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BS476:Part 21 Fire Resistance Tests

The Construction and Testing of Three Loaded CHS Columns Filled with Concrete

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SUMMARY

BS476:PART 21 FIRE RESISTANCE TESTS

THE CONSTRUCTION AND TESTING OF THREE LOADED CHS COLUMNS FILLED WITH CONCRETE

D.E. Wainman and R.P. Toner

BS476:Part 21 standard fire resistance tests have been carried out on three different sizes of circular hollow section filled with concrete. The tests were performed at the Loss Prevention Council, Borehamwood, during November 1991.

The dimensions of the hollow sections were:-

1. 244.5 mm O/D × 6.3 mm wall, (Grade 43C)
2. 323.9 mm O/D × 6.3 mm wall, (Grade 43C)
3. 355.6 mm O/D × 9.5 mm wall, (Grade 43C)

The loads applied to the columns were calculated using the CTICM/VALEXY computer programme 'FEUGODTU'. They were determined using the measured material properties and according to the intended fire survival times. The major purpose of the test loadings was to validate the design procedure for concrete filled circular hollow sections, both in its interpretation and use.

The loads applied were 635.4 kN, 1864 kN and 900 kN respectively.

The performance of the three test assemblies was judged against the load bearing capacity criterion outlined in Section 6 of BS476:Part 21:1987. The fire resistance ratings obtained were:-

1. 56 minutes, (60 minutes intended)
2. 45 minutes, (60 minutes intended)
3. 142 minutes, (120 minutes intended)

The columns failed when the combined strength of the steel and concrete had reduced to the level of the applied load.

The full test load appropriate to each column was re-applied approximately 18 hours after the completion of each test. In all cases the column supported the applied load and therefore the requirements of the residual load bearing capacity test were satisfied.

A full assessment of the test data has still to be undertaken. However, a preliminary assessment of the results show that the computer model can accurately predict the loads which the columns can carry in a fire situation provided that proper account is taken of the columns effective length and the actual strength properties of the concrete infill.

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Fire Resistance	Concrete
+ BS 476	Sections (structural)
Columns	Sections (hollow)
Lab Reports	

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INITIAL CIRCULATION

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COMMERCIAL

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BS476:PART 21 FIRE RESISTANCE TESTS**THE CONSTRUCTION AND TESTING OF THREE LOADED CHS COLUMNS FILLED WITH CONCRETE****1. INTRODUCTION**

Hollow structural steel sections are generally considered to be very efficient in resisting compressive loadings. However, by combining steel and concrete together in one structural component, the advantages of each material can be better exploited and the load carrying capacity of such columns can be increased substantially. In recent years the use of composite steel-concrete structures has become increasingly popular, and has developed into an important form of construction. Compared with more traditional steel or concrete structures the composite steel-concrete system offers a number of benefits which may be summarised as:-

- (1) Reduced overall dimensions for a column required to support a given load, or a reduction in the number of columns required to support the total load.
- (2) Good resistance to instability.
- (3) Easy prefabrication and erection. The presence of the steel sections dispenses with the need for any formwork or shuttering for the concrete.
- (4) Permanent fire protection. A high fire resistance rating can be obtained without the need for additional surface fire protection of the steel.
- (5) The reduced column dimensions, or number of columns required, together with the elimination of surface fire protection may result in an increase in the usable space within a building and overall reductions in cost.

During the last 10 years, or so, tests to determine the fire resistance ratings of concrete filled hollow steel columns have been carried out in a number of laboratories throughout the world. Several research organisations have also been engaged in the development of calculation methods for predicting the behaviour of this form of construction, based on the data obtained from the various full scale standard fire tests. Much of the European work in this field has been carried out on columns with square cross sections, although some work has also been undertaken on circular sections. These studies are complimentary to those carried out by, for example, the National Research Council of Canada, which have featured predominantly circular cross section columns.

In the UK there is only limited experience available concerning the behaviour of circular, or other, hollow sections infilled with concrete and for this reason they were not included in Section 8 of BS5950. Design guidance for concrete filled hollow sections is currently being given based on an intuitive interpretation of the available data. A generalised computer program⁽¹⁾ for predicting the behaviour of concrete filled sections has been developed within the framework of CIDECT⁽²⁾ and has become the basis on which much of the design guidance on these products is generally given⁽³⁾.

As regards circular members the program has only been validated over a relatively small range of section sizes and for short duration fire resistance periods. There is clearly a need for additional data covering larger section sizes and extended fire resistance periods in order to extend the program validation.

The program FEUGODTU may be used in a number of ways. In its more usual mode of operation details concerning the section parameters, together with the applied load, are used as input and a prediction of the fire resistance rating for the system is obtained. In the current work, however, the intended fire resistance time was fixed and the maximum permissible loading for the system to survive for this length of time was predicted. The purpose of these test loadings was therefore to validate the overall design procedure based on program FEUGODTU, both in its interpretation and use. The work is of particular importance since this design method could eventually be included in Eurocode EC4⁽⁴⁾.

BS476:Part 21 standard fire resistance tests were carried out on three sizes of concrete filled circular hollow section columns. This report is concerned only with aspects of the construction and testing of these columns. The test data obtained are presented in full in both tabular and graphical formats. No attempt has been made to interpret these data at the present time.

2. DETAILS OF THE TEST ASSEMBLIES

The three sizes of circular hollow sections selected for the study were:-

- (1) 244.5 mm O/D \times 6.3 mm wall thickness
- (2) 323.9 mm O/D \times 6.3 mm wall thickness
- (3) 355.6 mm O/D \times 9.5 mm wall thickness

The steel quality for each was BS4360:Grade 43C.

The tubes were infilled, without re-inforcement, using a nominally Grade 40 granitic aggregate concrete mix.

Each assembly was instrumented such that the temperatures of both the steel tube and the concrete infill could be recorded throughout the test.

Loads of 635.4 kN, 1864 kN and 900 kN were applied to the assemblies respectively. These were calculated using the computer program FEUGODTU.

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

- (1) Steel supply, analysis, properties and dimensions.
- (2) Test piece construction/fabrication.
- (3) Concrete infilling/sampling.
- (4) Instrumentation.
- (5) Assembly/Loading/Loads applied.
- (6) Failure criteria.

3. EXPERIMENTAL RESULTS

The test assemblies achieved the following fire resistance ratings:-

- (1) 244.5 mm O/D \times 6.3 mm wall - 56 min (intended rating 60 min).
- (2) 323.9 mm O/D \times 6.3 mm wall - 45 min (intended rating 60 min).
- (3) 355.6 mm O/D \times 9.5 mm wall - 142 min (intended rating 120 min).

Detailed descriptions of the actual tests are contained in Appendices 2-4.

3.1 Residual Load Bearing Capacity Tests

The full test load appropriate to each column was re-applied approximately 18 hours after the completion of each test. In all cases the column supported the applied load. The requirements of the residual load bearing capacity test were therefore considered to have been satisfied.

4. SUMMARY AND CONCLUSIONS

BS476:Part 21 standard fire resistance tests have been carried out on three different sizes of circular hollow section filled with concrete.

The sections, which were all Grade 43C steel, had nominal dimensions of:-

244.5 mm O/D × 6.3 mm wall
 323.9 mm O/D × 6.3 mm wall and
 355.6 mm O/D × 9.5 mm wall

Loads of 635.4 kN, 1864 kN and 900 kN were applied to the columns respectively. These loads were calculated using the CTICM/VALEXY computer program FEUGODTU, and were determined using actual material properties.

The intended fire resistance periods were 60 minutes in the case of the two smaller section sizes and 120 minutes for the larger section. Actual fire resistance ratings of 56, 45 and 142 minutes were obtained for the 244.5 mm, 323.9 mm and 355.6 mm O/D sections respectively.

A full assessment of the test data has still to be undertaken. However, a preliminary assessment of the results show that the computer model can accurately predict the loads which the columns can carry in a fire situation provided that proper account is taken of the columns' effective length and the actual strength properties of the concrete infill.

5. FURTHER WORK

Further work is planned in which the test assemblies will be sectioned to permit an examination of the concrete infill to be carried out. It is anticipated that it may then be possible to correlate the concrete characteristics with the thermal histories.

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1. Computer Programme 'FEUGODTU' Residing at CTICM and VALEXY, (ex Cometube), Paris, France.

2. W. Klingsch and K. Kordina, 'Fire Resistance of Composite Columns with Concrete Filled Hollow Sections, Parts I and II, Final Report CIDECT Programme 15C', CIDECT Report No. 15 C1/C2-83/27, Studiengesellschaft für Anvendugstechnik Von Stahl und Eisen e.V., Dusseldorf, Germany, 1983.
3. L. Twilt and P.W. Van de Haar, 'Harmonisation of the Calculation Rules for the Fire Resistance of Concrete Filled Structural Hollow Section Columns'. CIDECT Report No. 15F-86/7-0 (TNO Fire Report B-86-461). TNO Building and Construction Research, Delft, The Netherlands, August 1986.
4. Eurocode No. 4, Design of Composite Structures, Part 10: Structural Fire Design (Draft), 1990. Commission of the European Communities, Brussels, April 1990.

DTS

APPENDIX 1

DETAILS OF THE TEST ASSEMBLIES

A1.1 STEEL SUPPLY

The steel sections used in the construction of all three test assemblies were obtained by the LPC from Randle Steels Ltd., a steel stockholder based in Daventry. For each test a 3.4 m length of the appropriate size of circular hollow section in BS4360:Grade 43C steel was required. In addition a piece approximately 400 mm in length, cut from the same parent section, was required for evaluation purposes. The three sizes of circular hollow sections selected for the work were:-

- (1) 244.5 mm O/D × 6.3 mm wall thickness
- (2) 323.9 mm O/D × 6.3 mm wall thickness
- (3) 355.6 mm O/D × 9.5 mm wall thickness

Samples were taken from each of the 400 mm long sections for chemical analysis and for mechanical testing. The chemical compositions and room temperature tensile results are given in Tables A1.1 and A1.2 respectively. These show that in terms of chemical analysis all three sections satisfied the requirements specified in BS4360 for Grade 43C steel.

From its chemical composition it would be expected that the largest diameter tube would have the highest tensile strength and this is confirmed by the results in Table A1.2. The other two products have UTS values which are at, or below, the minimum specification for a Grade 43C steel. Considering the lean composition of the 323.9 mm diameter tube material it is perhaps not surprising that it has a UTS of only 422 N/mm².

Examination of the 400 mm long off cuts indicated that the largest diameter tube was a hot finished, seamless product, whereas the other two section sizes had both been produced by the ERW route.

Examination of the test certificates supplied by Randle Steels Ltd., reveals the origin of the products to be as follows:-

- (1) 244.5 mm O/D × 6.3 mm CHS

This was supplied from British Steels' 20 inch ERW Mill at Hartlepool against an export order from Germany. It was manufactured to conform with DIN1626-1984 St.37.0 and appears to have been imported back into the UK.

- (2) 323.9 mm O/D × 6.3 mm CHS

This was manufactured in Germany by Stahlwerke Gebr. Fuchs, possibly to ASTM A370 or API 5L specifications.

- (3) 355.6 mm O/D × 9.5 mm CHS

This was manufactured in France by Vallourec Industries.

The results of the chemical analyses and mechanical property determinations carried out at Swinden Laboratories were not available prior to the fabrication of the test columns and their filling with concrete.

A1.2 TEST PIECE CONSTRUCTION DETAILS

A1.2.1 Fabrication

Fabrication details for each of the three tubes were identical, and were as follows:-

10 mm diameter steam vent holes were drilled at four positions spaced equally around the circumference and at a distance of 400 mm from each end of the tube, (see Fig. A1.1). A 35 mm diameter hole to accommodate the thermocouple leads was drilled 90 mm from one end of the tube, this end then being defined to be the 'bottom' end with respect to its eventual position within the test furnace.

A mild steel plate, 8 mm thick and approximately 400 mm square, was lightly tack welded to the 'top' end of the tube to form a temporary end cap. Six permanent end caps having the dimensions shown in Fig. A1.2 were prepared at this time for later use.

A1.2.2 Concrete Infilling

The three tubes were placed in an upright position with the temporary end plate at the base and were located adjacent to an elevated walkway which gave access to their open ends. The general arrangement is shown in Fig. A1.3. Thus the tubes were notionally inverted during the concrete filling operation, this being done to allow a harness of thermocouple leads, (see A1.3.1), to exit through the hole provided at the 'bottom' end of the tube. The tubes were filled, in turn, with a granitic aggregate concrete mix having a minimum 28 day cube strength of nominally 40 N/mm². Filling took place on July 18th 1991.

Samples of the as-delivered concrete were taken by Stanger Consultants Ltd., based in Elstree, for subsequent independent assessment of its compressive strength after curing for periods of 7, 28 and 90 days. Additionally, two containers, each having a volume of approximately 0.03 m³, were filled with concrete and poker vibrated. These were retained by Swinden Laboratories pending further evaluation.

Sufficient concrete was discharged into the steel sections to give an infill depth of approximately 400/450 mm which was then poker vibrated to ensure complete compaction. The procedure was repeated, using similar incremental depths of concrete, until the sections were completely filled. During the filling of each tube three 'spiders', each supporting nine thermocouples, were introduced, (see A1.3.1). Their positions were as indicated in Fig. A1.4, with the accuracy of location being \pm approximately 10 mm. The only exception to this arose in the case of the 323.9 mm diameter tube where the C level spider became misplaced. Its final location was 2110 mm from the true base of the section and not 2550 mm as shown in Fig. A1.4.

The concrete was finished flush with the upper end of the section in all cases. It was checked for contraction after approximately 24 hours and any surface depressions were made good. This was only necessary in the case of the 323.9 mm diameter tube where the concrete level had dropped uniformly by about 5-6 mm over the whole surface. Moisture draining from the vent holes had ceased within 24 hours of filling each tube.

The tubes were left in the as-filled position for a period of four days before the temporary end plates were removed. Any minor grouting repairs to the exposed concrete were carried out as required. The tubes were then left for a further period of 24 days with both ends open to allow some drying out of the concrete to take place. The permanent end plates were attached to the tubes using a 9 mm continuous fillet weld on August 15th 1991. The test pieces were then stored, horizontally, until required for assembly in the furnace. Their ages at the time of testing were as follows:-

(1) **244.5 mm O/D \times 6.3 mm CHS**

Test Date: November 5th 1991
Age at Test: 110 days

(2) **323.9 mm O/D \times 6.3 mm CHS**

Test Date: November 12th 1991
Age at Test: 117 days

(3) 355.6 mm O/D × 9.5 mm CHS

Test Date: November 26th 1991
 Age at Test: 131 days

A1.3 INSTRUMENTATION**A1.3.1 Temperature Measurement**

A total of 27 'K' type thermocouples, formed from glass-fibre covered Ni-Cr/Ni-Al conductors, were used to monitor the temperature of the concrete infill during each test. The thermocouples were attached to three 'spiders' formed from 12 gauge galvanised mild steel mesh. These were positioned within the concrete as indicated in Fig. A1.4 and described in Section A1.2.2. The thermocouples were identified by the numbers 1-9, prefixed by A, B or C depending on their level within the concrete.

Twelve 1.5 mm diameter mineral insulated 'K' type thermocouples, each with insulated hot junctions and Inconel sheaths, were used to monitor the temperature of the steel tube during each test. The thermocouples were embedded to the mid-thickness position in the tube wall. They were identified by the numbers 10-13 which were also prefixed by A, B or C as appropriate.

The disposition of the concrete and steelwork thermocouples was as shown in Fig. A1.5. Note that in Fig. A1.4 the column is shown in the position in which it was tested and that Fig. A1.5 is a plan view on the column in this position.

After the test assembly had been located within the furnace a further six thermocouples were installed in order to monitor the furnace atmosphere temperature at positions along its height. These thermocouples were of identical construction to those used in the steelwork but were of 3 mm diameter. 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 ATM1-6 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

It is worth noting that the LPC also have a thermocouple located at the junction between the two furnace shells. Thus the furnace atmosphere temperature is actually monitored and controlled by means of seven thermocouples. Hence there may be some variation between the temperatures presented in this report and those contained in documents prepared by the LPC.

