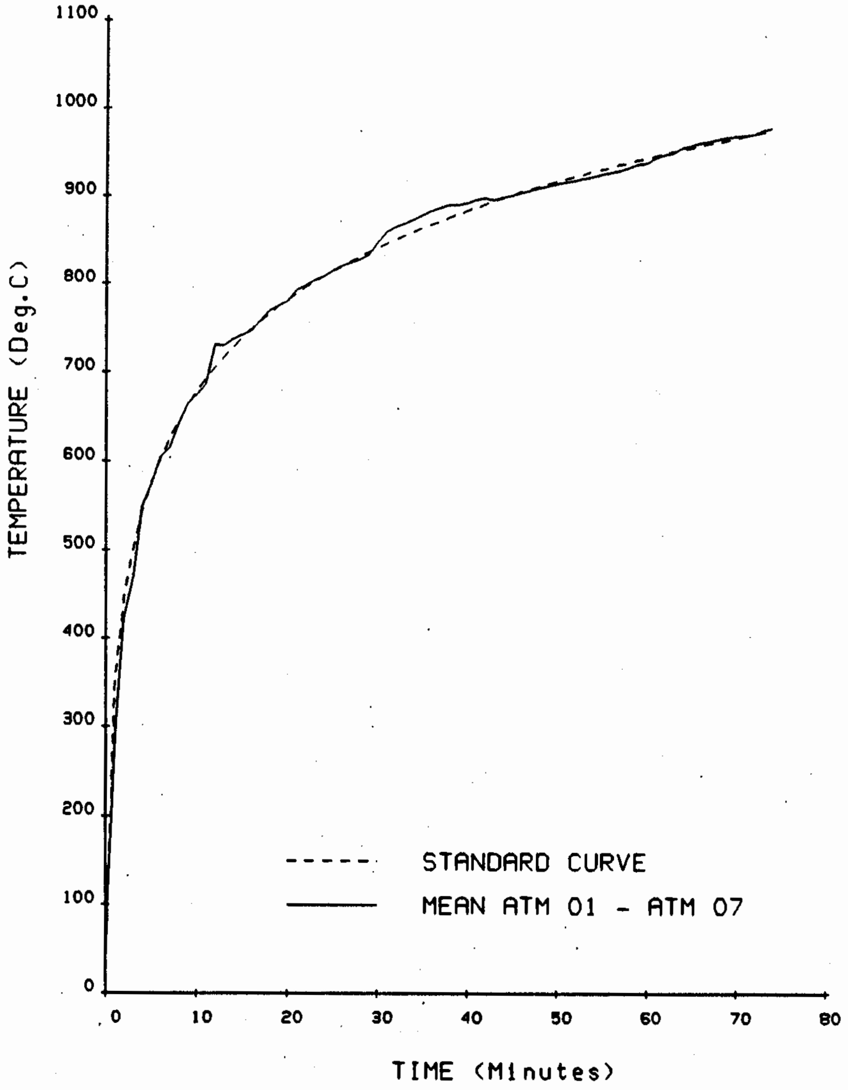


FIG. A2.2 **COMPARISON OF AVERAGE FURNACE ATMOSPHERE TEMPERATURE AND THE STANDARD TEMPERATURE/TIME CURVE**

TEST NO. LPC 83064

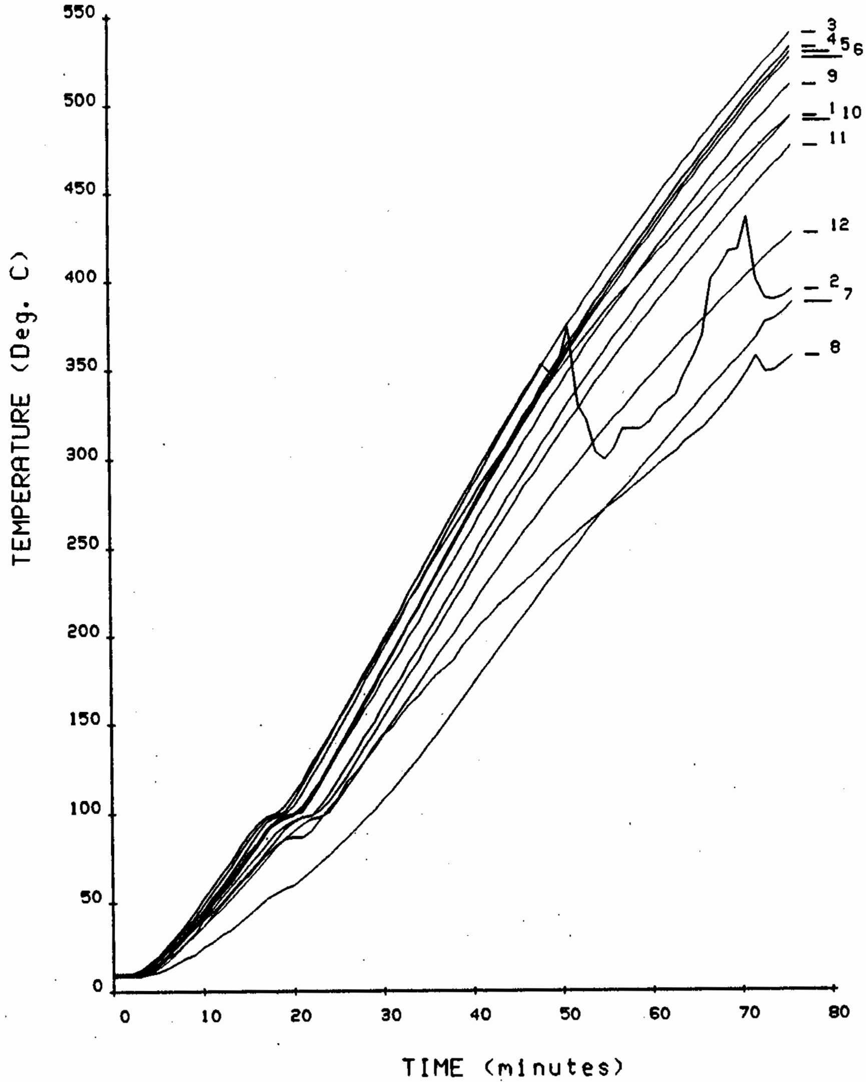


FIG. A2.3 **TEMPERATURES RECORDED IN THE STEELWORK**

TEST NO. LPC 83064

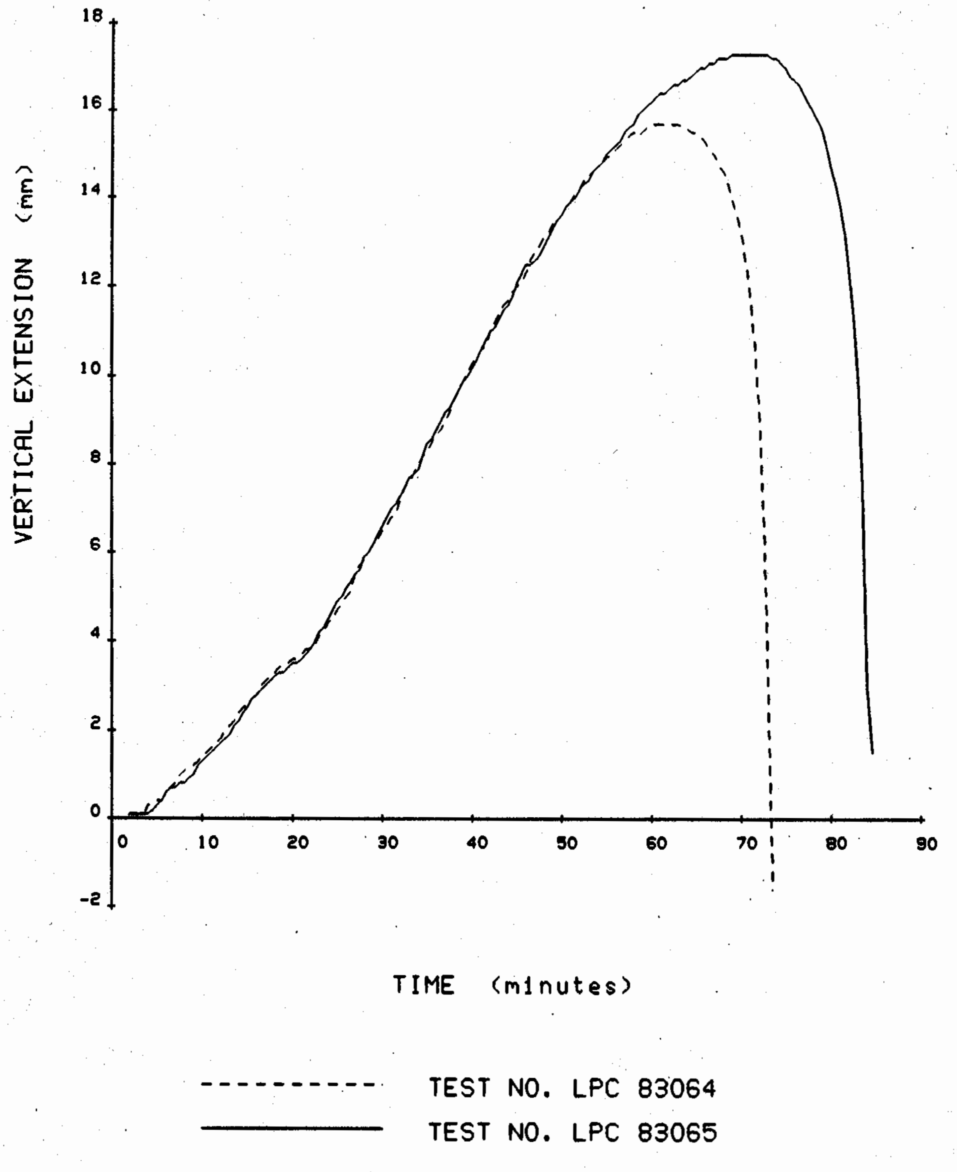


FIG. A2.4 VERTICAL EXTENSION OF THE COLUMNS

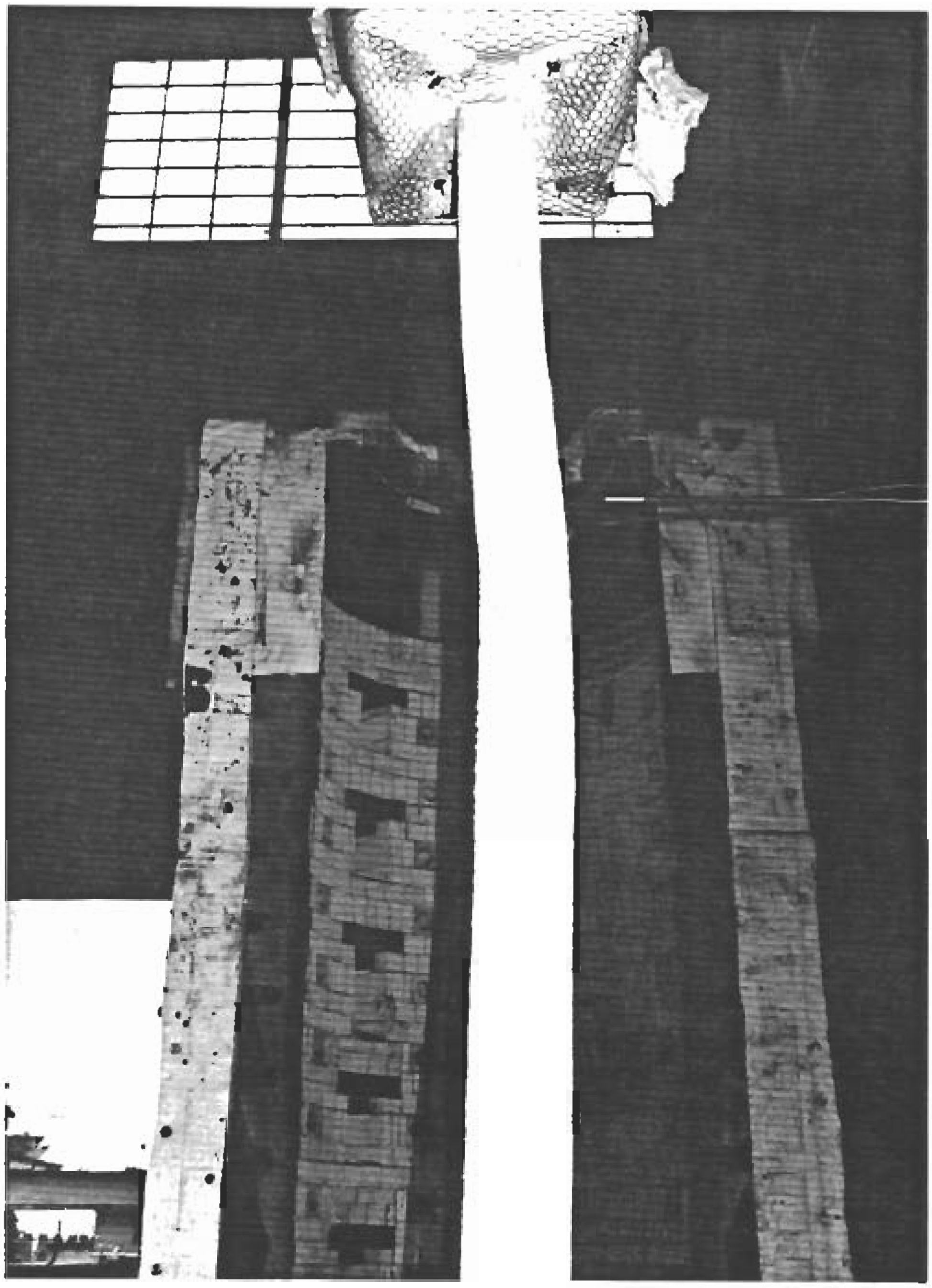