A1.3.2 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.

A1.4 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. A1.6). 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. Views of one of the columns installed in the furnace prior to testing are shown in Figs. A1.7(a) and (b).

The load was applied to the column by means of two hydraulic jacks acting through the lower crosshead member. It was applied 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.

A1.5 LOADS APPLIED

The loads to be applied to the test columns were calculated using the computer program FEUGODTU, to which reference has already been made. All aspects concerning this code were the responsibility of the Tubes Division Research organisation based in Corby. It is understood that the loads were determined using the measured material properties for the steel and concrete components and according to the intended fire survival times. The fire resistance ratings specified were 120 minutes, in the case of the 355.6 mm O/D section, and 60 minutes for the two smaller sections. Calculation procedures were revised during the programme to take account of information gleaned from earlier tests. The loads actually applied were:-

(1) 244.5 mm O/D × 6.3 mm CHS

Load = 635.4 kN

(2) 323.9 mm O/D × 6.3 mm CHS

Load = 1686 kN

(3) 355.6 mm O/D × 9.5 mm CHS

Load = 900 kN

A1.6 CONCRETE CUBE TEST DATA

The concrete cube samples taken by Stanger Consultants Ltd. were tested in accordance with the requirements of the appropriate parts of BS1881:1983. The values reported by them for the compressive strength and density of the concrete after curing periods of 7, 28 and 90 days are shown in Table A1.3.

A1.7 COLUMN DIMENSIONS

The cross sectional dimensions of the three columns were measured at positions around the circumference as indicated in Fig. A1.8. The mean dimensions were recorded as:-

(1) 244.5 mm O/D × 6.3 mm CHS

Nominal Hp/A	= 163 m ⁻¹
Mean diameter	= 244.5 mm
Mean wall thickness	= 6.34 mm
Hp/A based on mean dimensions	= 162 m ⁻¹

(2) 323.9 mm O/D × 6.3 mm CHS

Nominal Hp/A	= 162 m ⁻¹
Mean diameter	= 324.0 mm
Mean wall thickness	= 6.17 mm
Hp/A based on mean dimensions	= 165 m ⁻¹

(3) 355.6 mm O/D × 9.5 mm CHS

Nominal Hp/A	= 108 m ⁻¹
Mean diameter	= 356.0 mm
Mean wall thickness	= 8.64 mm
Hp/A based on mean dimensions	= 119 m ⁻¹

A1.8 FAILURE CRITERIA

The performance of all three test assemblies was judged against the load bearing capacity criterion outlined in Section 6 of BS476:Part 21:1987^(A1.1) and in accordance with the general principles embodied in BS476:Part 20:1987^(A1.2).

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.

REFERENCES

- A1.1 Fire Tests on Building Materials and Structures, Part 21 - Methods for Determination of the Fire Resistance of Load Bearing Elements of Construction, BS476:Part 21:1987, BSI London 1987.
- A1.2 Fire Tests on Building Materials and Structures, Part 20 - Methods for Determination of the Fire Resistances of Elements of Construction, (General Principles), BS476:Part 20:1987, BSI London 1987.

TABLE A1.1
CHEMICAL COMPOSITIONS OF THE STEEL SECTIONS 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
1M12D	244.5 mm O/D × 6.3 mm thick wall Circular hollow section Test Date: 05/11/1991 Test I/D: LPC 81441	0.064	0.23	0.55	0.021	0.003	0.02	<0.005	<0.02	0.035	<0.02	0.0082	<0.005	<0.005	<0.005	<0.005
1M13D	323.9 mm O/D × 6.3 mm thick wall Circular hollow section Test Date: 12/11/1991 Test I/D: LPC 81442	0.089	0.02	0.31	0.011	0.007	0.03	<0.005	0.02	0.037	<0.02	0.0060	<0.005	<0.005	<0.005	<0.005
1M14D	355.6 mm O/D × 9.5 mm thick wall Circular hollow section Test Date: 26/11/1991 Test I/D: LPC 81443	0.12	0.28	0.90	0.011	0.017	0.15	0.035	0.11	0.032	0.19	0.012	<0.005	0.009	<0.005	<0.005
	BS4360:1990 Grade 43C Product Analysis	0.24 max.	0.55 max.	1.40 max.	0.06 max.	0.06 max.										

**TABLE A1.2
TENSILE TEST RESULTS FROM THE STEEL SECTIONS
USED IN THE FIRE RESISTANCE TESTS**

BS Code	Section and Test Details	Yield Stress (LYS) N/mm ²	Tensile Strength N/mm ²	Elongation %
1M12D	244.5 mm O/D × 6.3 mm thick wall Circular hollow section Test Date: 05/11/1991 Test I/D: LPC 81441	355	430	41
1M13D	323.9 mm O/D × 6.3 mm thick wall Circular hollow section Test Date: 12/11/1991 Test I/D: LPC 81442	354	422	42
1M14D	355.6 mm O/D × 9.5 mm thick wall Circular hollow section Test Date: 26/11/1991 Test I/D: LPC 81443	348	489	45
	BS4360:1990 Grade 43C Product Analysis	275 (min.)	430/580	22 (min.)

**TABLE A1.3
RESULTS OF TESTS ON CONCRETE CUBES
(REPORTED BY STANGER CONSULTANTS LTD.)**

Stanger Test No.	Curing Period (days)	Compressive Strength N/mm ²		Density, kg/m ³	
		Actual	Average	Actual	Average
EM 11588 (1)	7	46.0	45.75	2350	2350
EM 11588 (2)	7	45.5		2350	
EM 11588 (3)	28	55.5	56.5	2355	2355
EM 11588 (4)	28	57.5		2355	
EM 11588 (5)	90	61.0	61.5	2360	2360
EM 11588 (6)	90	62.0		2360	

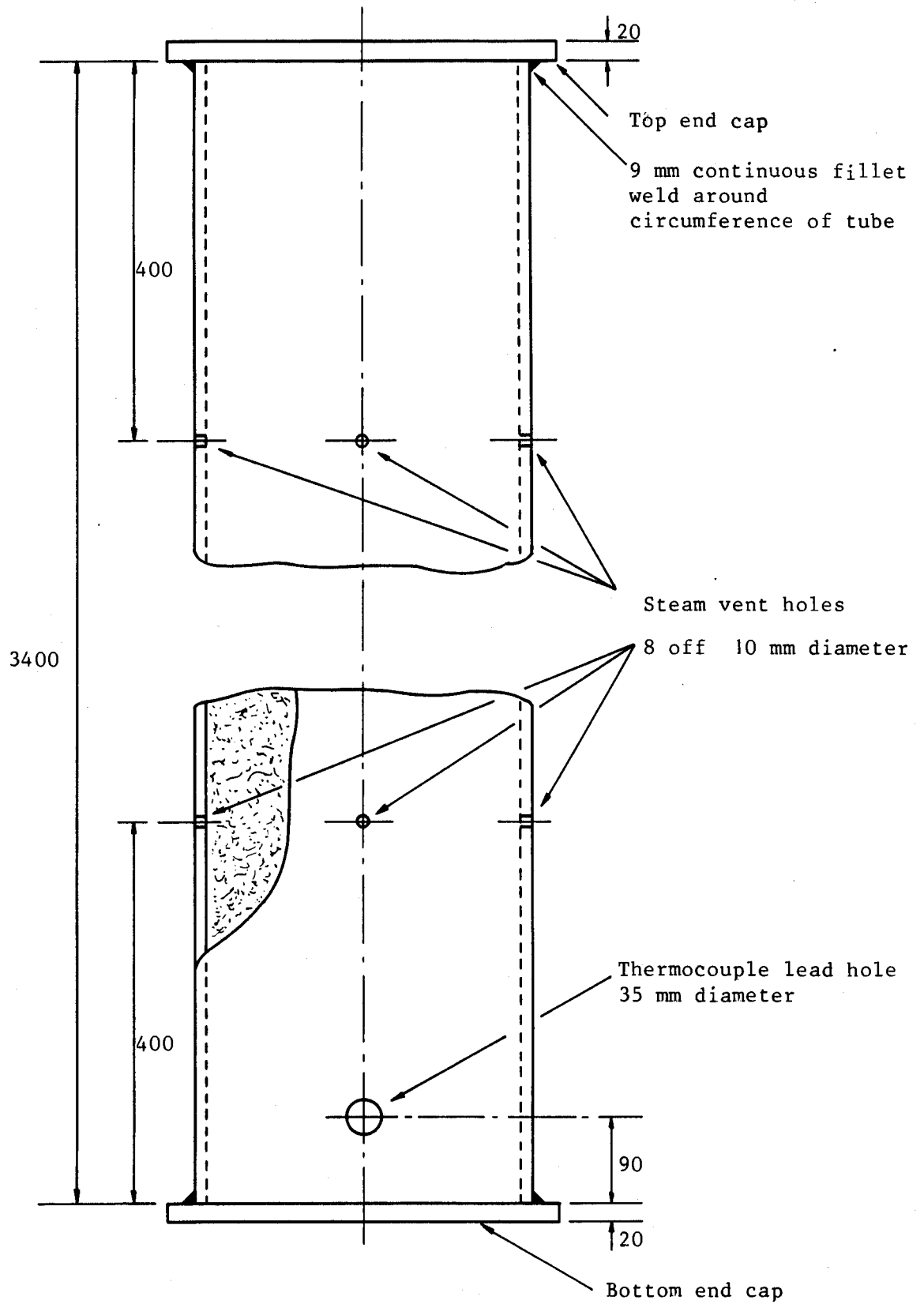


FIG. A1.1 FABRICATION DETAILS FOR COMPLETED TEST SPECIMENS (R3/9413)

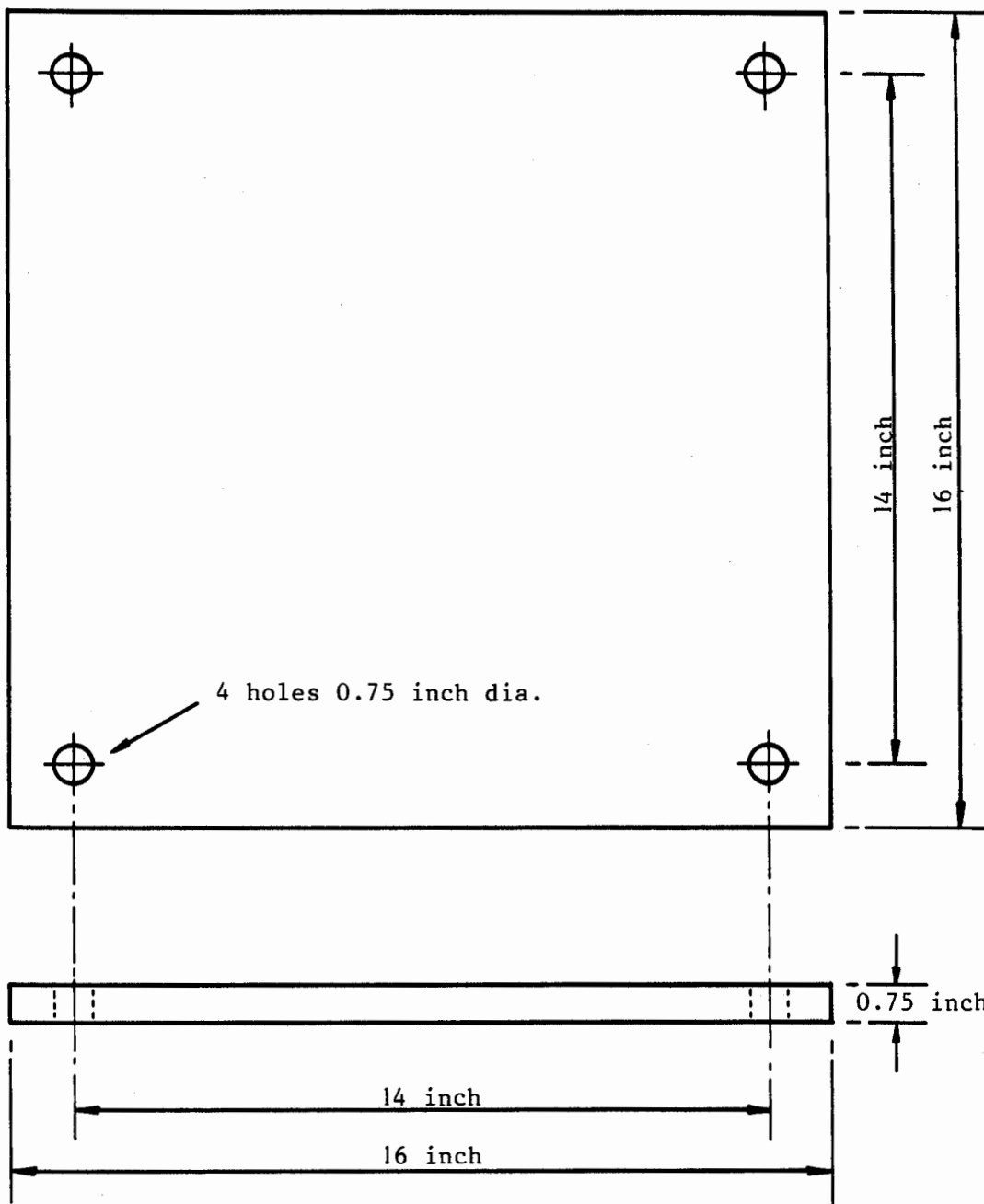


FIG. A1.2 DIMENSIONAL DETAILS OF THE PERMANENT TOP AND BOTTOM END PLATES

(R3/94 14)

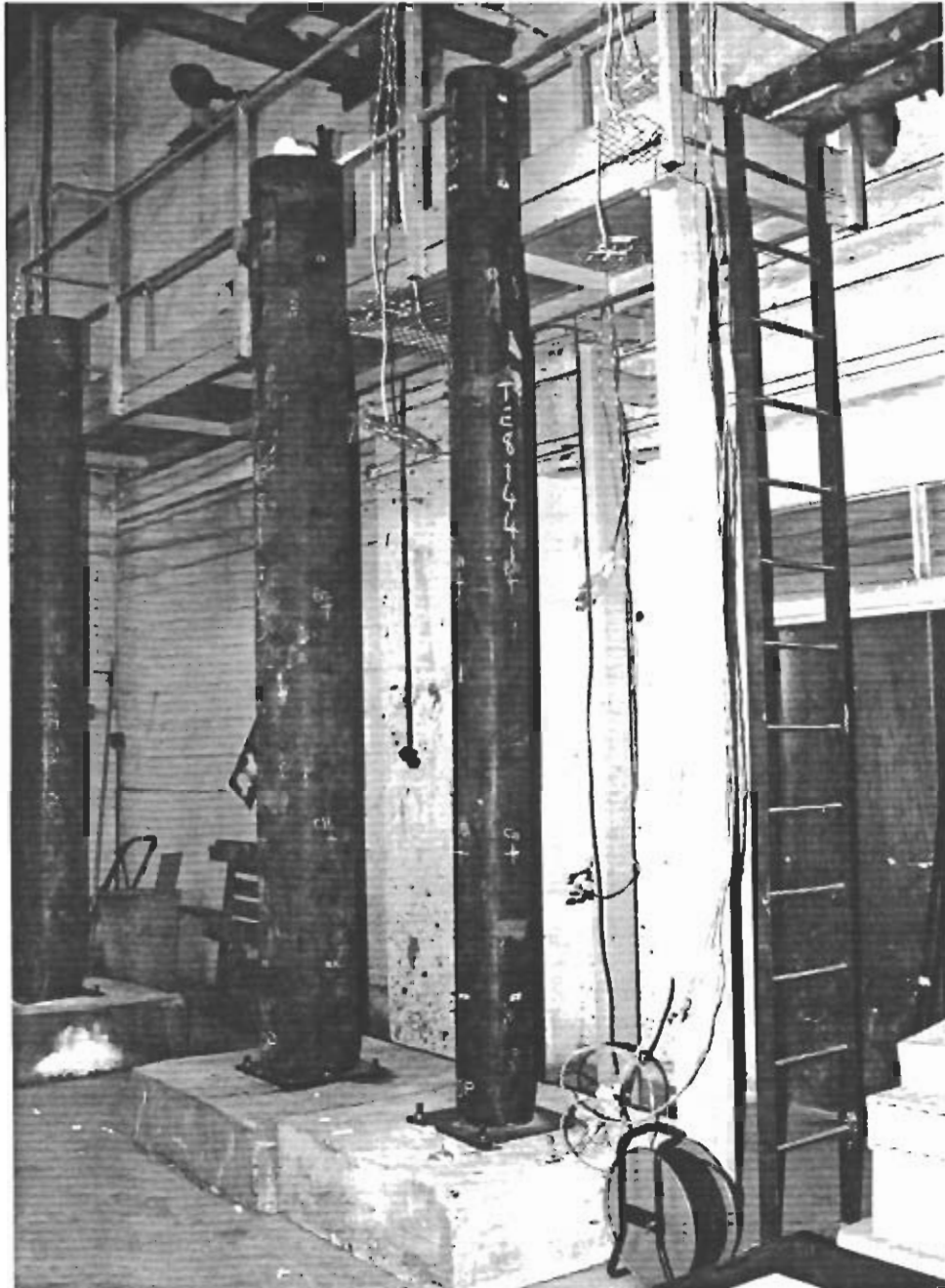
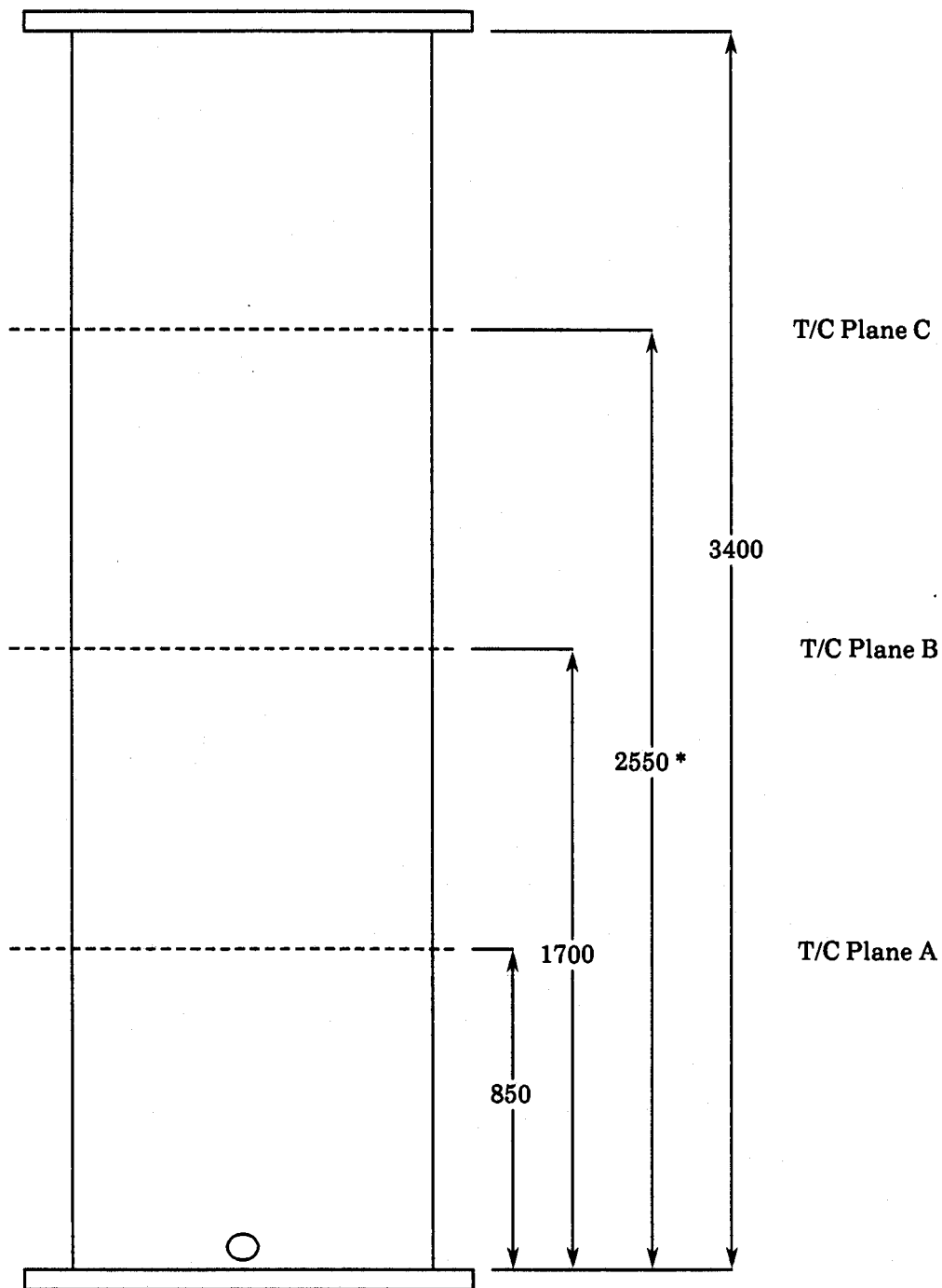


FIG. A1.3 GENERAL ARRANGEMENT OF HOLLOW SECTIONS
FOR FILLING WITH CONCRETE ON 18/7/91



* 2110 mm on 323.9 mm O/D CHS

All dimensions in mm

**FIG. A1.4 THERMOCOUPLE POSITIONS IN THE STEEL AND CONCRETE
(VERTICAL DISPOSITION)**

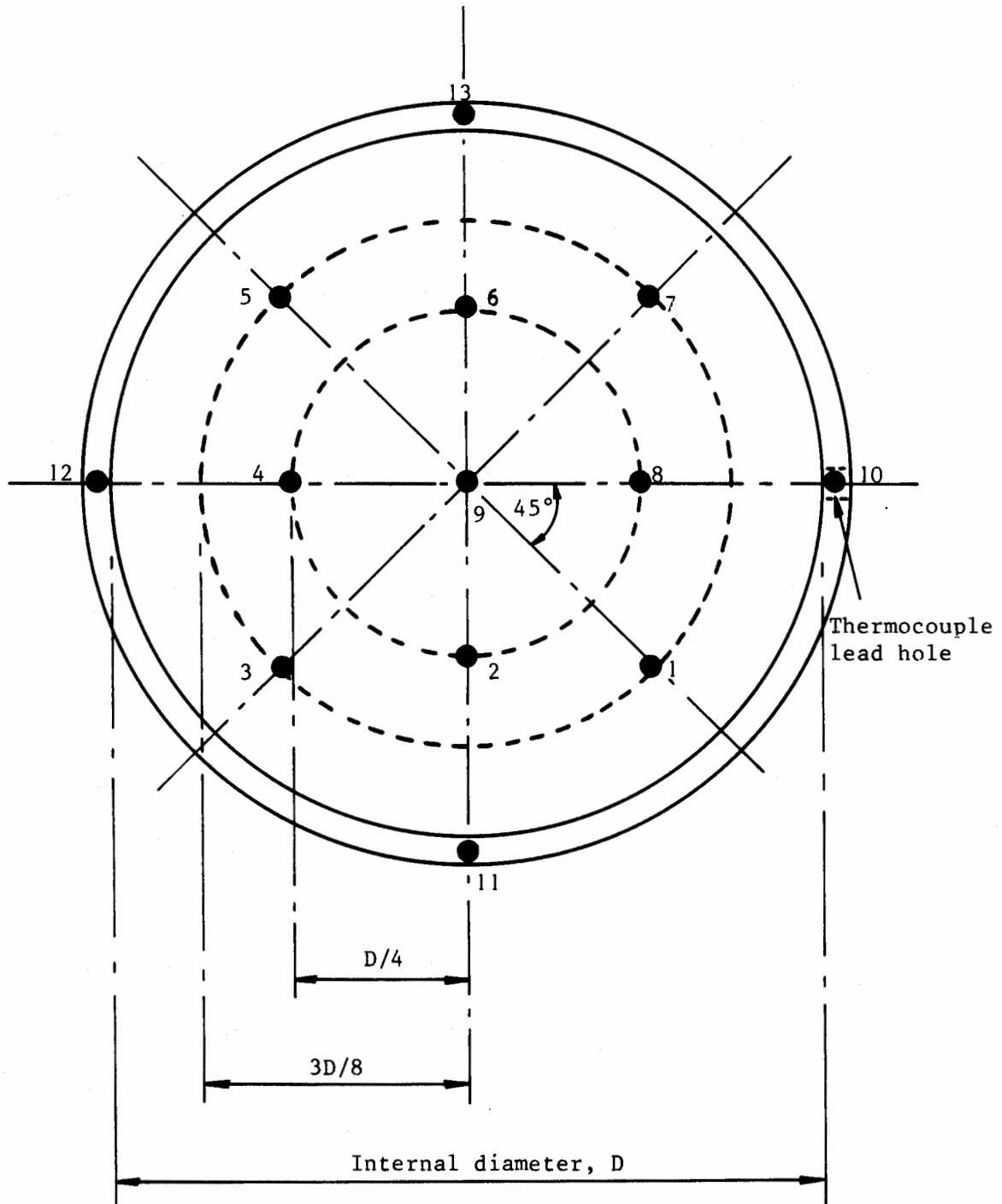


FIG. A1.5 THERMOCOUPLE POSITIONS IN THE STEEL AND CONCRETE
(HORIZONTAL DISPOSITION)

(R3/9416)