FIG. A2.5 COLUMN AFTER THE TEST, VIEWED FROM THE SOUTH POSITION

TEST NO. LPC 83064

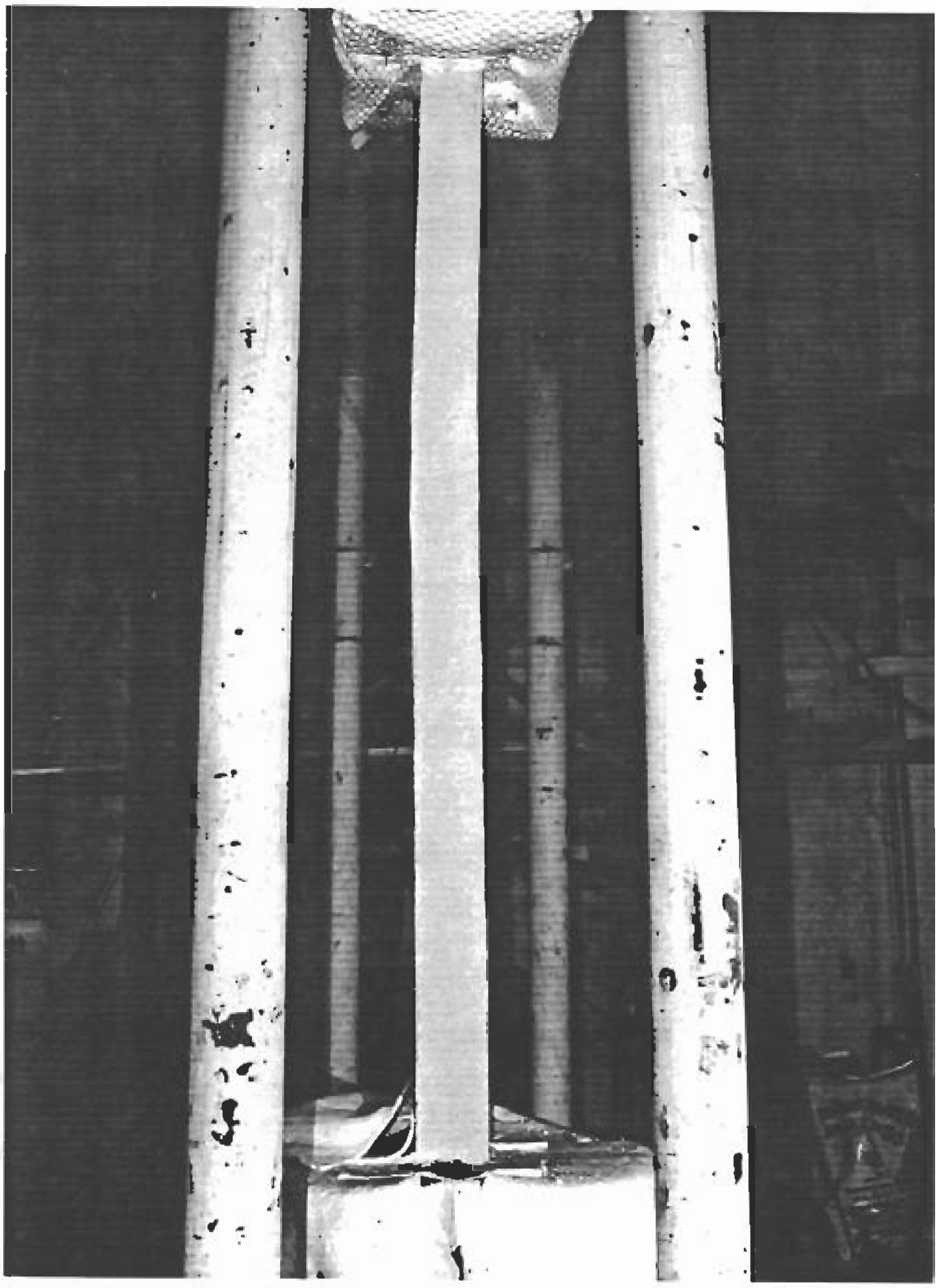


FIG. A2.6 COLUMN AFTER THE TEST, VIEWED FROM THE WEST POSITION

TEST NO. LPC 83064

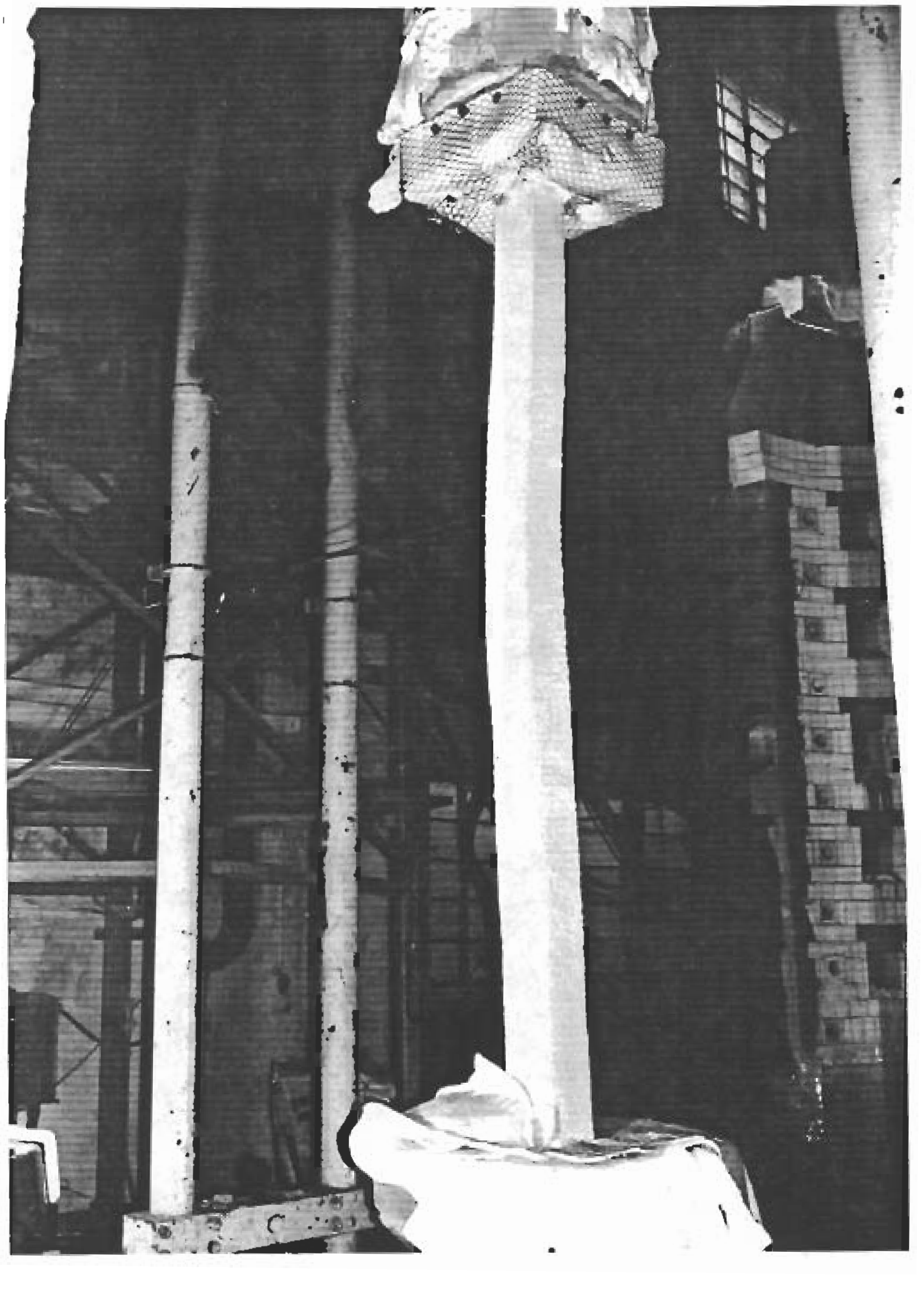


FIG. A2.7 COLUMN AFTER THE TEST, VIEWED FROM THE NORTH WEST POSITION

TEST NO. LPC 83064

FIG. A2.8

COLUMN AFTER REMOVAL FROM THE FURNACE
(FIRE PROTECTION REMOVED FROM DEFORMED AREA)