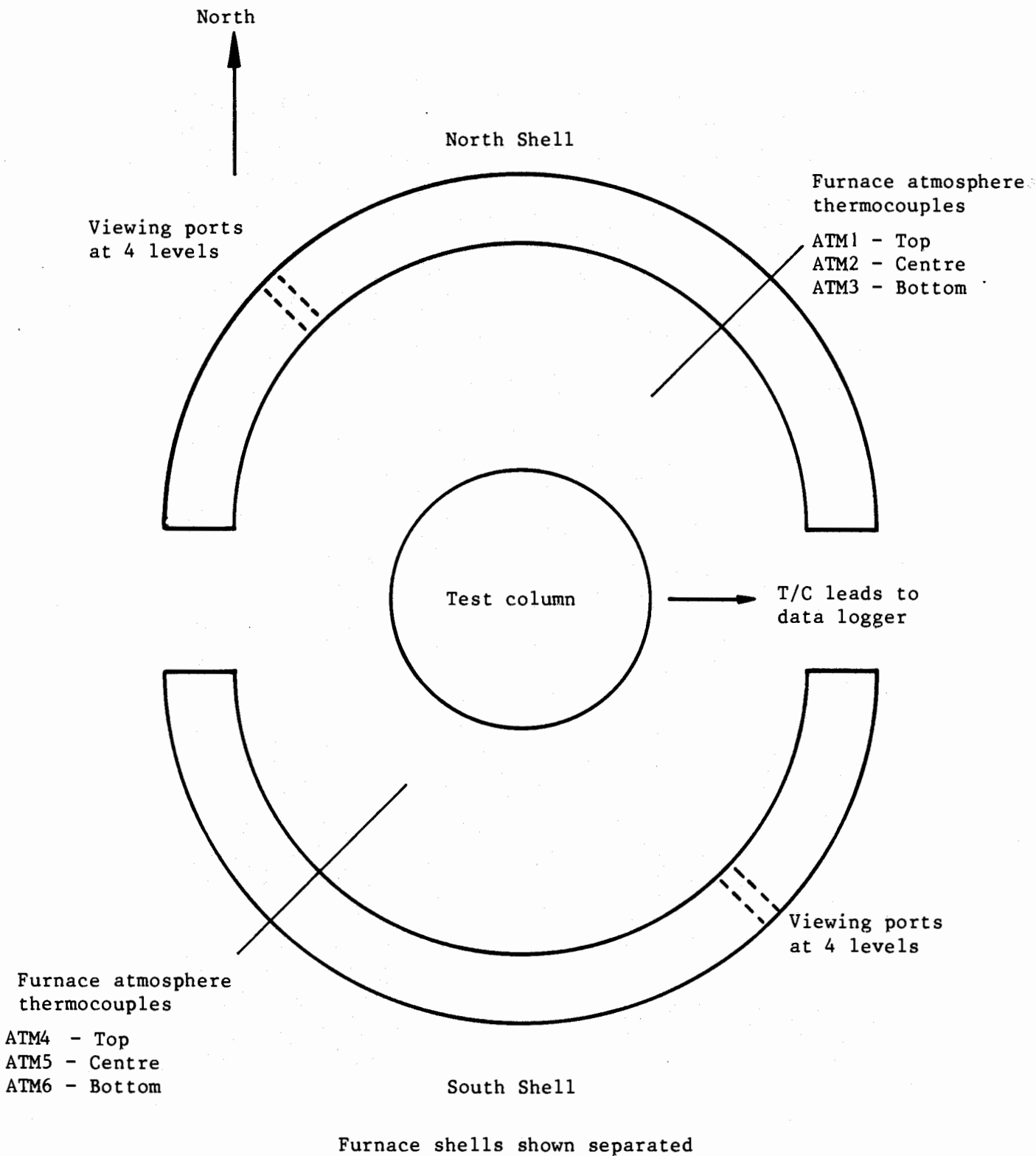


FIG. A1.6 LPC COLUMN TEST FURNACE - POSITION AND ORIENTATION (R3/9417)
OF MAJOR COMPONENTS

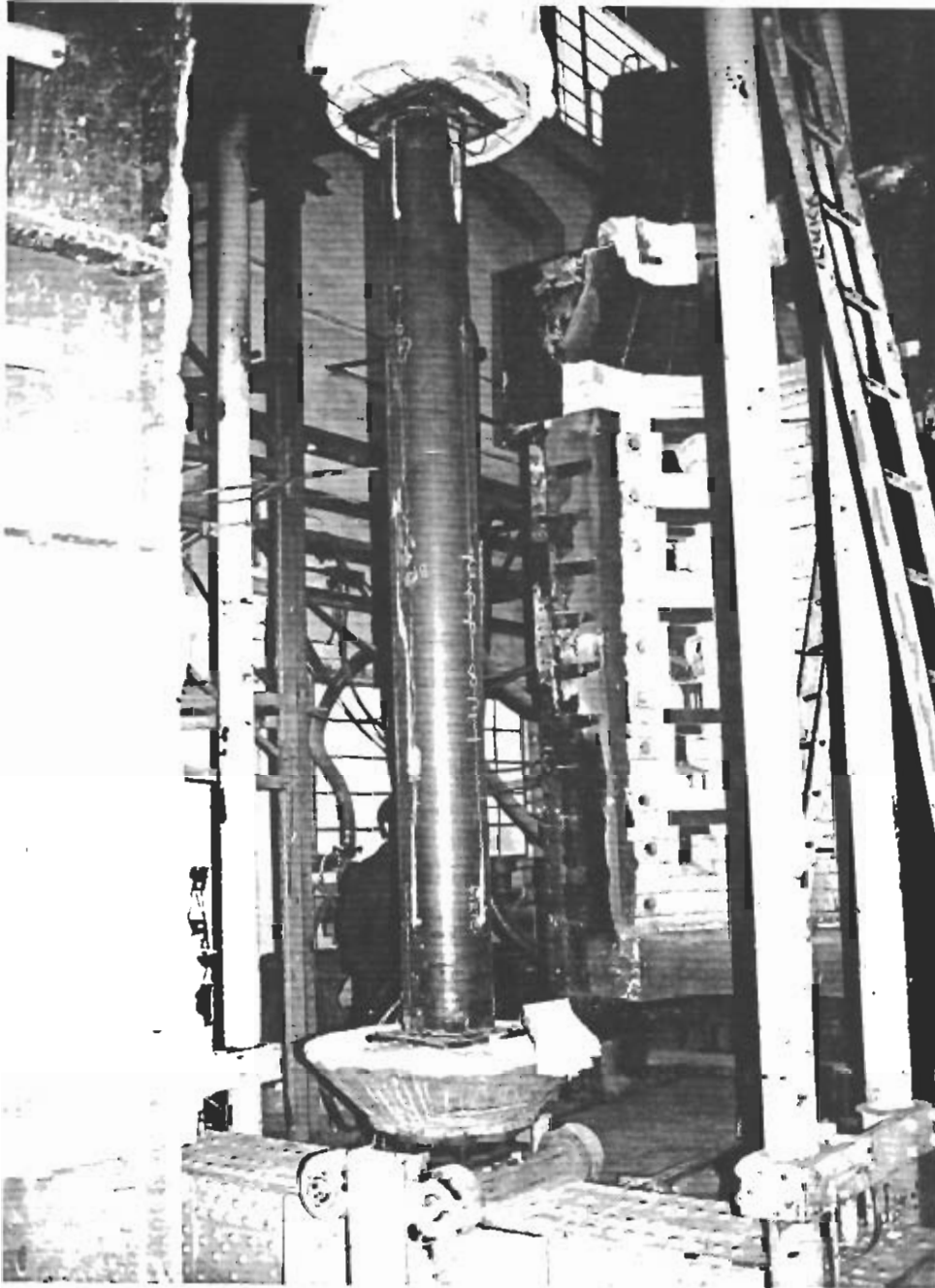


FIG. A1.7a TEST COLUMN DURING COURSE OF ASSEMBLY

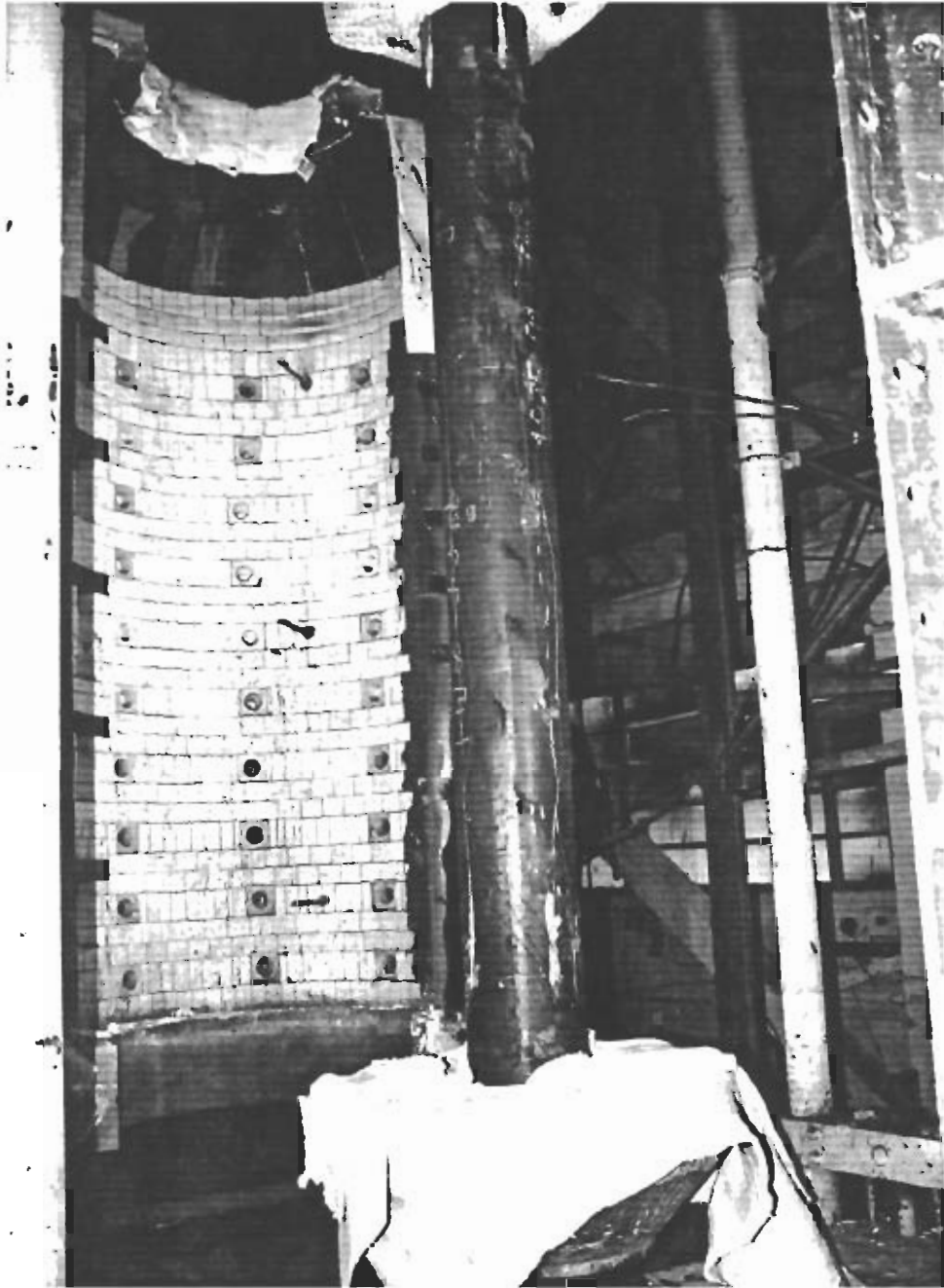
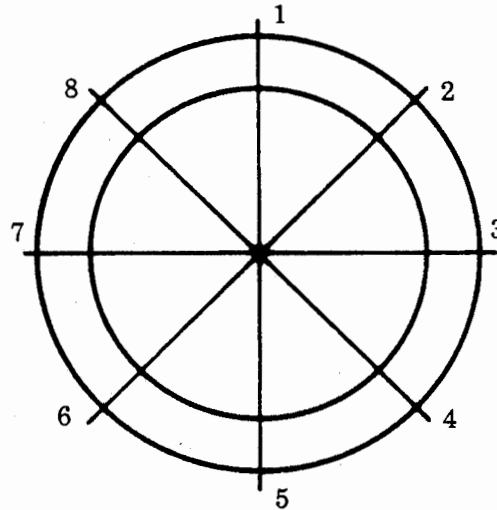


FIG. A1.7b TEST COLUMN DURING COURSE OF ASSEMBLY



Parameter	BS Code	1M12D	1M13D	1M14D
<u>Nominal Dimensions</u>				
Outer diameter, mm		244.5	323.9	355.6
Wall thickness, mm		6.3	6.3	9.5
Hp/A, m ⁻¹		163	162	108
<u>Actual Dimensions</u>				
Outer Diameters, mm				
Between Positions 1 & 5		243.5	323.0	356.0
Between Positions 2 & 6		244.5	324.0	356.0
Between Positions 3 & 7		245.5	324.5	356.0
Between Positions 4 & 8		244.5	324.5	356.0
Mean outer diameter, mm		244.5	324.0	356.0
Wall Thicknesses, mm				
At Position No. 1		6.31	6.15	8.94
At Position No. 2		6.33	6.17	9.11
At Position No. 3		6.35	6.12	9.10
At Position No. 4		6.34	6.20	8.35
At Position No. 5		6.30	6.27	7.97
At Position No. 6		6.35	6.18	7.97
At Position No. 7		6.35	6.15	8.76
At Position No. 8		6.35	6.15	8.92
Mean wall thickness, mm		6.34	6.17	8.64
Hp/A, based on mean dimensions, m ⁻¹		162	165	119

On 1M12D and 1M13D the weld was at Position 1
There was no weld on 1M14D (seamless)

FIG. A1.8 DIMENSIONAL DATA FOR THE THREE TEST COLUMNS

APPENDIX 2

DETAILED EXPERIMENTAL RESULTS - 1ST COLUMN TEST

A2.1 TEST NO. LPC 81441 (244.5 MM OD × 6.3 MM THICK WALL CHS)

The test was carried out in accordance with Section 6 of BS476:Part 21:1987 at the LPC, Borehamwood, on 5th November 1991.

The column supported the full test load of 635.4 kN for a period of 56.5 minutes, after which time the load could no longer be supported. At 58 minutes a decreasing load was reduced to a pinch value and the test was terminated after 60 minutes. In accordance with the provisions of BS476:Part 21 the fire resistance rating of the test assembly was 56 minutes.

A2.1.1 Temperature Measurements

The temperatures recorded by the six thermocouples monitoring the furnace atmosphere are presented in Table A2.1. The table also gives the mean furnace atmosphere temperatures and the corresponding BS476 standard heating curve values. The temperature data from the twelve thermocouples embedded in the steelwork are presented in Table A2.2, together with the average temperatures at the three measurement planes. Similarly, the temperatures recorded in the concrete at the $\frac{3}{8}$ diameter, $\frac{1}{4}$ diameter and central positions are presented in Tables A2.3, A2.4 and A2.5 respectively.

In Fig. A2.1 the average furnace atmosphere temperature is compared with the BS476 time/temperature curve. It may be seen that after the first few minutes the average temperature remained below the aim value until about 30-35 minutes into the test. Thereafter there was much closer agreement with the standard curve values. The plot provided by the LPC shows much closer agreement between the furnace temperature and the aim values. However, as noted in Section A1.3.1, the LPC use seven thermocouples for furnace control purposes. The influence of this seventh thermocouple would therefore appear to be significant. It is suggested that in any future tests a thermocouple at this position should be included in the British Steel logging procedure.

The data presented in Table A2.2 for the steelwork are shown graphically in Figs. A2.2, A2.3 and A2.4. Similarly, Figs. A2.5 to A2.10 are plots of the data presented in Tables A2.3 and A2.4 for the concrete infill at the $\frac{3}{8}$ and $\frac{1}{4}$ diameter positions. Lastly, Fig. A2.11 is a plot of the data in Table A2.5 for the concrete core temperatures at the three measurement levels.

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 A2.6 and is shown plotted in Fig. A2.12. The maximum extension under load was 17.5 mm. This occurred 24.5 minutes from the commencement of the test, and was held until the 26th minute after which time the column began to contract. The column regained its original length after approximately 55.25 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/s	Event
-15.00	Load of 635.4 kN applied to the column. Displacement transducer set to zero.
00.00	Test commenced
20.00	Sound of steam issuing from the vent holes becoming noticeable.
24.30	Column extension reaches a maximum value of 17.5 mm
25.00	Steam emission very apparent (visually and audibly)
26.30	Column begins to contract
29.00	Steam emission continues. No evidence of any deformation of the column.
32.00	No change from conditions noted at 29.0 minutes.
34.00	A bulge starts to form in the column. It is estimated to be protruding approximately 10-15 mm from the tube wall and is about 80 mm in depth from just below its mid-height
40.00	No apparent change to bulge condition since 34.0 minutes. Concrete plugs appear to have been blown out of the lower vent holes.
46.00	No significant change to bulge condition. Steam emission continues.
51.00	No significant changes from 46.0 minutes.
55.00	Column length almost at its original value.
55.30	Column length less than its original value.
56.30	Column unable to support the load. Column started to bend at this time.
58.00	Load reduced to a pinch value.
60.00	Test estimated

A2.1.3.2 Subsequent to the Test

On opening up the furnace, immediately after the test, it was noted that there was a region approximately 400 mm in length at the bottom of the column which appeared to be considerably cooler than the remainder. The top of this region coincided with the four lower vent holes from which steam under considerable pressure continued to be emitted. There did not appear to be a corresponding cooler region at the top of the column.

Figures A2.13 and A2.14 are general views of the column, after cooling, taken from the South-East and West positions respectively. These give an overall indication of the extent to which the column deformed during the last few minutes of the test. They also confirm the observations made during the test that a bulge had formed just below the mid-height of the tube. A more detailed examination of the column revealed that the bulge was in fact of a spiral form. Its starting point was adjacent to the B11

thermocouple position. It then proceeded Westwards, through the B12 position, to the Northwest where it dropped approximately 75 mm in height before continuing around the tube to re-appear at the South side some 50 mm or so below its starting point. It then continued at this level onto the West side of the tube where it terminated. These details can be seen in Figs. A2.15-A2.18 which were taken from the SW, W, NW and NE positions respectively.

A feature which was not observed during the test was a second bulged area located roughly between the SE and NE faces of the tube. This can be seen in Fig. A2.13 and in more detail in Figs. A2.17 and A2.18. The peak of the bulge was situated approximately 300-350 mm below the mid-height of the tube.

Apart from the bowing of the column, and the two bulged areas, the remainder of the tube appeared to be free of any other deformations.

TABLE A2.1
FURNACE ATMOSPHERE TEMPERATURE DATA - LPC 81441
(244.5 mm OD × 6.3 mm THICK WALL CHS)

TIME MINS	ISO TEMP	ATM 1	ATM 2	ATM 3	ATM 4	ATM 5	ATM 6	ATM AVE
0	20	83	73	75	62	58	22	62
1	349	477	428	246	392	420	207	362
2	445	515	509	370	436	524	407	460
3	502	514	526	394	430	534	451	475
4	544	534	558	447	460	557	511	511
5	576	556	581	487	525	583	546	546
6	603	594	592	503	547	607	546	565
7	626	631	610	555	573	625	604	600
8	645	648	617	582	587	638	619	615
9	663	674	653	602	615	671	635	642
10	678	683	665	618	625	692	638	654
11	693	691	671	624	656	694	652	665
12	705	705	703	639	665	709	681	684
13	717	707	716	659	679	718	690	695
14	728	716	724	670	685	737	687	703
15	739	720	730	679	700	736	688	709
16	748	730	734	681	699	731	697	712
17	757	744	763	744	713	773	737	746
18	766	740	754	741	732	766	730	744
19	774	745	760	752	730	750	743	747
20	781	750	758	749	729	750	749	748
21	789	751	763	752	732	735	760	749
22	796	787	776	771	749	750	765	766
23	802	794	790	779	754	781	775	779
24	809	801	799	791	764	788	775	786
25	815	803	810	802	767	806	786	796
26	820	808	813	807	774	812	800	802
27	826	815	814	807	783	797	810	804
28	832	825	827	820	801	807	832	819
29	837	840	842	811	816	815	842	828
30	842	849	852	825	819	831	851	838
31	847	851	857	829	820	857	852	844
32	851	850	850	844	810	870	843	845
33	856	847	848	841	821	878	844	847
34	860	861	871	854	826	883	859	859
35	865	862	867	865	837	887	876	866
36	869	870	869	858	845	886	868	866
37	873	868	863	851	839	896	851	861
38	877	878	879	859	853	903	865	873
39	881	885	881	853	864	887	875	874
40	885	896	891	861	868	915	887	886
41	888	899	898	874	869	916	893	892
42	892	906	900	890	875	903	892	894
43	896	914	904	892	880	903	896	898
44	899	920	903	870	885	895	889	894
45	902	923	919	873	887	918	904	904
46	906	928	918	880	892	915	903	906
47	909	933	921	886	894	909	901	907
48	912	935	928	892	898	933	908	916
49	915	914	926	895	872	921	900	905
50	918	906	926	903	867	929	894	904
51	921	940	931	913	897	928	907	919
52	924	946	935	914	901	932	906	922
53	927	953	940	913	905	928	913	925
54	930	962	948	908	912	942	918	932
55	932	963	950	910	917	934	921	933
56	935	966	956	910	921	938	925	936
57	938	965	958	911	923	949	921	938
58	940	971	963	909	925	958	924	942
59	943	976	963	913	928	965	933	946
60	945	979	967	921	931	972	938	951

TABLE A2.2
TEMPERATURES RECORDED IN THE STEELWORK - LPC 81441
(244.5 mm OD x 6.3 THICK WALL CHS)

TIME MINS	A10	A11	A12	A13	A AVE	B10	B11	B12	B13	B AVE	C10	C11	C12	C13	C AVE
0	13	13	13	13	13	12	13	12	12	12	18	15	14	14	15
1	33	35	30	38	34	36	33	40	25	34	71	46	43	42	51
2	71	78	50	60	65	55	54	58	40	52	89	60	58	64	68
3	94	104	68	74	85	70	68	73	51	66	97	69	71	84	80
4	121	129	90	95	109	90	85	94	64	83	114	83	91	102	98
5	148	156	116	121	135	109	106	116	78	102	141	122	113	117	123
6	170	180	143	143	159	127	127	136	93	121	179	148	140	133	150
7	196	207	174	174	188	144	152	159	110	141	197	174	169	155	174
8	218	226	203	205	213	160	174	182	108	156	234	199	197	174	201
9	248	255	232	240	244	187	209	213	117	182	257	241	225	194	229
10	276	275	260	273	271	215	250	246	141	213	286	276	255	217	259
11	303	301	285	309	300	242	283	276	164	241	323	320	281	236	290
12	328	323	308	329	322	271	312	305	181	267	352	359	309	259	320
13	342	346	332	361	345	291	340	331	202	291	379	399	337	286	350
14	359	367	355	396	369	314	369	359	222	316	388	429	363	312	373
15	378	383	373	426	390	339	397	380	239	339	402	457	392	338	397
16	394	398	394	449	409	361	420	393	253	357	414	471	415	361	415
17	414	416	418	483	433	386	448	415	278	382	425	481	438	384	432
18	434	432	434	488	447	408	471	420	303	401	442	495	460	404	450
19	450	413	433	481	444	431	487	424	321	416	444	507	482	422	464
20	471	396	404	491	441	457	494	421	323	424	453	522	497	440	478
21	483	375	398	506	441	483	498	407	316	426	464	547	505	458	494
22	496	361	415	524	449	506	509	385	302	426	472	564	520	484	510
23	515	361	433	542	463	530	528	395	318	443	486	578	535	510	527
24	535	360	451	559	476	549	545	431	359	471	498	590	554	529	543
25	557	362	468	574	490	569	562	473	403	502	516	598	572	541	557
26	575	371	483	587	504	589	575	514	444	531	528	605	588	550	568
27	591	401	503	598	523	608	577	543	457	546	551	618	599	554	581
28	602	396	531	608	534	625	578	569	468	560	576	629	600	562	592
29	618	388	556	621	546	645	594	591	480	578	599	642	607	577	606
30	632	487	501	633	563	661	613	608	487	592	618	646	617	593	619
31	644	585	535	648	603	677	635	626	500	610	633	644	629	609	629
32	656	628	525	658	617	690	661	622	486	615	655	640	638	616	637
33	663	648	538	659	627	697	679	613	494	621	673	641	646	574	634
34	671	665	564	666	642	702	698	620	514	634	675	650	654	587	642
35	682	680	593	675	658	709	709	629	533	645	687	666	650	615	655
36	693	691	619	684	672	716	716	638	547	654	708	688	652	641	672
37	698	690	636	689	678	724	723	634	544	656	702	702	653	657	679
38	706	698	656	698	690	731	732	639	568	668	709	711	662	668	688
39	715	709	675	707	702	740	739	663	589	683	717	724	678	679	700
40	724	720	690	717	713	746	746	689	601	696	726	735	692	690	711
41	735	729	706	728	725	753	754	707	*	738	739	748	708	702	724
42	745	736	717	735	733	763	762	726	*	750	752	759	719	712	736
43	752	743	727	742	741	771	769	742	*	761	758	771	731	721	745
44	760	748	733	747	747	778	776	750	*	768	765	782	742	729	755
45	765	751	739	752	752	790	782	760	*	777	774	792	749	737	763
46	772	757	745	759	758	797	789	768	*	785	782	803	757	744	772
47	777	762	753	765	764	802	792	774	*	789	793	812	764	750	780
48	782	768	761	773	771	808	799	778	*	795	800	821	772	758	788
49	787	772	768	780	777	814	803	785	*	801	794	820	777	763	789
50	791	775	774	787	782	818	807	793	*	806	793	815	779	767	789
51	796	780	781	796	788	824	811	801	*	812	802	826	786	773	797
52	803	787	789	806	796	835	816	810	*	820	811	836	795	782	806
53	810	794	796	813	803	838	821	819	*	826	817	845	804	790	814
54	818	802	801	820	810	844	828	825	*	832	826	852	812	801	823
55	824	809	806	828	817	850	834	832	*	839	836	861	820	812	832
56	830	816	811	834	823	856	838	838	*	844	844	868	827	823	841
57	835	822	817	840	829	861	844	846	*	850	851	875	833	832	848
58	840	828	825	845	835	867	851	850	*	856	861	881	839	840	855
59	846	834	835	851	842	872	861	853	*	862	867	888	846	848	862
60	850	840	845	856	848	880	871	861	*	871	874	894	852	855	869

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

TABLE A2.3
TEMPERATURES RECORDED AT $\frac{3}{8}$ DIAMETER FROM CENTRE OF CONCRETE
- LPC 81441
(244.5 mm OD x 6.3 mm THICK WALL CHS)

TIME MINS	A1	A3	A5	A7	A AVE	B1	B3	B5	B7	B AVE	C1	C3	C5	C7	C AVE
0	12	12	12	13	12	14	14	12	12	13	14	14	14	14	14
1	12	12	12	13	12	14	14	12	12	13	14	14	14	14	14
2	13	13	13	13	13	14	14	13	13	14	14	14	14	14	14
3	13	13	13	14	13	14	14	13	16	14	14	14	14	14	14
4	16	15	16	17	16	18	16	15	21	18	15	15	16	15	15
5	20	18	19	22	20	21	19	18	25	21	18	18	19	18	18
6	24	22	22	28	24	26	23	22	30	25	21	21	22	21	21
7	29	27	26	36	30	31	26	26	36	30	25	24	26	26	25
8	88	33	31	61	53	36	30	32	45	36	29	27	31	33	30
9	97	43	88	72	75	43	34	41	89	52	63	39	98	96	74
10	102	65	98	85	88	74	38	55	100	67	82	98	106	94	95
11	108	83	104	94	97	87	39	67	106	75	91	104	112	89	99
12	110	93	109	105	104	95	41	78	112	82	97	108	118	96	105
13	116	101	115	115	112	103	94	89	120	102	104	116	122	121	116
14	122	108	120	125	119	111	91	99	131	108	112	123	128	127	123
15	128	115	126	133	126	118	85	108	143	114	120	130	134	134	130
16	134	122	133	138	132	125	89	117	160	123	126	136	140	139	135
17	141	128	146	144	140	132	97	126	180	134	131	139	145	142	139
18	147	134	163	149	148	138	124	133	198	148	137	145	151	148	145
19	151	140	179	154	156	144	139	139	215	159	144	152	157	153	152
20	156	145	188	158	162	149	144	146	225	166	149	157	161	157	156
21	161	150	198	163	168	155	149	153	231	172	155	162	165	163	161
22	164	153	218	205	185	160	145	159	234	175	158	165	166	164	163
23	166	156	232	237	198	165	144	164	240	178	163	169	169	166	167
24	169	159	244	277	212	170	146	169	250	184	170	174	173	171	172
25	171	162	250	304	222	175	151	172	264	191	172	176	174	171	173
26	173	165	247	300	221	181	159	175	258	193	174	178	178	172	176
27	174	168	235	283	215	188	163	177	248	194	174	180	182	177	178
28	174	171	225	273	211	190	173	179	219	190	172	182	185	178	179
29	176	175	203	262	204	193	179	182	195	187	175	186	185	176	181
30	182	176	187	256	200	197	182	185	192	189	179	187	183	176	181
31	185	179	186	256	202	204	185	187	194	193	182	190	180	177	182
32	184	183	175	256	200	214	184	186	191	194	188	191	180	183	186
33	179	183	171	259	198	227	180	186	187	195	187	194	183	182	187
34	176	179	170	266	198	238	177	188	192	199	184	193	178	176	183
35	175	178	175	275	201	248	178	191	210	207	180	200	179	177	184
36	175	179	175	281	203	258	184	196	226	216	179	205	179	178	185
37	175	180	165	284	201	267	191	199	233	223	171	202	170	171	179
38	193	188	159	288	207	276	200	202	244	231	165	204	165	170	176
39	207	200	159	293	215	286	212	207	259	241	162	211	163	173	177
40	219	213	168	299	225	295	223	214	274	252	162	220	162	179	181
41	230	224	179	306	235	305	234	221	287	262	165	230	165	184	186
42	241	236	192	313	246	314	244	229	299	272	171	241	170	186	192
43	252	248	204	319	256	323	253	237	311	281	181	252	178	191	201
44	264	258	215	326	266	332	262	245	323	291	194	263	190	198	211
45	275	268	225	333	275	341	270	251	334	299	209	275	204	209	224
46	286	278	235	340	285	349	278	257	346	308	222	285	217	221	236
47	297	288	244	347	294	358	286	263	357	316	237	294	230	235	249
48	307	297	253	355	303	366	294	268	368	324	251	304	243	248	262
49	317	306	261	362	312	375	301	272	379	332	265	313	254	260	273
50	327	315	270	370	321	383	309	277	391	340	278	323	265	272	285
51	336	323	278	378	329	391	317	280	402	348	291	332	276	282	295
52	345	332	287	386	338	399	324	283	412	355	302	341	286	291	305
53	354	341	296	393	346	406	332	286	422	362	313	350	294	298	314
54	361	350	303	400	354	413	339	289	432	368	322	357	303	306	322
55	369	359	310	407	361	419	345	292	442	375	333	361	311	313	330
56	377	368	317	415	369	426	351	295	451	381	342	368	319	321	338
57	385	377	322	421	376	434	359	298	461	388	352	374	326	328	345
58	393	386	329	428	384	442	364	299	471	394	361	381	333	337	353
59	401	395	339	435	393	450	368	303	480	400	371	387	320	*	359
60	409	404	349	442	401	458	374	308	489	407	380	394	340	*	371

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

TABLE A2.4
TEMPERATURES RECORDED AT 1/4 DIAMETER FROM CENTRE OF CONCRETE
- LPC 81441
(244.5 mm OD x 6.3 mm THICK WALL CHS)

TIME MINS	A2	A4	A6	A8	A AVE	B2	B4	B6	B8	B AVE	C2	C4	C6	C8	C AVE
0	12	12	12	13	12	14	12	12	12	13	14	14	14	14	14
1	12	12	12	13	12	14	12	12	12	13	14	14	14	14	14
2	13	13	13	13	13	14	13	13	13	13	14	14	14	14	14
3	13	13	13	13	13	14	13	13	13	13	14	14	14	14	14
4	13	13	13	13	13	14	13	13	13	13	14	14	14	14	14
5	13	13	13	13	13	14	13	13	13	13	14	14	14	14	14
6	13	13	13	13	13	14	13	13	13	13	14	14	14	14	14
7	13	13	13	14	13	15	13	15	13	14	15	15	15	15	15
8	14	15	14	14	14	15	14	17	13	15	16	15	15	15	15
9	19	48	74	44	46	16	15	21	13	16	18	23	18	17	19
10	22	75	105	72	69	17	17	71	26	33	45	86	68	26	56
11	60	89	111	98	90	24	37	86	80	57	84	100	92	35	78
12	102	98	116	107	106	37	60	94	107	75	97	108	102	54	90
13	112	119	122	114	117	59	89	101	115	91	105	114	109	83	103
14	119	125	127	120	123	77	113	108	120	105	113	120	116	98	112
15	126	131	133	126	129	89	122	114	126	113	120	126	122	107	119
16	132	137	138	132	135	99	130	120	131	120	126	132	127	113	125
17	137	142	143	138	140	107	135	125	135	126	130	136	129	117	128
18	141	148	148	143	145	113	139	131	139	131	136	142	135	124	134
19	146	151	154	148	150	118	143	136	144	135	142	148	142	131	141
20	150	151	155	153	152	123	145	141	148	139	146	152	147	136	145
21	154	155	160	156	156	129	150	146	152	144	151	158	150	143	151
22	157	160	163	159	160	134	155	150	156	149	153	160	151	144	152
23	160	162	166	162	163	138	159	153	160	153	156	163	155	147	155
24	163	164	169	165	165	143	161	157	163	156	162	168	160	152	161
25	165	166	171	167	167	147	164	160	167	160	163	170	164	154	163
26	168	165	173	169	169	151	165	162	169	162	167	172	167	158	166
27	163	167	175	172	169	152	153	163	169	159	170	173	170	159	168
28	143	167	178	174	166	149	146	162	171	157	173	178	174	153	170
29	138	165	181	177	165	147	140	165	172	156	173	180	175	149	169
30	137	146	184	180	162	145	135	167	166	153	179	181	173	145	170
31	141	142	186	183	163	147	133	168	155	151	186	194	166	143	172
32	147	141	184	183	164	155	127	175	141	150	184	190	168	144	172
33	172	142	181	178	168	160	127	176	126	147	183	185	179	170	179
34	175	146	175	174	168	164	130	174	133	150	180	180	177	169	177
35	174	164	168	173	170	166	136	174	137	153	181	179	177	173	178
36	175	173	174	173	174	168	145	174	144	158	181	177	176	175	177
37	164	164	163	163	164	166	163	165	158	163	173	172	170	170	171
38	157	157	156	157	157	161	159	160	160	160	166	165	163	166	165
39	154	154	153	154	154	159	157	161	157	159	162	162	160	163	162
40	152	152	151	152	152	159	155	164	156	159	161	161	159	162	161
41	152	151	151	151	151	160	155	169	156	160	162	162	160	162	162
42	152	152	152	152	152	163	156	174	157	163	166	163	161	164	164
43	156	154	155	154	155	166	158	180	159	166	167	164	163	165	165
44	163	156	158	157	159	169	160	186	160	169	171	165	164	167	167
45	171	159	161	160	163	172	162	194	163	173	176	166	166	169	169
46	179	161	164	163	167	175	165	201	164	176	181	168	167	171	172
47	186	164	168	166	171	179	167	208	166	180	186	171	169	173	175
48	192	167	172	169	175	183	168	216	169	184	191	173	172	176	178
49	198	171	175	172	179	188	170	224	171	188	195	175	174	178	181
50	204	176	179	175	184	194	172	231	173	193	200	177	176	180	183
51	210	180	182	178	188	199	173	238	175	196	204	179	177	182	186
52	215	185	185	181	192	201	174	243	176	199	208	180	179	183	188
53	220	189	188	183	195	203	174	249	178	201	212	181	180	184	189
54	225	195	192	184	199	207	173	254	180	204	216	184	181	184	191
55	230	200	196	186	203	210	172	258	183	206	220	186	182	184	193
56	234	207	199	189	207	214	174	262	187	209	223	189	183	186	195
57	239	213	201	192	211	218	179	266	192	214	227	194	184	188	198
58	243	219	203	196	215	227	185	269	197	220	*	200	188	192	193
59	247	226	207	200	220	234	192	273	200	225	*	203	193	199	198
60	249	233	210	203	224	240	201	277	205	231	*	210	197	*	204

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

TABLE A2.5
TEMPERATURES RECORDED AT THE CENTRE OF THE CONCRETE - LPC 81441
(244.5 mm OD × 6.3 mm THICK WALL CHS)