TEST NO. LPC 83064

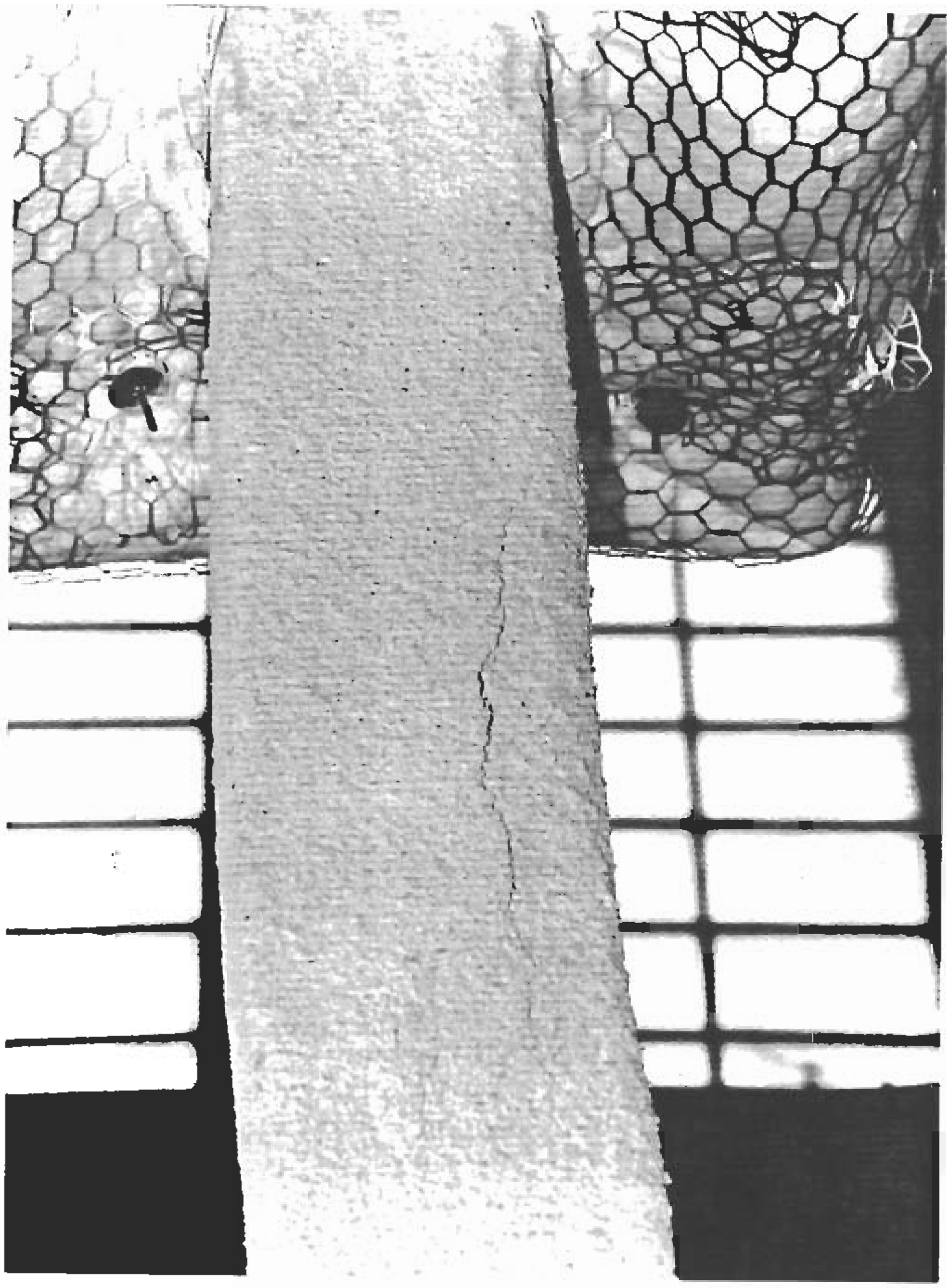


FIG. A2.9 SURFACE CRACKING IN THE FIRE PROTECTION MATERIAL

TEST NO. LPC 83064

APPENDIX 3

DETAILED EXPERIMENTAL RESULTS - 2ND COLUMN TEST

A3.1 TEST NO. LPC 83065

The test was carried out in accordance with Section 6 of BS 476:Part 21:1987 at the LPC, Borehamwood, on 18th February 1993.

The full test load of 850 kN was supported by the column for a period of 84.5 minutes at which time it was reduced to a pinch value. Heating of the unloaded column continued for a brief period thereafter, the test being terminated after a total heating time of 86 minutes. In accordance with the provisions of BS 476:Part 21 the fire resistance rating of the test assembly was therefore 84 minutes.

A3.1.1 Temperature Measurements

A3.1.1.1 Atmosphere Data

The temperatures recorded by the seven thermocouples monitoring the furnace atmosphere are presented in Table A3.1. The table also gives the mean furnace atmosphere temperatures and the corresponding BS 476 standard heating curve values. The individual thermocouple data are shown plotted in Figs. A3.1(a) to A3.1(g) which also include the BS 476 standard heating curve. From these it may be seen that only the traces for thermocouples ATM4, ATM5 and ATM7 show acceptably good agreements between the actual and aim values. The temperatures recorded by ATM3 initially correspond reasonably well with the standard curve but after about 25 minutes they drop below it and remain so until the end of the test. In the case of ATM1 and ATM2 the tendency is for the recorded temperatures to exceed their aim values throughout most of the test although ATM2 does recover after about 60 minutes and from then to the end of the test gives reasonable agreement with the standard curve. The trace for ATM6 shows poor agreement with the aim values, the recorded temperatures being very much lower throughout the entire duration of the test. It will be recalled that this was also the case in the preceding test, (see Section A2.1.1.1). However, although the effect is the same, its magnitude in the present test is not quite so great. As before all these deviations from the standard curve were evident in the LPC data recorded at the time of the test.

The average furnace atmosphere temperature is compared with the BS 476 time / temperature curve in Fig. A3.2. Apart from a brief period soon after the commencement of the test there was a tendency during the first 40 minutes, (approx.), for the furnace atmosphere to be very slightly hotter than the standard curve. During the remainder of the test the atmosphere temperature was slightly lower than the standard curve. Taken overall the mean furnace atmosphere temperature was therefore very close to that required by the standard and the degree of control would appear to be very good. However, as was noted before, (see Section A2.1.1.1), this plot gives a quite different impression of the accuracy to which the atmosphere temperature was controlled compared with the individual plots in Figs. A3.1(a)-(g).

A3.1.1.2 Steelwork Data

The temperature data from the twelve thermocouples embedded in the steelwork are presented in Table A3.2 and are shown graphically in Fig. A3.3. All the thermocouples appear to have performed satisfactorily throughout the 86 minutes of the test and all show a similar response with a moisture plateau at around 100°C. The temperatures at the conclusion of the test generally reflect the thermocouple positions within the section. The hottest portion of the column was situated around the mid-height / lower middle quarter position, (T/C's 6, 7 and 8). However, the temperature distribution in the part of the column between measurement positions T/C2 and T/C9 was such that the largest difference recorded between any two thermocouples was only 16 Centigrade degrees, (T/C4 and T/C7). Thermocouple 12, situated at the bottom end of the column, recorded the lowest final temperature of 460°C. This was 43 Centigrade degrees cooler than the next highest value which was recorded by T/C1 situated at the top end of the column. T/C12 was also 68 and 89 Centigrade degrees cooler than the next two adjacent thermocouple positions, i.e. T/C11 and T/C10 respectively.

At 'failure', (84 min), the following steelwork temperatures were recorded:-

- Highest individual value: 564°C (T/C7)
- Mean of 3 highest values: 561°C (T/C's 6, 7 and 8)
- Mean of T/C's 2-9 inclusive: 556°C
- Mean of T/C's 5-8 inclusive: 560°C
  (Covering region of deformation, see Section A3.1.3.2)

A3.1.2 Column Extension Data

The longitudinal extension of the column, as indicated by the linear displacement transducer, and logged by the LPC, is presented in Table A2.3. The data are shown plotted in Fig. A2.4. The maximum extension under load was 17.3 mm. This occurred 69 minutes after the commencement of the test and was maintained until 73 minutes had elapsed, after which time the column began to contract. The column never completely regained its original length.

A3.1.3 General Observations

A3.1.3.1 During the Test

The following observations were recorded during the conduct of the test.

Time min / seconds	Event / Observation
-16.00	- Load of 850 kN applied to the column. - Displacement transducer set to zero.
00.00	- Test commenced.
09.00	- Column just visible in the furnace.
14.00	- Corners of fire protection beginning to glow dull red.
20.00	- Glow associated with several high spots in the fire protection noticed around mid-height.
32.00	- Corners glowing brightly.
52.00	- A number of dark spots are evident on the surface of the fire protection. (see LPC 83064 - Appendix 2).
54.00	- No evidence of any cracking in the fire protection.
69.00	- Column extension reaches a maximum value of 17.3 mm.
73.00	- Column begins to contract.
84.30	- Column unable to support the load. - Load reduced to a pinch value.
85.00	- Load removed.
86.00	- Test terminated.

A3.1.3.2 Subsequent to the Test

The furnace was opened up within a few minutes of the test being terminated. At this time it was noted that the fire protection material was still intact over all four faces of the steel section. As in the previous test some minor surface cracking of the coating was apparent. Figures A3.4 and A3.5 are general views of the column, after cooling, taken from the South and South-West positions respectively. These give an indication of the extent to which the column deformed, (bowed), during the final few minutes of the test. The mode of failure was almost identical to that observed on the first test with the principal direction of bowing again being in the East-West orientation. There was also some deformation in the North-South direction but as before this was only very slight. The deformed portion was situated between approximately 1250 mm and 2100 mm from the true base of the section. Deformation was therefore situated more uniformly about the column mid-height position, (1700 mm), than in the earlier test. The region encompassed thermocouples T/C5-T/C8 inclusive.