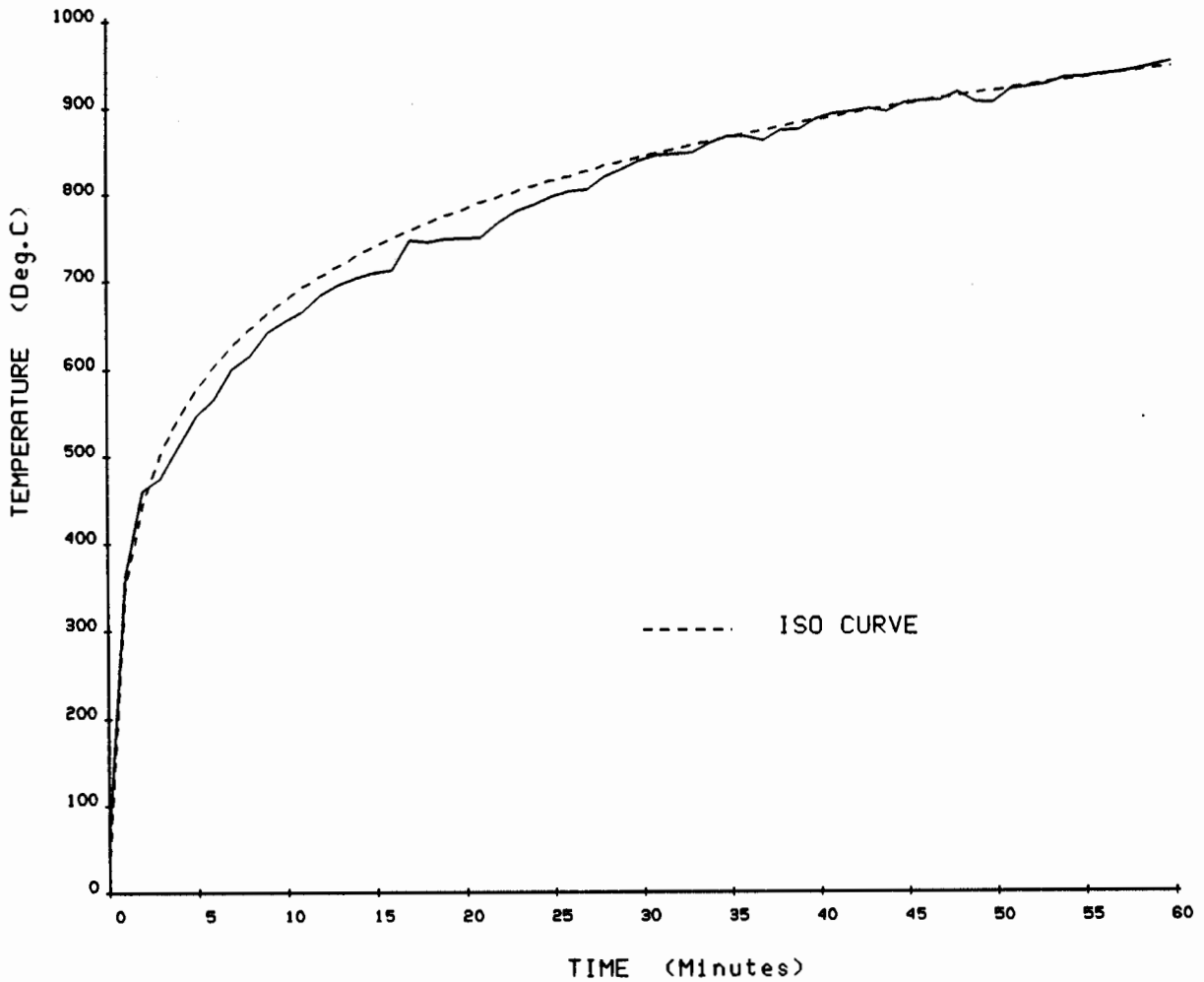
TIME MINS	A9	B9	C9
0	13	12	14
1	13	12	14
2	13	13	14
3	13	13	14
4	13	13	14
5	13	13	14
6	13	13	14
7	14	13	15
8	14	13	15
9	14	13	15
10	16	14	16
11	23	15	49
12	98	42	110
13	98	87	118
14	128	111	128
15	133	126	132
16	136	133	141
17	143	132	141
18	146	134	230
19	151	137	220
20	154	142	209
21	157	146	209
22	159	149	189
23	161	155	188
24	164	155	232
25	165	154	247
26	167	151	203
27	169	137	195
28	170	136	185
29	171	121	177
30	168	115	172
31	151	111	177
32	139	100	216
33	134	100	205
34	143	107	199
35	169	115	195
36	172	123	191
37	164	167	177
38	157	162	168
39	154	159	164
40	152	158	163
41	151	158	164
42	152	160	168
43	154	161	171
44	156	162	177
45	158	165	182
46	161	163	185
47	163	164	187
48	166	167	189
49	169	170	190
50	171	171	189
51	173	172	189
52	175	173	187
53	176	173	180
54	176	175	177
55	176	177	186
56	176	181	185
57	175	183	184
58	174	184	186
59	173	186	189
60	172	192	192

TABLE A2.6
DEFLECTION DATA RECORDED DURING EACH OF THE THREE FIRE TESTS

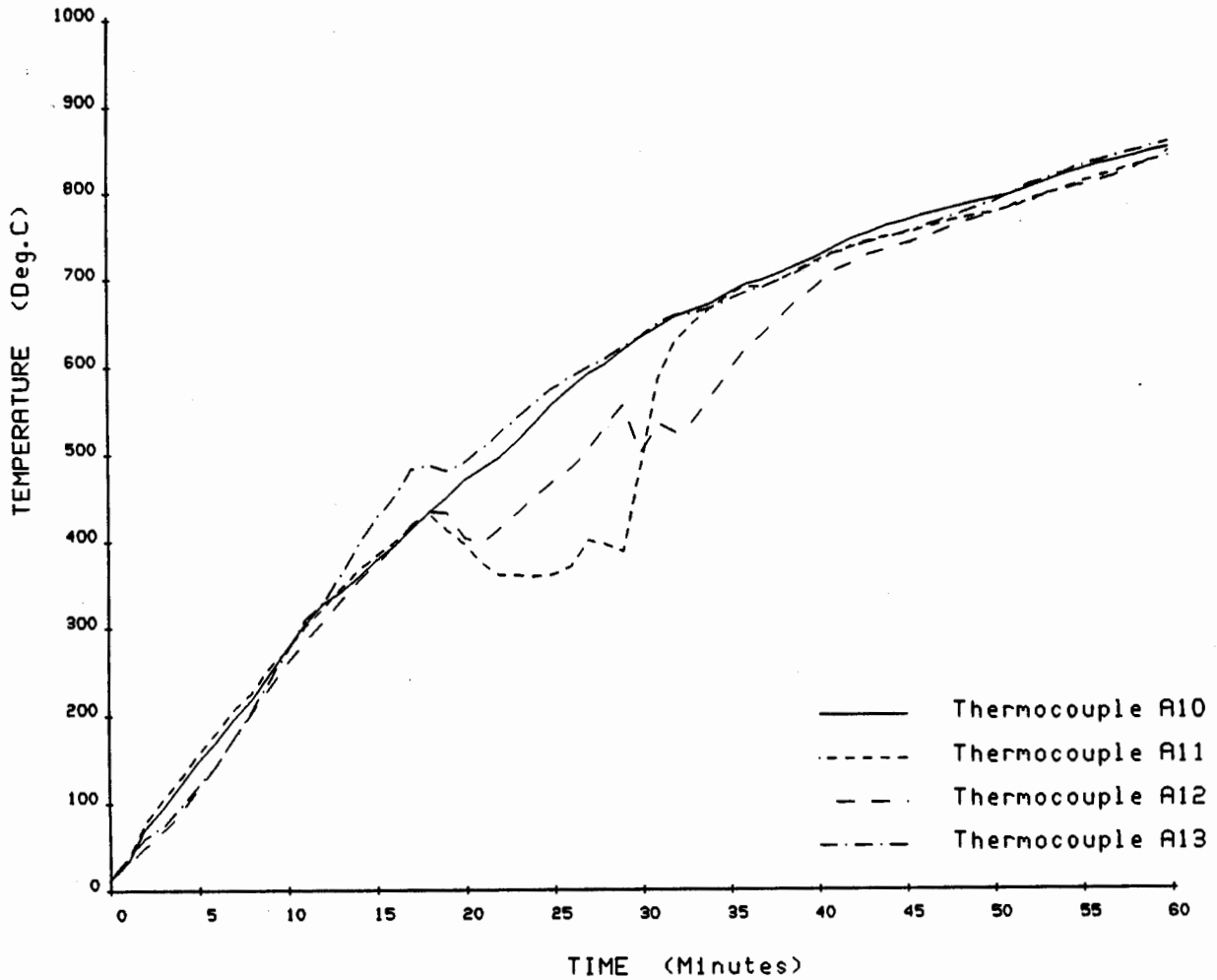
TIME MINS	DEFLECTION (mm)			TIME MINS	DEFLECTION (mm)		
	81441	81442	81443		81441	81442	81443
0	0.00	0.00	0.00	35	10.30	-0.30	16.20
0.50	0.00	0.00	0.10	35.50	10.20	-0.30	15.80
1	0.10	0.10	0.40	36	10.20	-0.30	15.30
1.50	0.30	0.20	0.50	36.50	10.10	-0.40	14.80
2	0.50	0.30	0.60	37	9.90	-0.50	14.30
2.50	0.70	0.50	0.80	37.50	9.70	-0.60	13.70
3	0.80	0.60	1.00	38	9.60	-0.80	13.40
3.50	1.00	0.70	1.40	38.50	9.50	-0.90	13.10
4	1.30	0.80	1.80	39	9.40	-1.00	12.70
4.50	1.60	1.00	2.20	39.50	9.30	-1.20	12.30
5	2.10	1.10	2.50	40	9.20	-1.30	12.00
5.50	2.50	1.30	2.90	40.50	9.10	-1.50	11.60
6	2.90	1.60	3.40	41	9.00	-1.70	11.30
6.50	3.30	1.80	3.80	41.50	8.90	-1.80	11.00
7	3.80	2.00	4.30	42	8.70	-1.90	10.70
7.50	4.30	2.20	4.80	42.50	8.60	-2.00	10.50
8	4.70	2.40	5.40	43	8.40	-2.20	10.30
8.50	5.20	2.60	5.90	43.50	8.30	-2.50	10.00
9	5.80	2.80	6.50	44	8.10	-2.80	9.70
9.50	6.40	3.00	7.00	44.50	7.80	-3.40	9.40
10	7.00	3.20	7.50	45	7.60	-4.80	9.20
10.50	7.50	3.40	8.00	45.50	7.40	-8.20	9.00
11	8.00	3.60	8.50	46	7.10	-12.70	8.80
11.50	8.50	3.80	9.10	46.50	6.80	-18.40	8.50
12	9.10	3.90	9.60	47	6.50	-24.50	8.30
12.50	9.60	4.10	10.20	47.50	6.30		8.10
13	10.20	4.20	10.60	48	5.90		7.90
13.50	10.70	4.20	11.10	48.50	5.70		7.80
14	11.20	4.20	11.50	49	5.40		7.60
14.50	11.70	4.20	12.00	49.50	5.00		7.40
15	12.20	4.10	12.40	50	4.80		7.20
15.50	12.70	4.00	12.90	50.50	4.50		7.00
16	13.20	3.90	13.30	51	4.10		6.80
16.50	13.50	3.80	13.70	51.50	3.80		6.70
17	14.00	3.60	14.10	52	3.50		6.60
17.50	14.50	3.30	14.50	52.50	3.10		6.40
18	14.90	3.00	14.90	53	2.80		6.30
18.50	15.30	2.60	15.30	53.50	2.40		6.20
19	15.60	2.20	15.70	54	1.90		6.10
19.50	15.90	1.90	16.10	54.50	1.30		5.90
20	16.20	1.60	16.60	55	0.60		5.90
20.50	16.40	1.50	17.00	55.50	-0.50		5.80
21	16.50	1.40	17.40	56	-1.90		5.70
21.50	16.70	1.30	17.80	56.50	-4.40		5.60
22	16.80	1.20	18.10	57	-7.90		5.50
22.50	17.00	1.10	18.50	57.50	-12.20		5.40
23	17.20	1.00	18.80	58	-19.30		5.30
23.50	17.30	0.90	19.00	58.50	-26.00		5.20
24	17.40	0.70	19.30	59	-28.00		5.10
24.50	17.50	0.70	19.50	59.50	-29.30		5.10
25	17.50	0.60	19.70	60	-29.90		5.00
25.50	17.50	0.50	19.90	60.50			4.90
26	17.50	0.50	20.00	61			4.80
26.50	17.30	0.50	20.10	61.50			4.80
27	17.00	0.50	20.10	62			4.70
27.50	16.50	0.40	20.20	62.50			4.70
28	16.10	0.40	20.10	63			4.60
28.50	15.70	0.30	20.20	63.50			4.50
29	15.20	0.30	20.10	64			4.50
29.50	14.50	0.30	20.10	64.50			4.40
30	13.70	0.20	20.00	65			4.30
30.50	13.10	0.10	19.70	65.50			4.30
31	12.30	0.10	19.40	66			4.20
31.50	11.70	0.00	19.10	66.50			4.20
32	11.30	0.00	18.70	67			4.10
32.50	11.00	-0.10	18.00	67.50			4.10
33	10.70	-0.20	17.40	68			4.00
33.50	10.50	-0.20	17.20	68.50			4.00
34	10.40	-0.20	16.90	69			4.00
34.50	10.40	-0.20	16.60	69.50			4.00

TABLE A2.6
(CONTINUED)

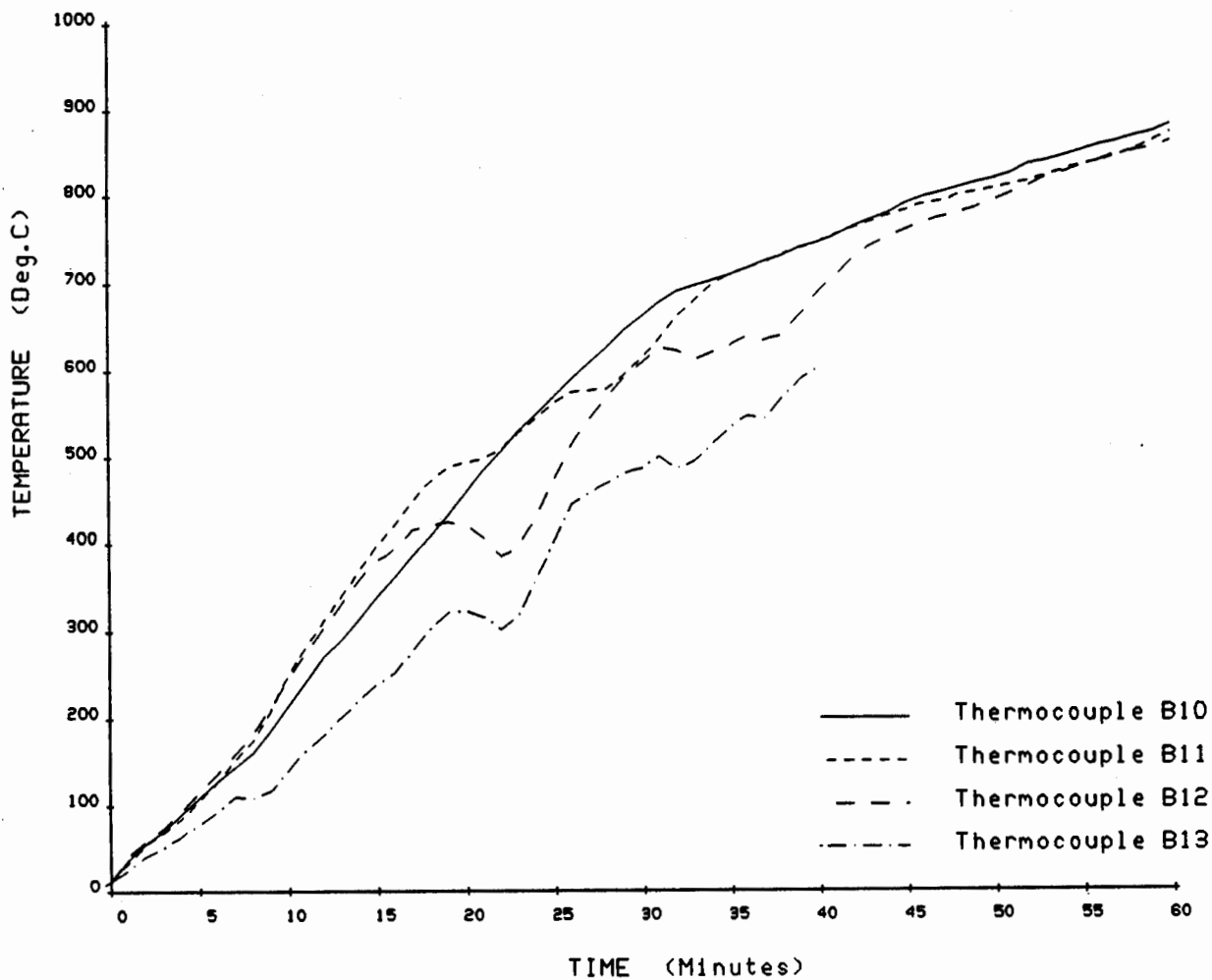
TIME MINS	DEFLECTION (mm)			TIME MINS	DEFLECTION (mm)		
	81441	81442	81443		81441	81442	81443
70			3.90	107			1.30
70.50			3.90	107.50			1.30
71			3.90	108			1.20
71.50			3.90	108.50			1.20
72			3.80	109			1.20
72.50			3.80	109.50			1.10
73			3.70	110			1.10
73.50			3.70	110.50			1.10
74			3.60	111			1.00
74.50			3.60	111.50			1.00
75			3.50	112			0.90
75.50			3.50	112.50			0.90
76			3.50	113			0.80
76.50			3.50	113.50			0.80
77			3.50	114			0.70
77.50			3.50	114.50			0.60
78			3.50	115			0.60
78.50			3.50	115.50			0.50
79			3.40	116			0.40
79.50			3.40	116.50			0.40
80			3.40	117			0.30
80.50			3.30	117.50			0.30
81			3.20	118			0.20
81.50			3.20	118.50			0.10
82			3.20	119			0.00
82.50			3.20	119.50			-0.10
83			3.20	120			-0.10
83.50			3.20	120.50			-0.20
84			3.20	121			-0.30
84.50			3.20	121.50			-0.40
85			3.20	122			-0.50
85.50			3.10	122.50			-0.50
86			3.10	123			-0.60
86.50			3.00	123.50			-0.80
87			3.00	124			-0.90
87.50			2.90	124.50			-1.00
88			2.90	125			-1.10
88.50			2.90	125.50			-1.30
89			2.80	126			-1.40
89.50			2.80	126.50			-1.50
90			2.80	127			-1.70
90.50			2.70	127.50			-1.90
91			2.70	128			-2.00
91.50			2.70	128.50			-2.20
92			2.60	129			-2.40
92.50			2.60	129.50			-2.60
93			2.50	130			-2.80
93.50			2.50	130.50			-3.00
94			2.50	131			-3.30
94.50			2.40	131.50			-3.50
95			2.40	132			-3.80
95.50			2.40	132.50			-4.10
96			2.30	133			-4.40
96.50			2.30	133.50			-4.70
97			2.30	134			-5.10
97.50			2.20	134.50			-5.50
98			2.20	135			-5.80
98.50			2.10	135.50			-6.20
99			2.10	136			-6.80
99.50			2.10	136.50			-7.20
100			2.00	137			-7.80
100.50			1.90	137.50			-8.40
101			1.90	138			-9.20
101.50			1.80	138.50			-10.10
102			1.80	139			-11.10
102.50			1.70	139.50			-12.20
103			1.70	140			-13.30
103.50			1.70	140.50			-14.90
104			1.60	141			-16.60
104.50			1.60	141.50			-18.70
105			1.50	142			-22.60
105.50			1.50	142.50			-31.10
106			1.40	143			-33.30
106.50			1.40				



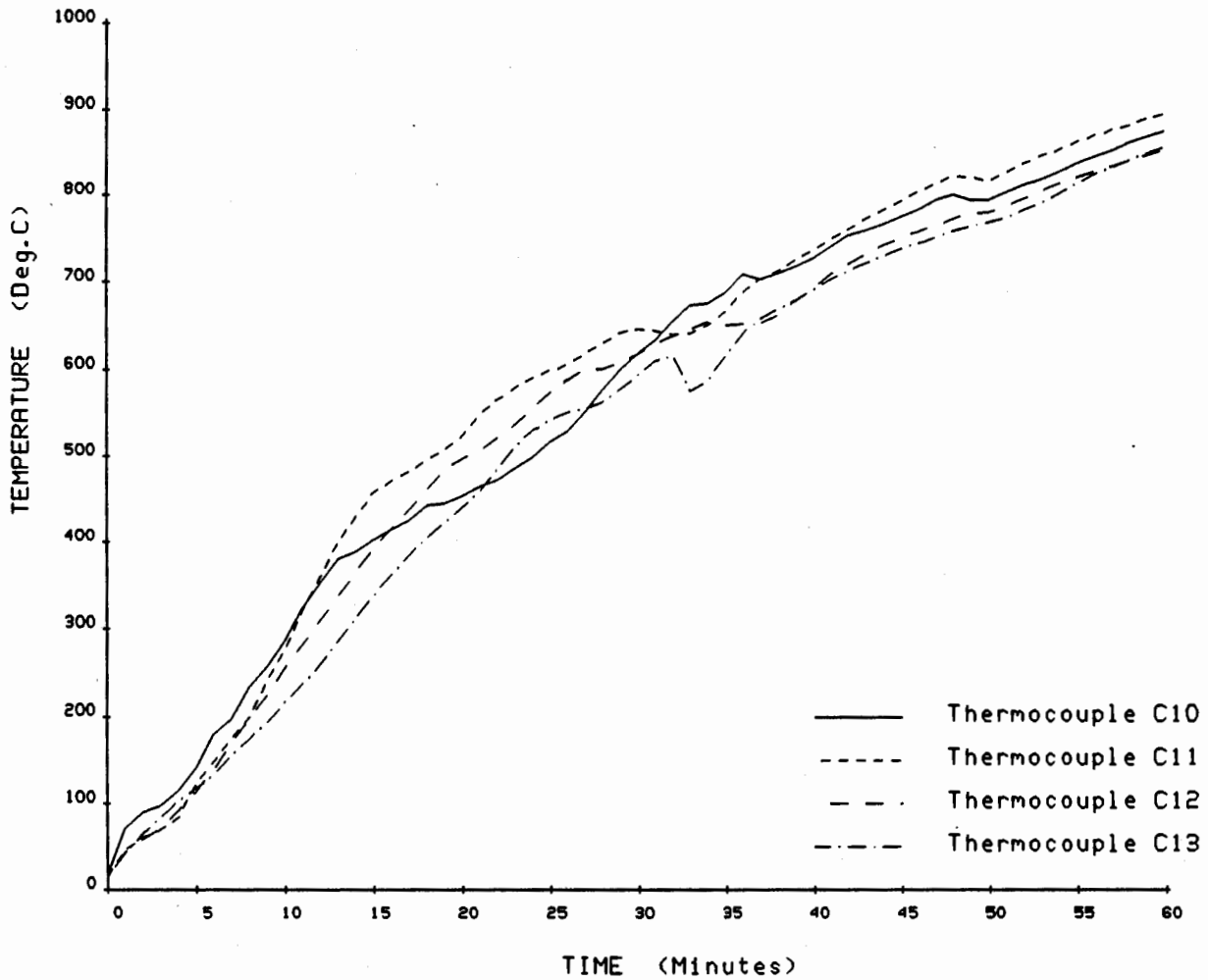
**FIG. A2.1 COMPARISON OF AVERAGE FURNACE ATMOSPHERE TEMPERATURE
AND THE STANDARD TEMPERATURE/TIME CURVE
TEST NO. LPC 81441
(244.5 mm O/D × 6.3 mm WALL CHS)**



**FIG. A2.2 TEMPERATURES RECORDED IN THE STEELWORK AT THE A POSITION
TEST NO. LPC 81441
(244.5 mm O/D × 6.3 mm WALL CHS)**



**FIG. A2.3 TEMPERATURES RECORDED IN THE STEELWORK AT THE B POSITION
TEST NO. LPC 81441
(244.5 mm O/D × 6.3 mm WALL CHS)**



**FIG. A2.4 TEMPERATURES RECORDED IN THE STEELWORK AT THE C POSITION
TEST NO. LPC 81441
(244.5 mm O/D × 6.3 mm WALL CHS)**

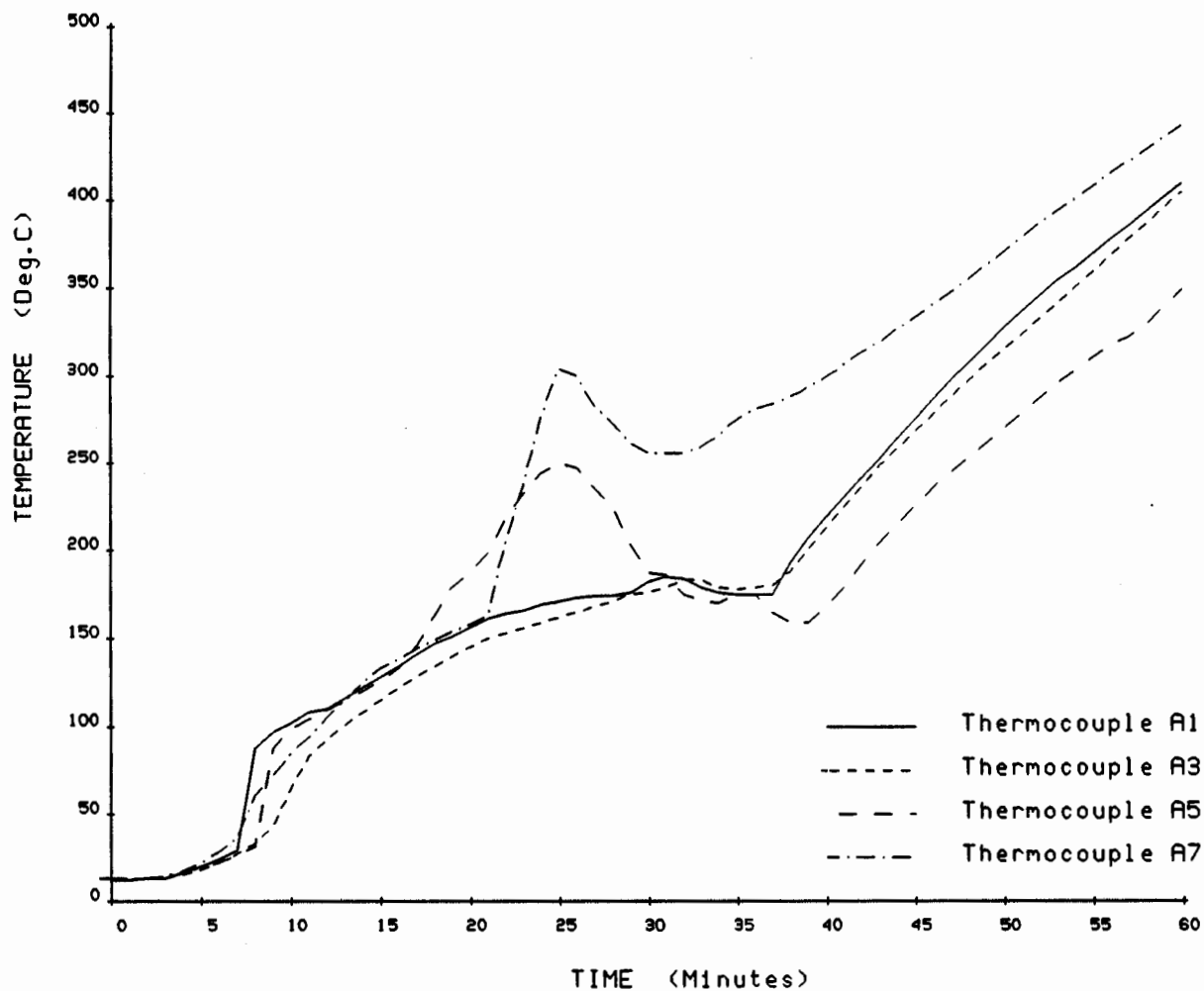


FIG. A2.5 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{3}{8}$ DIAMETER POSITION - LEVEL A
 TEST NO. LPC 81441
 (244.5 mm O/D \times 6.3 mm WALL CHS)

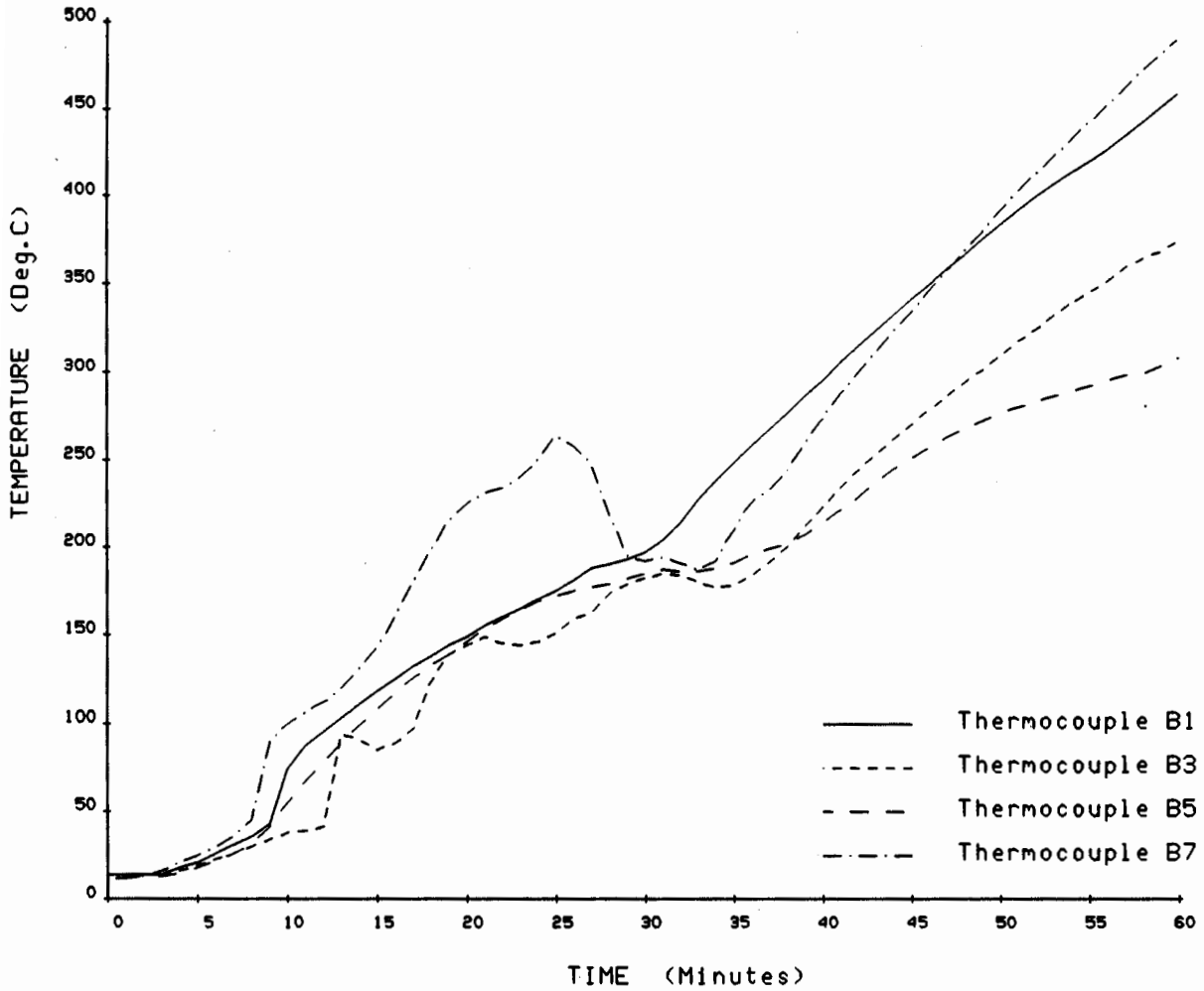


FIG. A2.6 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{3}{8}$ DIAMETER POSITION - LEVEL B
 TEST NO. LPC 81441
 (244.5 mm O/D \times 6.3 mm WALL CHS)