TABLE A3.1
FURNACE ATMOSPHERE TEMPERATURE DATA - LPC 83065

TIME MINS	ISO TEMP	ATM 1	ATM 2	ATM 3	ATM 4	ATM 5	ATM 6	ATM 7	ATM MEAN
0	20	58	62	88	64	49	20	32	53
1	349	366	315	215	313	381	148	350	298
2	445	497	486	499	431	511	450	494	481
3	502	507	489	514	447	520	442	497	488
4	544	535	524	548	501	549	500	529	527
5	576	555	532	564	556	570	513	546	548
6	603	598	557	580	576	587	545	565	573
7	626	663	636	635	622	631	600	630	631
8	645	681	675	659	654	655	622	661	658
9	663	694	693	683	675	688	638	683	679
10	678	704	704	696	687	697	650	697	691
11	693	711	714	707	718	707	655	706	703
12	705	720	720	710	732	710	662	709	709
13	717	754	729	723	742	721	667	721	722
14	728	764	736	728	749	725	675	727	729
15	739	773	749	750	761	742	704	745	746
16	748	780	755	756	765	749	712	750	752
17	757	789	760	760	770	761	716	757	759
18	766	792	765	764	776	766	725	764	765
19	774	804	788	775	783	784	738	778	779
20	781	815	803	786	793	800	746	792	791
21	789	821	812	791	798	807	749	797	796
22	796	827	815	794	804	811	756	804	802
23	802	831	820	801	812	818	762	810	808
24	809	835	826	806	817	826	765	814	813
25	815	842	831	810	820	829	771	822	818
26	820	844	834	812	826	829	778	825	821
27	826	852	849	823	833	845	795	839	834
28	832	857	853	825	839	853	791	844	837
29	837	863	858	828	842	857	800	850	843
30	842	866	863	836	849	859	808	854	848
31	847	871	867	839	855	864	809	859	852
32	851	875	871	843	858	866	815	863	856
33	856	879	873	845	859	872	815	866	858
34	860	883	877	849	864	869	825	871	863
35	865	887	882	853	869	876	829	875	867
36	869	890	884	855	873	880	833	878	870
37	873	895	888	860	875	884	837	881	874
38	877	898	892	861	880	892	839	885	878
39	881	900	894	862	882	889	847	889	880
40	885	905	898	869	885	889	850	893	884
41	888	908	901	871	889	897	851	895	887
42	892	910	903	873	892	896	853	898	889
43	896	915	906	876	894	902	858	901	893
44	899	915	907	877	895	902	859	905	894
45	902	917	911	880	899	906	866	908	898
46	906	920	913	883	903	905	869	911	901
47	909	925	916	885	906	908	872	915	904
48	912	926	919	887	909	909	874	916	906
49	915	931	921	890	911	909	877	920	908
50	918	933	924	889	912	909	883	922	910
51	921	934	927	893	919	919	888	925	915
52	924	938	929	899	919	921	888	927	917
53	927	939	931	900	920	922	892	930	919
54	930	943	933	899	924	922	895	933	921
55	932	945	935	901	926	926	895	935	923
56	935	945	937	906	928	925	895	936	925
57	938	951	940	908	931	929	900	939	928
58	940	953	941	909	932	929	903	942	930
59	943	955	943	912	935	933	903	944	932
60	945	957	946	910	938	933	907	946	934

(continued)

TABLE A3.1
(continued)

TIME MINS	ISO TEMP	ATM 1	ATM 2	ATM 3	ATM 4	ATM 5	ATM 6	ATM 7	ATM MEAN
61	948	961	954	922	941	941	917	953	941
62	950	965	957	922	944	939	919	957	943
63	953	965	959	927	947	946	923	958	946
64	955	971	962	929	948	951	927	961	950
65	957	973	965	928	949	952	930	964	952
66	960	976	967	933	956	951	932	966	954
67	962	978	969	935	957	956	931	970	957
68	964	981	969	936	959	957	937	972	959
69	966	982	973	939	960	959	936	974	960
70	968	984	975	943	964	963	939	975	963
71	971	986	977	942	963	965	943	979	965
72	973	989	980	945	968	967	944	980	968
73	975	990	981	947	970	968	947	983	969
74	977	993	982	950	970	972	946	985	971
75	979	993	984	950	973	971	947	985	972
76	981	997	987	952	976	973	952	989	975
77	983	998	989	954	976	980	949	990	977
78	985	999	990	958	979	978	957	993	979
79	986	1002	992	962	981	980	959	995	982
80	988	1006	993	962	982	985	960	997	984
81	990	1007	996	964	985	981	959	1000	985
82	992	1009	997	962	988	986	962	1002	987
83	994	1009	998	966	987	987	961	1002	987
84	996	1008	997	966	990	987	955	1002	986
85	997	1012	1001	971	992	989	956	1003	989
86	999	1015	1003	973	994	992	969	1005	993

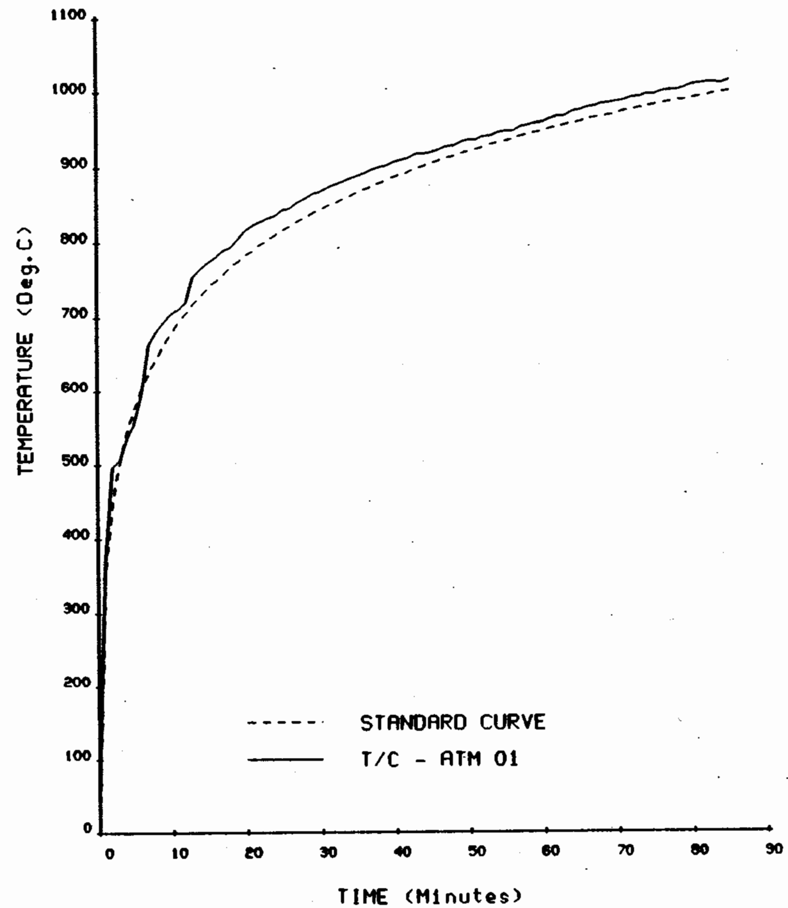
TABLE A3.2
TEMPERATURES RECORDED IN THE STEELWORK - LPC 83065

TIME MINS	T/C 01	T/C 02	T/C 03	T/C 04	T/C 05	T/C 06	T/C 07	T/C 08	T/C 09	T/C 10	T/C 11	T/C 12
0	18	16	16	16	16	16	16	16	16	16	16	16
1	18	17	17	17	17	17	17	17	17	16	16	16
2	18	17	17	17	17	17	17	17	17	16	16	16
3	19	17	17	18	17	17	17	17	17	16	16	16
4	22	19	17	21	19	18	19	19	18	18	16	16
5	26	23	20	24	23	22	23	24	22	22	19	19
6	31	27	24	29	27	26	27	29	26	27	24	23
7	35	32	28	33	32	30	32	34	31	32	29	27
8	41	37	33	39	37	36	38	39	37	37	34	32
9	46	42	39	44	42	41	43	45	42	42	39	37
10	52	48	44	50	48	46	49	51	48	48	45	42
11	57	54	50	56	53	52	55	57	54	54	51	47
12	63	60	56	62	59	58	61	63	59	60	57	52
13	70	66	62	69	66	64	68	69	66	67	63	58
14	77	73	68	76	72	71	74	76	72	73	69	63
15	83	79	75	82	79	77	81	82	79	79	76	69
16	89	86	81	89	85	84	87	88	85	86	82	75
17	95	92	88	95	91	90	93	94	91	91	88	80
18	99	97	94	99	96	95	97	98	96	95	93	86
19	100	100	98	100	99	98	99	99	99	98	97	90
20	103	101	100	103	100	100	101	102	100	100	98	94
21	109	106	101	110	104	103	108	109	102	106	100	97
22	117	113	103	117	112	109	116	117	109	112	106	98
23	125	121	111	125	120	117	124	125	117	119	114	103
24	133	128	120	134	128	125	132	133	125	127	121	109
25	141	136	129	142	136	133	141	142	134	135	130	116
26	149	144	138	151	144	141	149	150	142	143	137	122
27	157	153	147	160	153	150	158	158	151	151	146	129
28	165	161	155	169	161	158	167	167	159	159	154	136
29	173	170	164	177	170	167	176	176	168	167	162	143
30	181	178	174	186	178	176	185	184	176	176	170	150
31	189	187	182	195	187	185	193	193	185	184	178	157
32	197	196	191	204	195	193	202	202	194	193	186	164
33	204	205	200	213	204	202	211	211	202	201	194	171
34	212	213	209	221	213	211	220	219	211	209	202	178
35	220	222	218	230	221	220	228	228	219	217	210	185
36	227	231	227	238	229	228	237	237	228	226	218	192
37	235	239	236	247	238	237	246	245	236	234	226	198
38	242	248	244	255	247	245	255	254	245	242	234	205
39	249	256	253	263	255	254	263	263	253	250	242	212
40	257	264	262	272	263	263	272	271	262	258	250	219
41	264	273	270	280	272	271	280	279	270	266	257	225
42	271	281	278	288	280	279	288	287	278	274	265	232
43	278	289	287	296	288	288	296	296	286	282	272	239
44	285	297	295	304	296	296	304	304	294	290	280	245
45	292	305	303	311	304	304	312	311	302	298	287	251
46	298	313	311	319	312	312	320	320	310	305	295	258
47	305	321	319	327	320	320	328	327	318	313	302	264
48	311	329	327	334	328	328	336	335	325	320	309	270
49	318	337	334	342	335	335	344	342	333	328	316	276
50	324	344	342	349	343	343	352	350	340	335	323	282
51	330	352	350	356	350	351	359	358	348	342	330	288
52	336	359	357	364	358	358	366	365	355	349	337	294
53	342	367	365	371	365	366	374	373	362	357	344	300
54	348	374	372	378	373	373	381	380	370	363	351	306
55	354	381	379	385	380	380	388	387	377	370	357	311
56	360	388	386	391	387	387	396	394	384	377	364	317
57	366	396	393	398	394	394	402	401	391	384	370	322
58	371	403	400	404	401	401	409	407	397	391	377	328
59	377	409	407	411	407	408	416	414	404	397	383	333
60	382	416	414	417	414	415	423	421	411	404	389	339

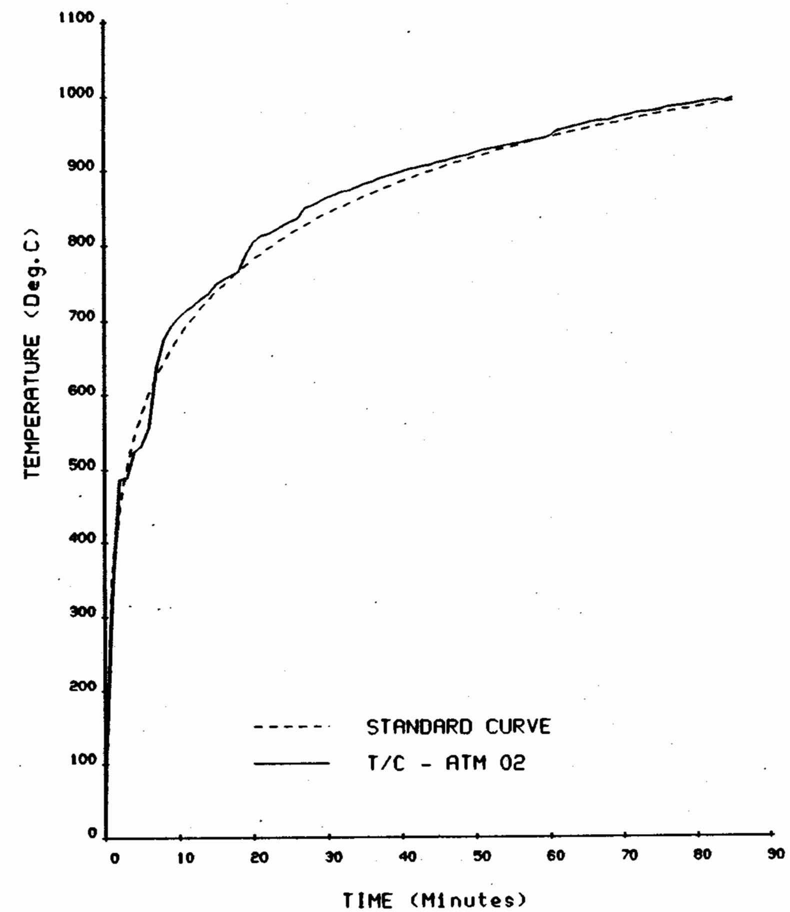
(continued)

TABLE A3.2
(continued)

TIME MINS	T/C 01	T/C 02	T/C 03	T/C 04	T/C 05	T/C 06	T/C 07	T/C 08	T/C 09	T/C 10	T/C 11	T/C 12
61	388	423	421	423	421	422	429	428	417	410	396	344
62	393	430	427	430	428	429	436	434	424	417	402	349
63	398	436	434	436	435	435	443	441	430	423	408	354
64	403	443	441	442	441	442	449	447	437	429	414	360
65	408	449	447	448	448	448	456	454	443	436	420	365
66	413	455	453	454	454	455	462	460	449	441	425	370
67	418	462	459	460	460	461	468	466	456	448	431	375
68	424	468	466	466	467	468	474	472	462	453	437	380
69	428	475	472	472	473	474	481	479	468	459	443	384
70	433	481	478	477	479	480	487	485	474	466	449	389
71	438	487	484	483	485	486	493	491	480	471	454	394
72	443	492	489	488	491	492	499	496	486	477	460	399
73	448	498	496	494	497	498	504	502	492	483	465	404
74	452	504	501	499	503	504	510	508	498	488	470	409
75	457	510	507	504	508	509	516	514	503	493	476	413
76	461	515	513	510	514	515	522	519	509	499	481	418
77	466	521	518	515	520	521	527	525	515	504	486	422
78	470	527	523	519	525	526	533	530	520	510	491	427
79	474	532	529	525	531	532	538	536	525	515	496	431
80	479	537	534	529	536	537	543	541	530	520	501	435
81	483	543	539	534	542	543	548	546	536	525	505	440
82	487	548	544	539	547	548	554	551	541	530	510	444
83	491	553	549	544	552	553	559	556	546	535	515	448
84	496	558	554	548	557	558	564	561	551	540	520	452
85	499	563	559	553	562	563	568	566	556	545	524	456
86	503	567	564	557	567	568	573	571	561	549	528	460



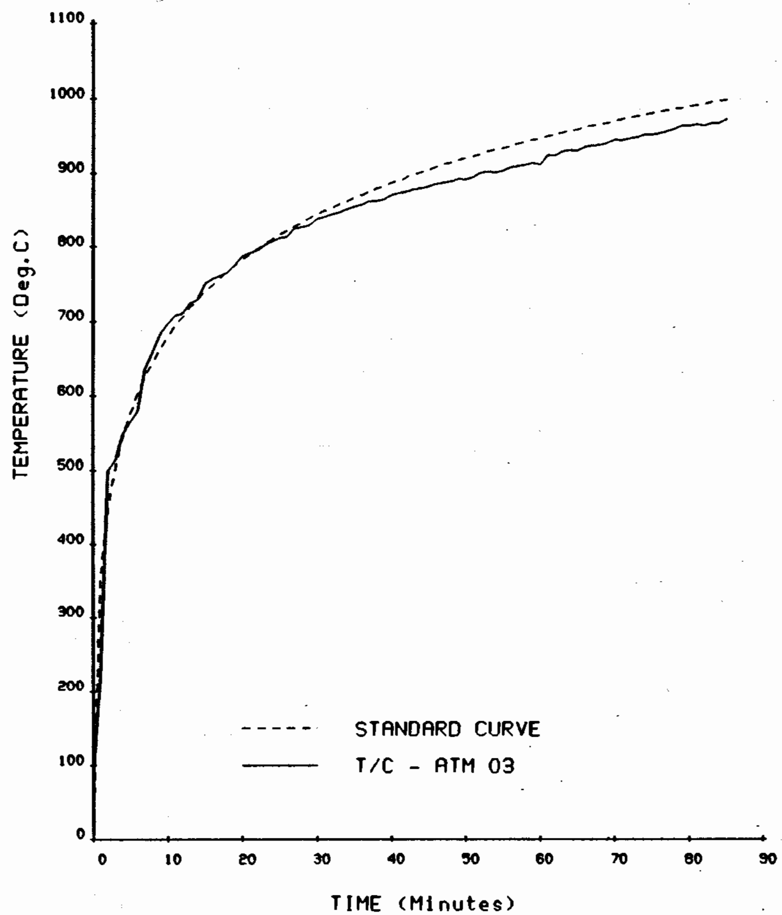
(a) North Shell - Top



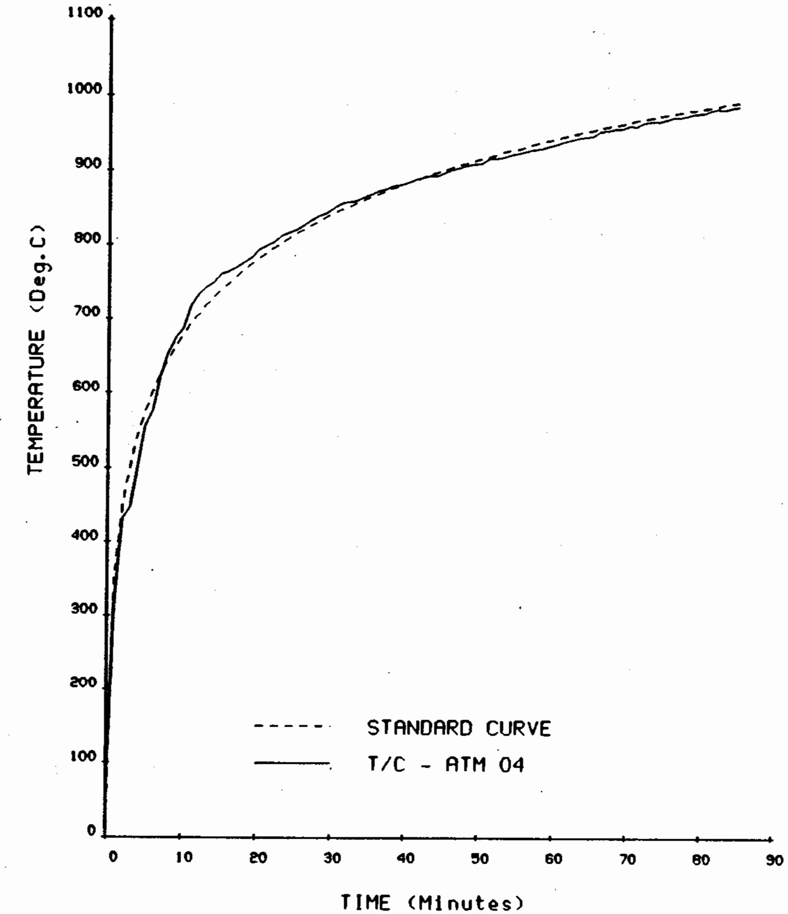
(b) North Shell - Centre

FIG. A3.1a-b COMPARISONS OF INDIVIDUAL FURNACE ATMOSPHERE TEMPERATURES AND THE STANDARD TEMPERATURE/TIME CURVE

TEST NO. LPC 83065



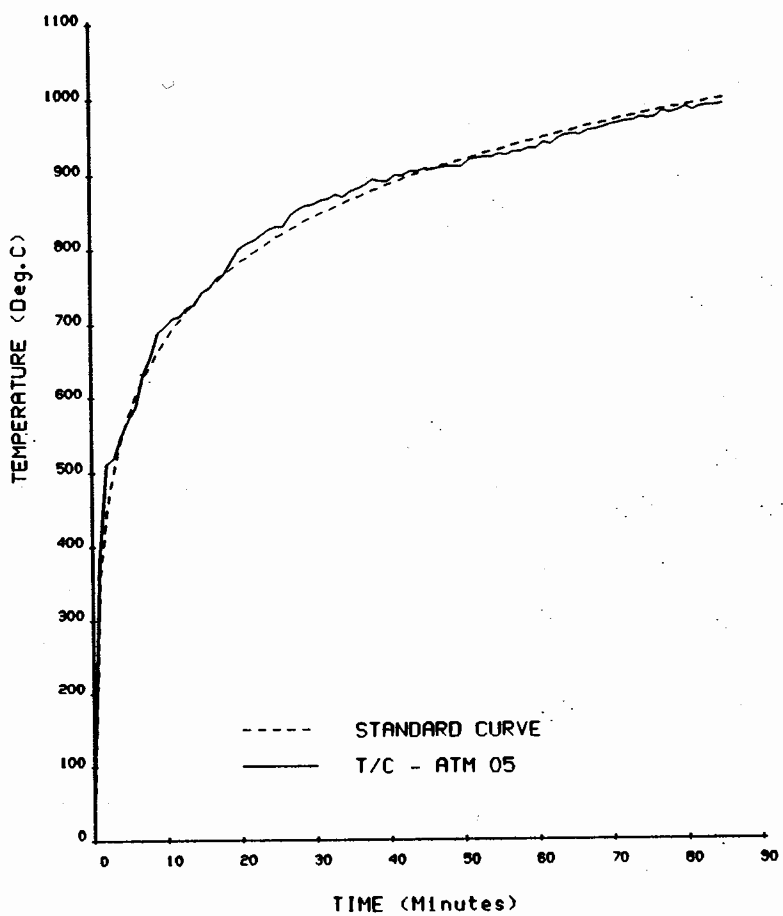
(c) North Shell - Bottom



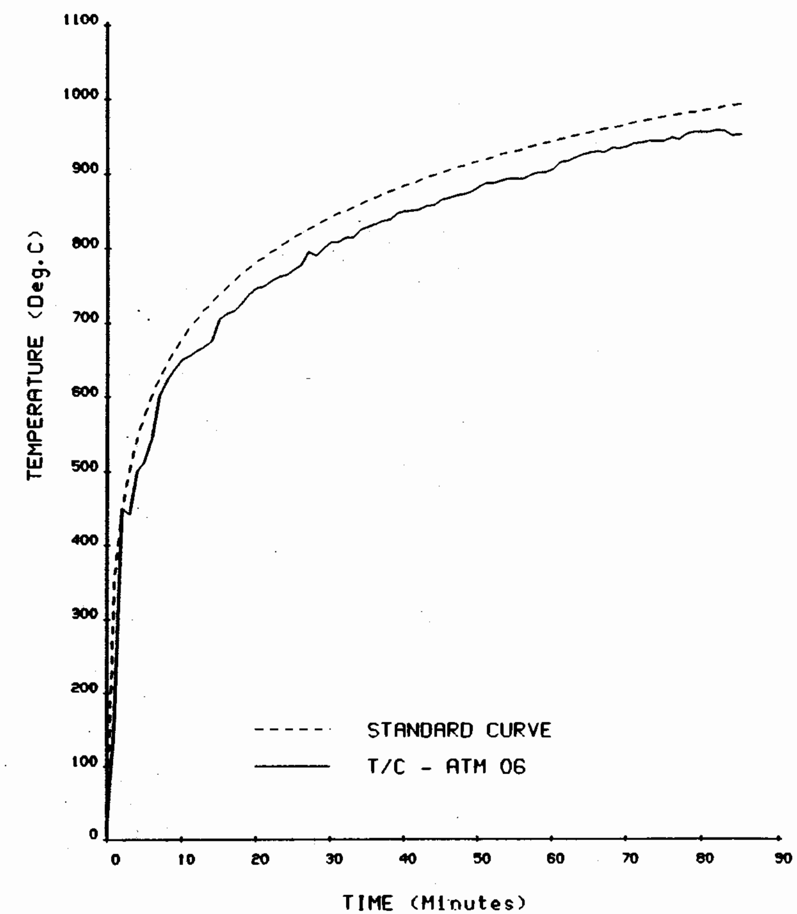
(d) South Shell - Top

FIG. A3.1c-d COMPARISONS OF INDIVIDUAL FURNACE ATMOSPHERE TEMPERATURES AND THE STANDARD TEMPERATURE / TIME CURVE

TEST NO. LPC 83065



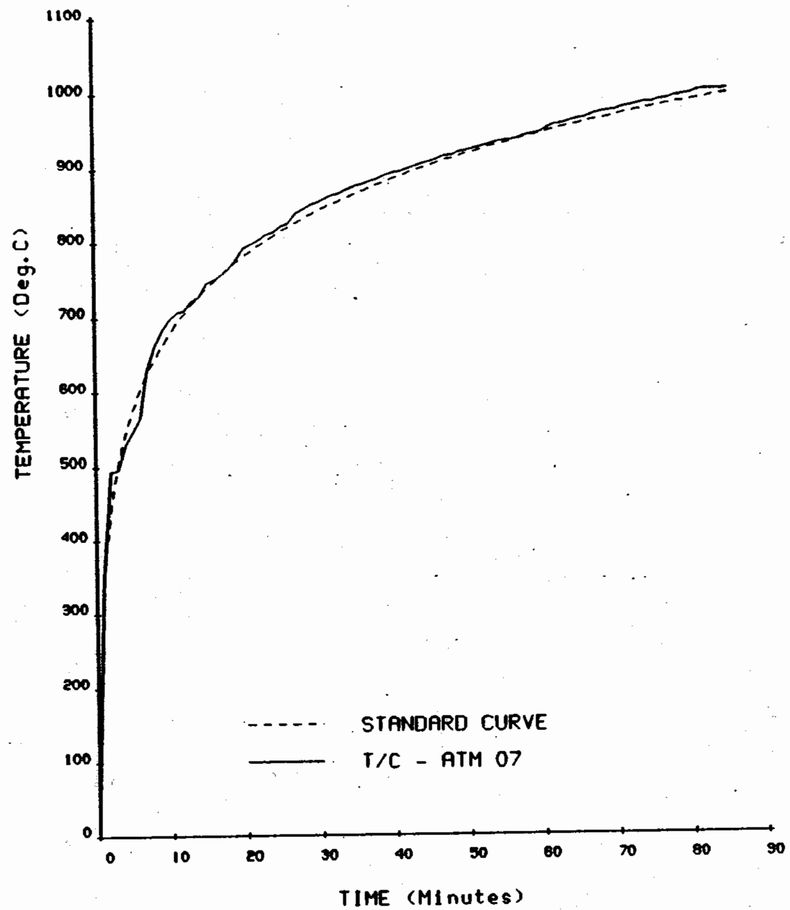
(e) South Shell - Centre



(f) South Shell - Bottom

FIG. A3.1e-f COMPARISONS OF INDIVIDUAL FURNACE ATMOSPHERE TEMPERATURES AND THE STANDARD TEMPERATURE / TIME CURVE

TEST NO. LPC 83065



(g) Between Shells - Centre

FIG. A3.1g COMPARISONS OF INDIVIDUAL FURNACE ATMOSPHERE TEMPERATURES AND THE STANDARD TEMPERATURE/TIME CURVE

TEST NO. LPC 83065

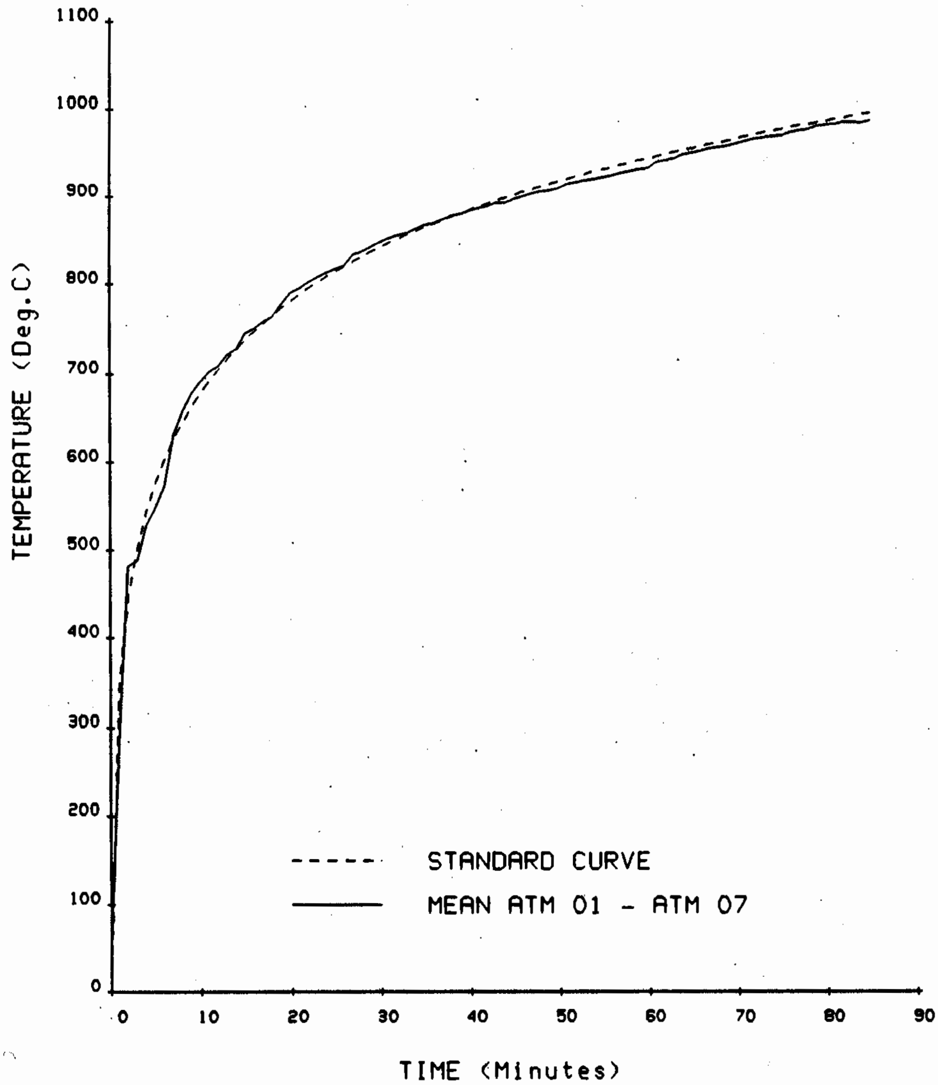


FIG. A3.2 **COMPARISON OF AVERAGE FURNACE ATMOSPHERE TEMPERATURE AND THE STANDARD TEMPERATURE / TIME CURVE**

TEST NO. LPC 83065

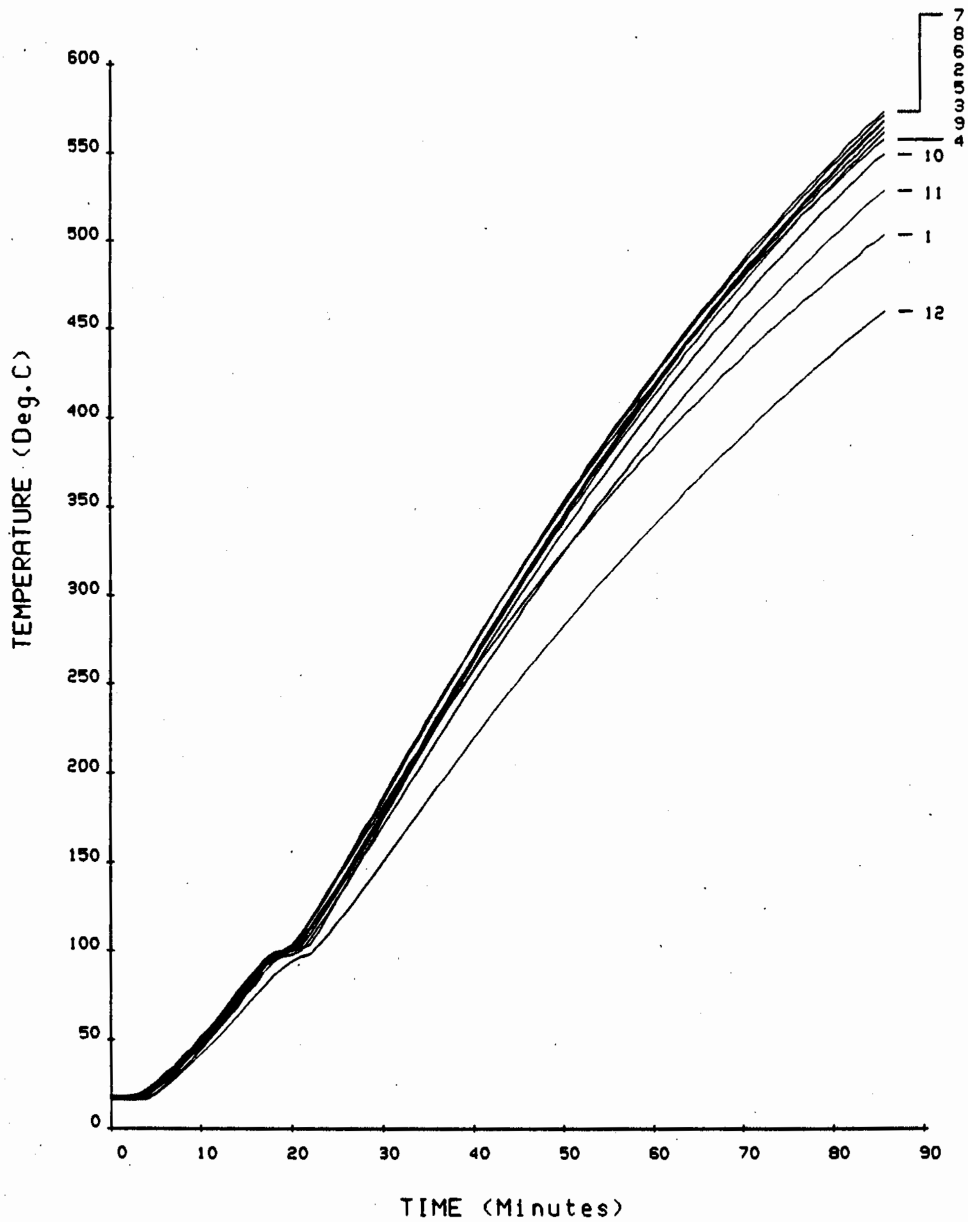


FIG. A3.3 TEMPERATURES RECORDED IN THE STEELWORK

TEST NO. LPC 83065

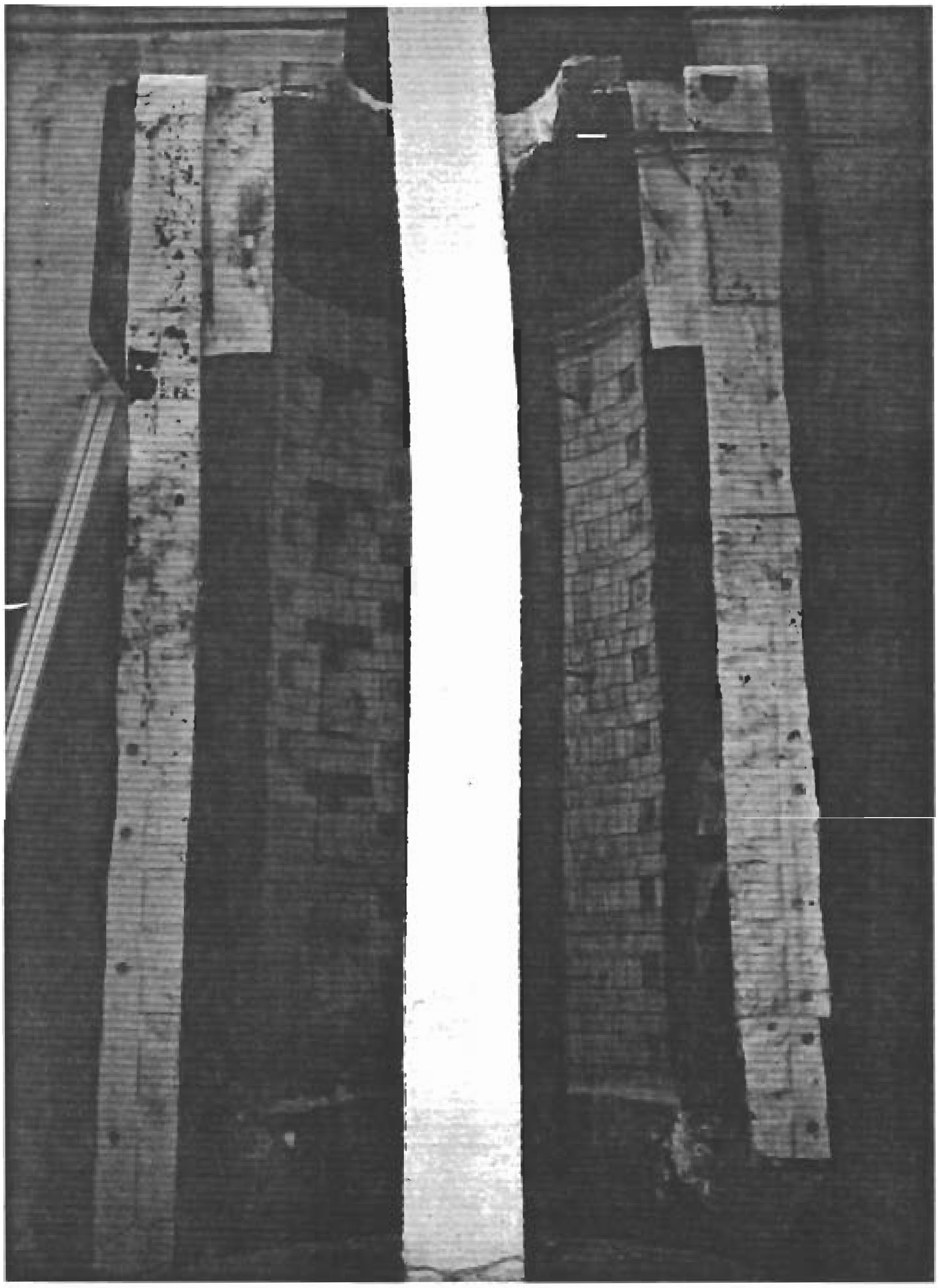


FIG. A3.4 COLUMN AFTER THE TEST, VIEWED FROM THE SOUTH POSITION

TEST NO. LPC 83065

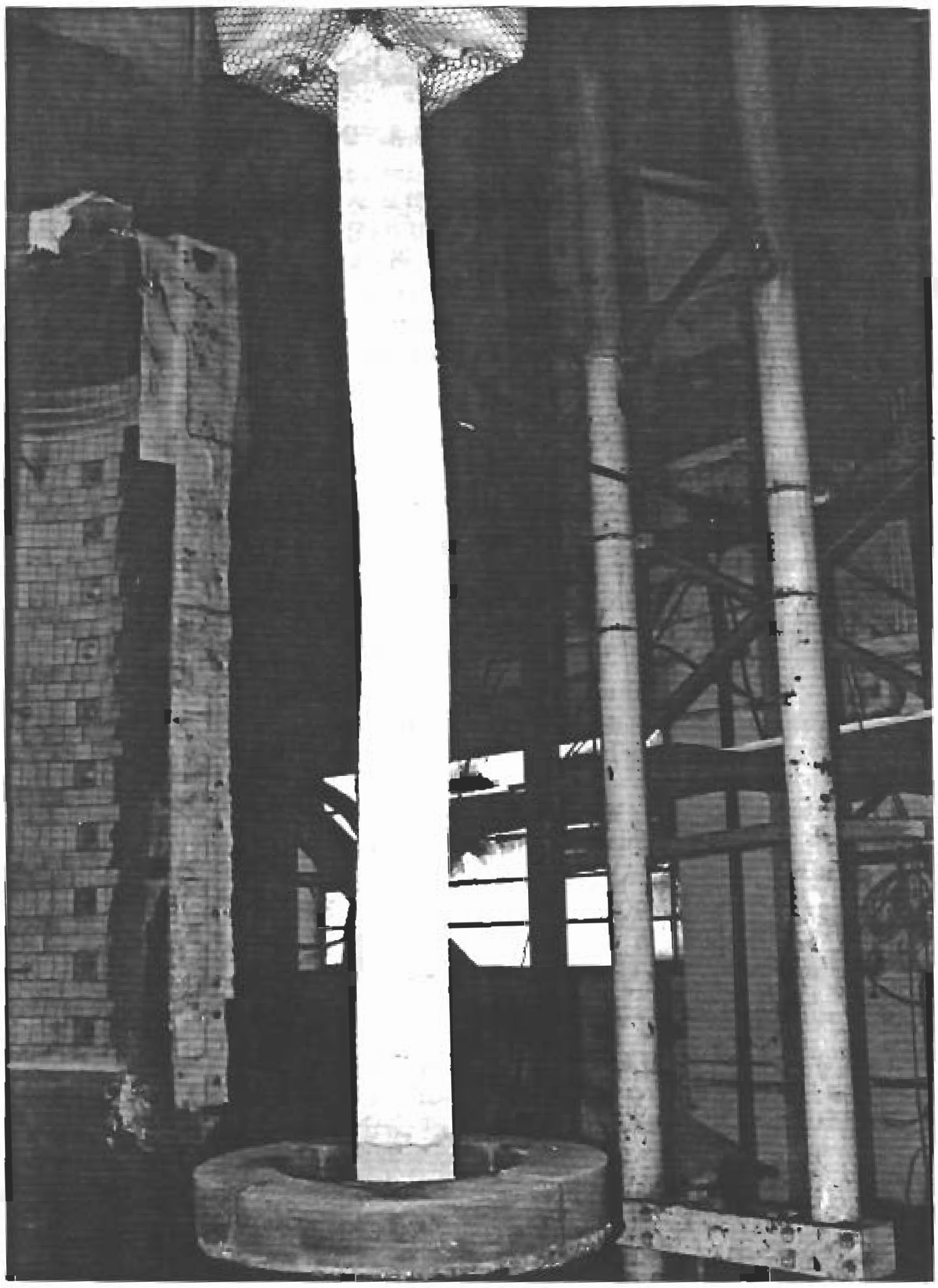


FIG. A3.5 COLUMN AFTER THE TEST, VIEWED FROM THE SOUTH-WEST POSITION

TEST NO. LPC 83065

APPENDIX 4

FURTHER CONSIDERATIONS ON THE COLUMN DESIGN STRENGTH AND THE RESULTING LIMITING TEMPERATURES UNDER THE APPLIED TEST LOADS

A4.1 TEST SPECIMEN DESIGN STRENGTH AND NOMINAL PERFORMANCE

A4.1.1 Room Temperature Design Methodology

At present, most structural steelwork is designed in the UK on a limit states basis to BS 5950:Part 1. This standard assumes the exclusive use of hot rolled sections and assigns Structural Hollow Sections to buckling curve 'A' when calculating their room temperature compression resistance, based on the nominal material strength of the finished steel product to EN 10 210-1 and nominal section properties to BS 4848: Part 2, Hollow Sections.

In contrast, ENV 1993-1-1, (i.e. Eurocode 3.1), specifically allows the use of cold formed structural hollow sections as compression members. Design is also on an ultimate limit states basis and allows for the use of two alternative procedures to estimate the room temperature compressive resistance. However, both design methods are based on the strength of the original steel strip used to make the structural hollow section before cold forming of the section. The first method uses buckling curve 'B' and the original strip strength, (see Option 1, below), whilst the second uses buckling curve 'C' and EITHER the calculated 'enhanced' yield after forming the section, (see Option 2, below), OR the average yield as indicated by a squash load test on the full section.

Moreover, a European standards committee, (ECISS TC10/SC1), is at present drafting a new steel product standard, (prEN 10219-1). They intend that this standard should define the mechanical requirements for cold formed structural hollow sections using the properties of the finished product as validated by test coupons cut from the centre of the flat face of an RHS product.

It is expected that this will result in a modification to Eurocode 3, which will ultimately adopt the following procedures:-

(i) both hot and cold formed CHS will be designed using curve 'A'

(ii) hot formed RHS will be designed using curve 'A'

(iii) cold formed RHS will be designed using curve 'B'

Finally, it has to be recognised that, with the lack of a clear design code for such sections, design offices may alternatively attempt compatibility with the European ultimate limit states fire design code, (see below), and produce their own rational design capacities using buckling curve 'C' and the nominal yield strength of the section as cited by the manufacturer.

A4.1.2 Fire Design Methodology

Within the UK, fire resistant design of both unprotected and protected structural steelwork using hot rolled sections can be undertaken using BS 5950:Part 8:1990. A draft European fire resistant design code prENV 1993-1-2, (i.e. Eurocode 3, draft Part 1.2), is also available which is deemed to be equally applicable to hot finished and cold formed sections. Both employ an ultimate limit states design approach based on the concept of using a fire design load ratio, (LR), to obtain a resulting limiting temperature, (LT), based on an (often implicit) associated steel strength reduction factor, (SRF). These parameters are discussed further and quantified according to UK practice in Section A4.1.4 below. There are significant differences of interpretation of both the SRF and resulting LR in draft prENV 1993-1-2 compared to BS 5950:Part 8, but this is outside the scope of the present report.

More importantly, the most immediately significant explicit difference between these design codes is that:-

(a) According to BS 5950:Part 8, the LR of a compression member in fire is assessed using the fire design loads and the room temperature axial resistance of the column according to BS 5950:Part 1, i.e. the buckling performance of a column in fire is deemed to be identical to the room temperature performance, and therefore the same buckling curve can be used.

(b) Draft prENV 1993-1-2 is more conservative and states that the LR of a compression member in fire must be assessed using the room temperature axial resistance of the column based on buckling curve 'C', irrespective of the section type, i.e. the buckling performance of a column in fire is deemed to be lower than the room temperature performance, (but see later Section A4.2.2 for further discussion). Moreover, the SRF is to be assessed at a more optimistic 2% strain level, while the LR is, in effect, to be increased by using a 1.2 modification factor.

A4.1.3 Test Specimen Notional Design Resistance

It can be seen from the above that there are several possible ways of calculating the room temperature design resistance of the selected SHS test columns. The four most obvious are:-

Option 1: the present EC3 method #1: viz., use buckling curve 'B' and the notional original strip strength; i.e. the 0.2% proof strength of the material as measured after soaking at 900°C for 60 minutes.

i.e. use $p_y = 310\ \text{N/mm}^2$ (Table A1.5)

Option 2: the present EC3 method #2: viz., use buckling curve 'C' and the average yield formula given in Fig. 5.5.2 of EC3, based on the notional original mechanical properties of the original strip material; i.e. the properties as measured after soaking at 900°C for 60 minutes.

i.e. use $p_y = 310\ \text{N/mm}^2$ and $p_u = 428\ \text{N/mm}^2$ (Table A1.5)

so, from average yield formula:-

$$
\begin{aligned}
p_{ya} &= p_y + (k.n.t^2) \times [(p_u - p_y) / A] \\
&= 310 + [7 \times 4 \times (0.815)^2] \times [(428 - 310) / 44.72] \\
&= 310 + 49 \\
&= \underline{359\ \text{N/mm}^2}
\end{aligned}
$$

Option 3: the proposed EC3 method 1: viz., use buckling curve 'B' and the measured material strength; i.e. the 0.2% proof strength of the RHS as measured at room temperature using test coupons cut from the flat face of the RHS.

i.e. use $p_y = 357\ \text{N/mm}^2$ (Table A1.4)

Option 4: a hybrid EC3 method: viz., use buckling curve 'C' and the material strength as given by the works test certificate supplied with the original RHS mill length.

i.e. use $p_y = 407\ \text{N/mm}^2$ (Table A1.4)

Column design resistance had to be assessed and test load levels had to be set prior to the actual placing of the test specimen in the furnace. Accordingly, the most optimistic option, (4 above), was initially selected and a design resistance calculated using material properties as cited on the material test certificate, the exact SHS cross-section properties and a notional column length of 360 cm.

The exact SHS cross section properties were obtained using a computer program held at British Steel - Tubes and Pipes, Corby and the actual dimensions and corner radii given in Appendix 1 of this report, viz:-

	Cross sectional area	=	$44.72\ cm^2$
	Mean wall thickness	=	8.17 mm
	Radius of gyration	=	5.74 cm

since:	Nominal column length (for test load calculation)	=	360 cm
then:	Nominal column effective length in fire, l_e,	=	0.7×360
		=	252 cm

i.e.	Column design slenderness	=	l_e / r_y
		=	252 / 5.78
		=	43.6 (say 44)

Interpolating Table 27(c) BS 5950:Part 1:-

for $p_y = 407\ N/mm^2$ and $l_e / r_y = 44$

$p_c = 328\ N/mm^2$

So,	axial resistance P_c	=	$328 \times 44.72 / 10$
		=	<u>1467 kN</u>

A4.1.4 Test Load Levels

In limit states design, the design resistance of a member must equal or exceed the worst case combination of the total factored applied loads. The magnitude of the load factors will depend on the design case being considered.

When designing to BS 5950:Part 1 a typical room temperature design load, RTDL, is given by:-

$$RTDL = 1.4 \times \text{Dead Load} + 1.6 \times \text{Live Load}$$

However, when designing for fire to BS 5950:Part 8 a typical fire design load, FDL, will be:-

$$FDL = \text{Dead Load} + \text{Live Load}$$

So, the load ratio for a column in fire will typically be:-

$$LR = \frac{\text{Dead Load} + \text{Live Load}}{1.4 \times \text{Dead Load} + 1.6 \times \text{Live Load}}$$

i.e. under normal circumstances: $1/1.6 < LR < 1/1.4$

i.e. $0.625 < LR < 0.714$

So, for the design option initially selected, the expected load in fire will typically lie in the range:-

$$0.625 \times 1467 < \text{Fire Design Load} < 0.714 \times 1467$$

i.e. $917\ kN < \text{Fire Design Load} < 1048\ kN$

The two test loads should ideally encompass the expected load range which, in practice, will depend upon the ratio of dead and live loading for the particular situation. Since the first test was to be based on the most optimistic prediction of the column compressive resistance, an initial upper bound test load of 1060 kN was selected. In the light of the very good test performance of this first column, the second test load was deliberately set low at 850 kN in order to ensure clearly higher test temperatures. This gave notional test load ratios (TLR) as follows:-

For Test 1 (LPC 83064, performed 16th Feb. 1993);

TLR = 1060 / 1467
= 0.723

For Test 2 (LPC 83065, performed 18th Feb. 1993);

TLR = 850 / 1467
= 0.579

A4.1.5 Resulting Notional Limiting Temperatures

In practical design the load ratio, (LR), will usually have a value in the range 0.2 to 0.7 and the resulting limiting temperature, (LT), can be assessed by a linear interpolation of Table 5 in BS 5950:Part 8. The LR for Test 1 lies outside this range. However, Table 5 is based on a known interpretation of the material strength reduction factors, (SRF), given in Table 1 of the design code, i.e. for columns with a slenderness ratio < 70:-

SRF (Table 1 at a 0.5% strain) = LR × 0.85

So, for Test 1:-

$$SRF = 0.85 \times 1060 / 1467$$

$$= 0.614$$

and, from Table 1:-

$$LT = 500 + 50 \times (0.622 - 0.614) / (0.622 - 0.492)$$

$$= 503°C$$

For Test 2:-

$$SRF = 0.85 \times 850 / 1467$$

$$= 0.493$$

and, from Table 1:-

$$LT = 500 + 50 \times (0.622 - 0.493) / (0.622 - 0.492)$$

$$= 549.5°C$$

A4.2 POST TEST ASSESSMENT OF COMPARATIVE PERFORMANCE

A4.2.1 General

After fabrication of the test specimens, it was realised that changes in working practice at the Loss Prevention Council Test Centre meant that their standard column test specimens were, in fact, now 20 cm shorter than assumed, i.e.-

Column actual length = 340 cm
Column effective length in fire = 0.7 × 340
= 238 cm

So, true column design slenderness = l_e / r_y
= 238/5.74
= <u>41.46</u>

Using the true slenderness ratio, more accurate design resistances were assessed for each of the original four design options. Again, in each case the compressive strength was obtained by interpolating Table 27 in BS 5950:Part 1. The resulting design resistances are given in Table A4.1.

The resulting load ratio, strength reduction factor and associated limiting temperature were also re-assessed for each design option, again using Table 1 of BS 5950:Part 8. All these quantities are given in Table A4.2. The mean temperature of the critical length of each specimen at failure, (MFT), has also been included in this table to facilitate direct comparison of the design options.

A4.2.2 Discussion

In practice, an ultimate limit states fire resistant design will be undertaken on a protected section to achieve one of two possible aims:-

EITHER: given known design loads and column section size, to assess a resulting limiting temperature, with the further aim of assessing the minimum required thickness of a given insulation to ensure that this temperature is not exceeded over a required fire resistance time.

OR: given a known section size and thickness and type of insulation, to assess the resulting temperature after heating to the standard temperature-time curve for a required fire resistance time, with the further aim of assessing the resulting load ratio and hence the design loads the column could withstand.

Moreover, the design procedures nested in BS 5950:Part 8 are known to be a highly accurate method of assessing the fire performance of hot finished sections, since the design tables have been derived from and correlated against a large number of indicative material and full size section furnace tests.

The two tests described in this report demonstrate that UK fire design procedures based on the fire performance of hot formed material can be used to predict the performance of cold formed sections with the same accuracy, since inspection of Table A4.2 shows that the failure temperature of the two specimens was within 12°C of those predicted by the most optimistic design assessment (i.e. Option 4). This also infers that cold formed material is heated in fire too rapidly for there to be any difference in performance compared to hot finished, stress relieved material.

Inspection of this table also indicates that design assessments based on UK material properties but using existing Eurocode 3.1 procedures (Options 1 & 2) may be conservative; i.e. actual failure temperatures are 26-70°C higher than predicted. This infers that existing EC3 design procedures may predict either a greater thickness of protection than needed for a required design load ratio or, alternatively, produce an under-assessment of the room temperature design resistance (typically, as here, by 10-17%), with a similar underestimate of the fire design load that could be sustained for a known limiting temperature. However, a fuller analysis has still to be undertaken.

Finally, inspection of the same table shows that applying the proposed alternative Eurocode 3.1 design procedure (Option 3) at the accepted UK strain level of 0.5% produced only a marginally conservative under-assessment of the room temperature design resistance (i.e. <6%) and gave rise to predicted limiting temperatures only 17-23°C lower than the measured failure temperatures.

TABLE A4.1
RESULTING COLUMN DESIGN RESISTANCE ACCORDING TO EACH DESIGN OPTION

Design Option Number	Buckling Curve	Material Design Strength (p_y) N/mm^2	Material Compressive Strength (p_c) N/mm^2	Design Resistance (P_c) kN
1	b	310	278	1243
2	c	359	303	1355
3	b	357	317	1418
4	c	407	336	1503

TABLE A4.2
ASSESSED LOAD RATIO AND PREDICTED LIMITING TEMPERATURE ACCORDING TO EACH DESIGN OPTION PLUS ACTUAL TEMPERATURE AT FAILURE

Design Option Number	Buckling Curve	Design Resistance kN	Test 1 (LPC 83064)					Test 2 (LPC 83065)				
			Applied Load = 1060 kN					Applied Load = 850 kN				
			TLR	SRF	LT	MFT	Diff	TLR	SRF	LT	MFT	Diff
1	b	1243	0.853	0.725	446	516	+70	0.684	0.581	515	560	+45
2	c	1355	0.782	0.665	478	516	+38	0.627	0.533	534	560	+26
3	b	1418	0.748	0.636	493	516	+23	0.599	0.509	543	560	+17
4	c	1503	0.705	0.599	508	516	+8	0.566	0.481	555	560	+5

TLR: Test Load Ratio
SRF: Material Strength Reduction Factor = 0.85 × LF
LT: Predicted Limiting Temperature (°C)
MFT: Mean Failure Temperature (°C)
Diff: MFT - LT (°C)