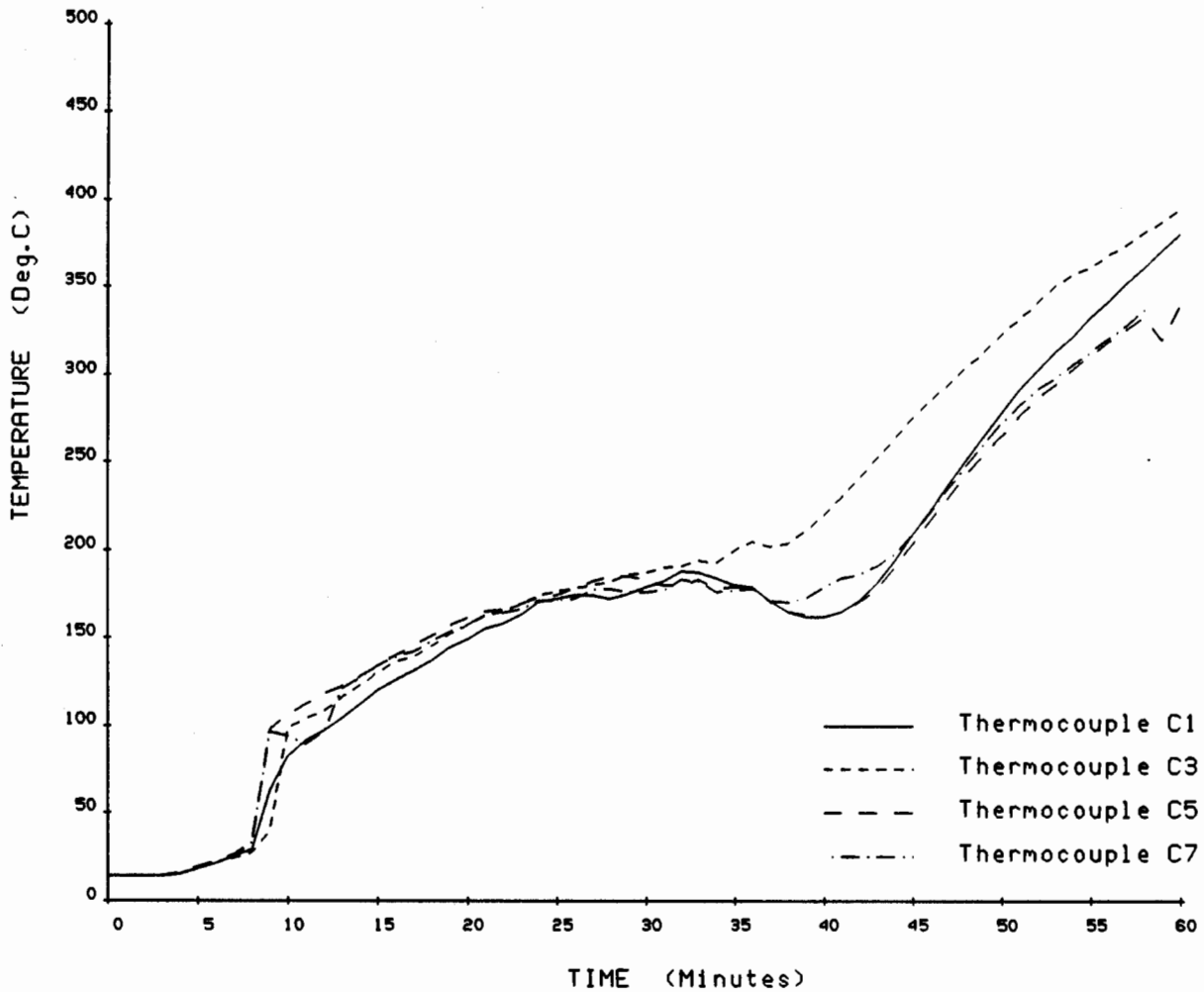


FIG. A2.7 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{3}{8}$ DIAMETER POSITION - LEVEL C
TEST NO. LPC 81441
(244.5 mm O/D \times 6.3 mm WALL CHS)

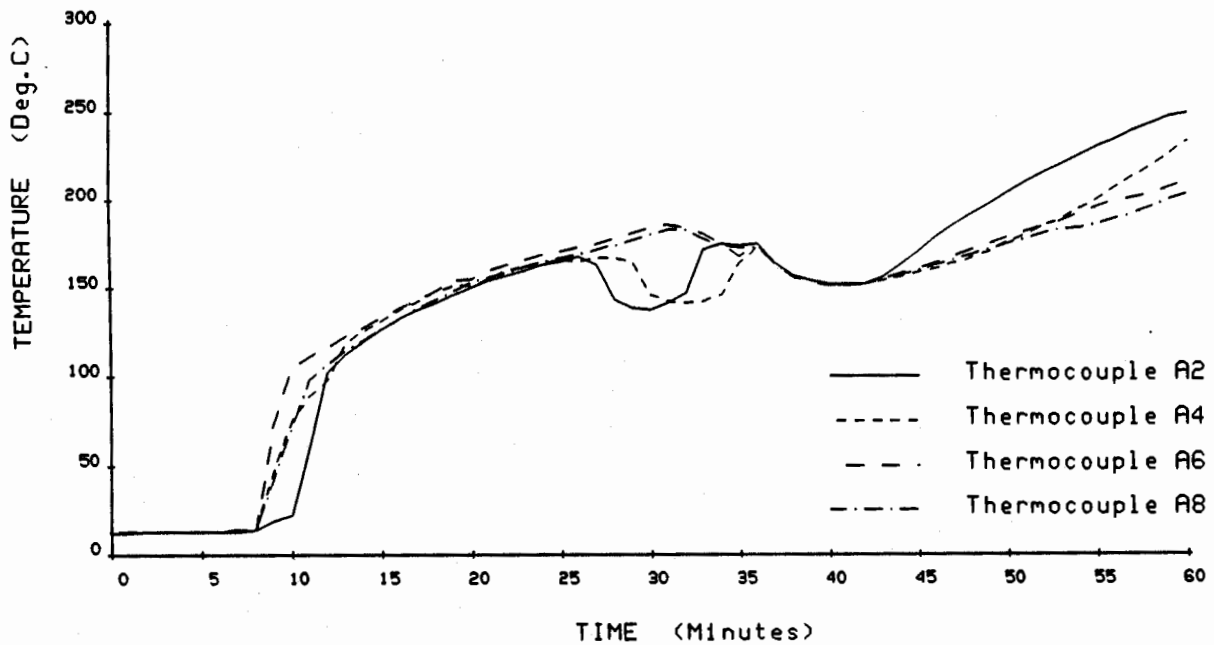


FIG. A2.8 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{1}{4}$ DIAMETER POSITION - LEVEL A
TEST NO. LPC 81441
(244.5 mm O/D \times 6.3 mm WALL CHS)

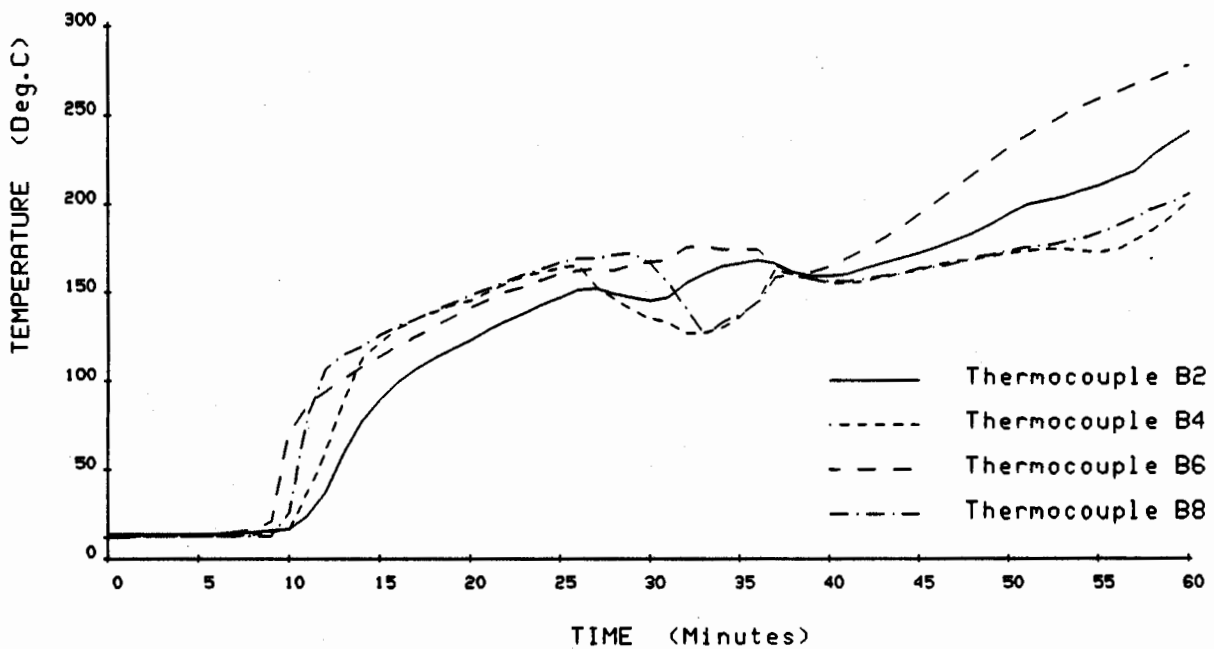


FIG. A2.9 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{1}{4}$ DIAMETER POSITION - LEVEL B
TEST NO. LPC 81441
(244.5 mm O/D \times 6.3 mm WALL CHS)

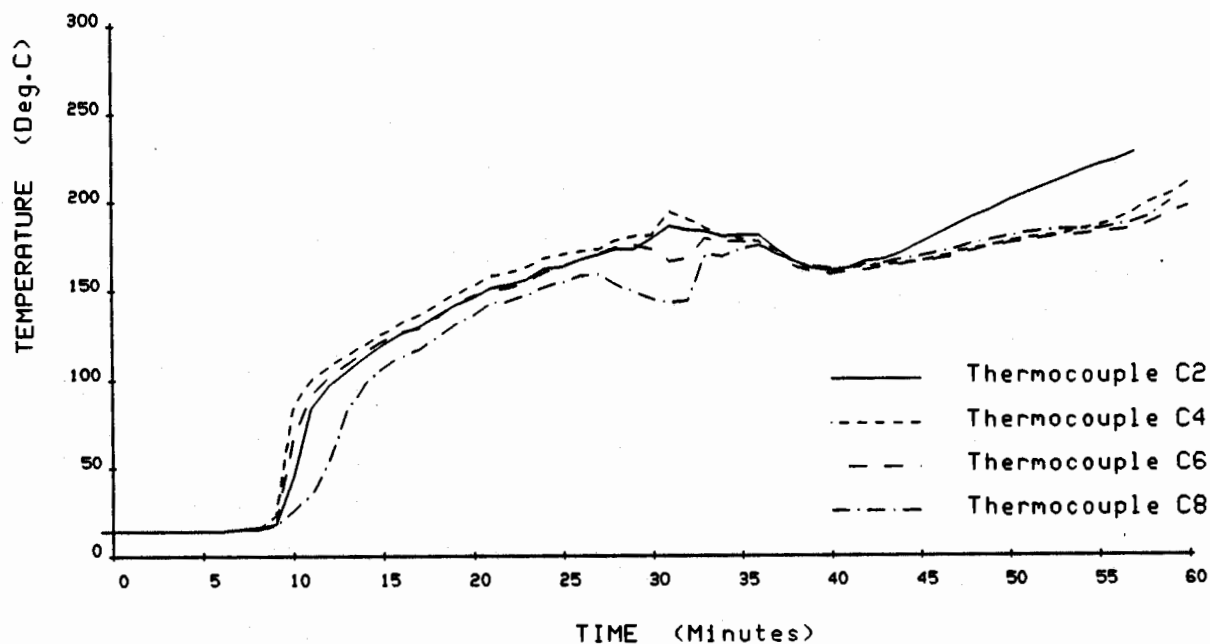
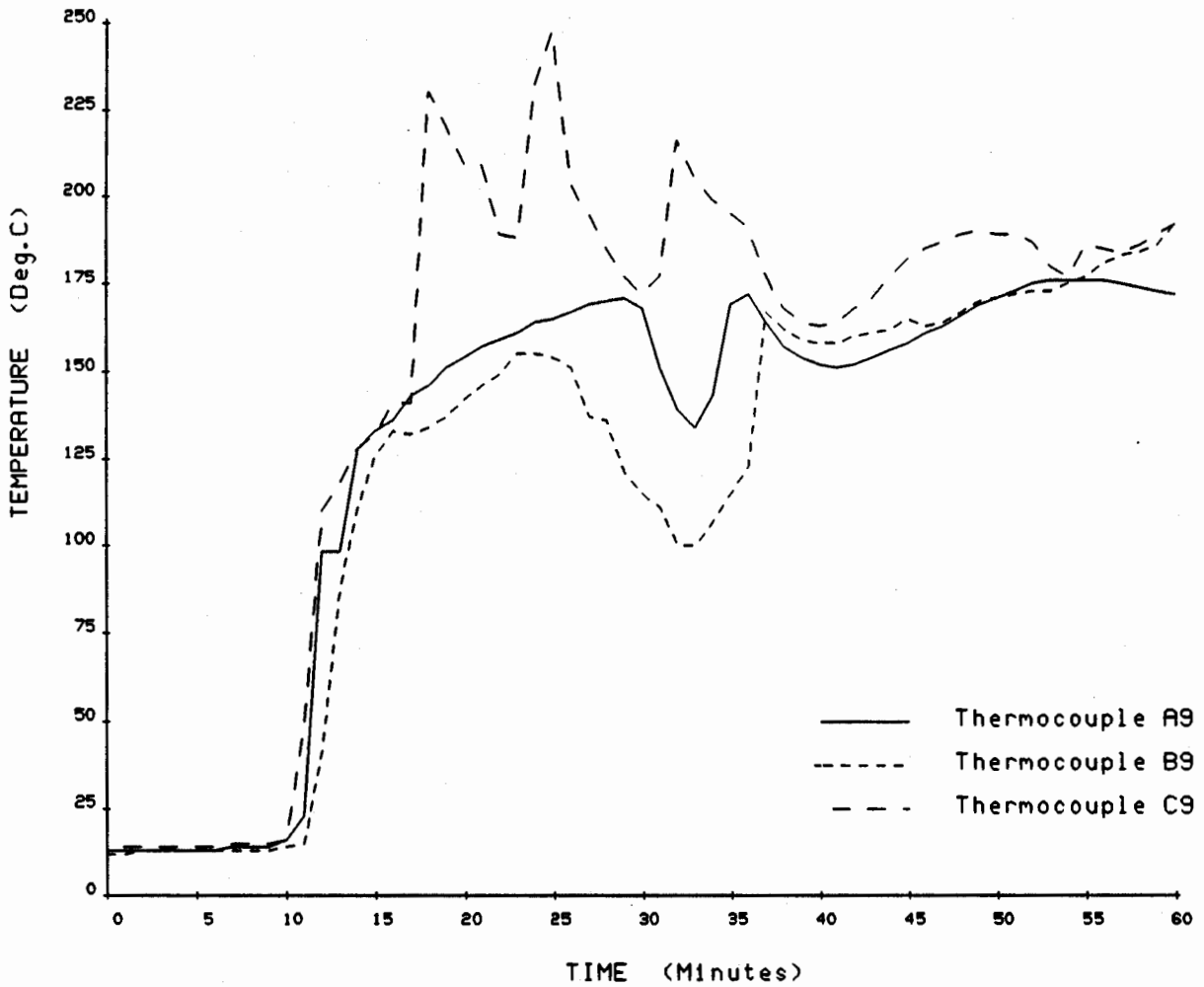
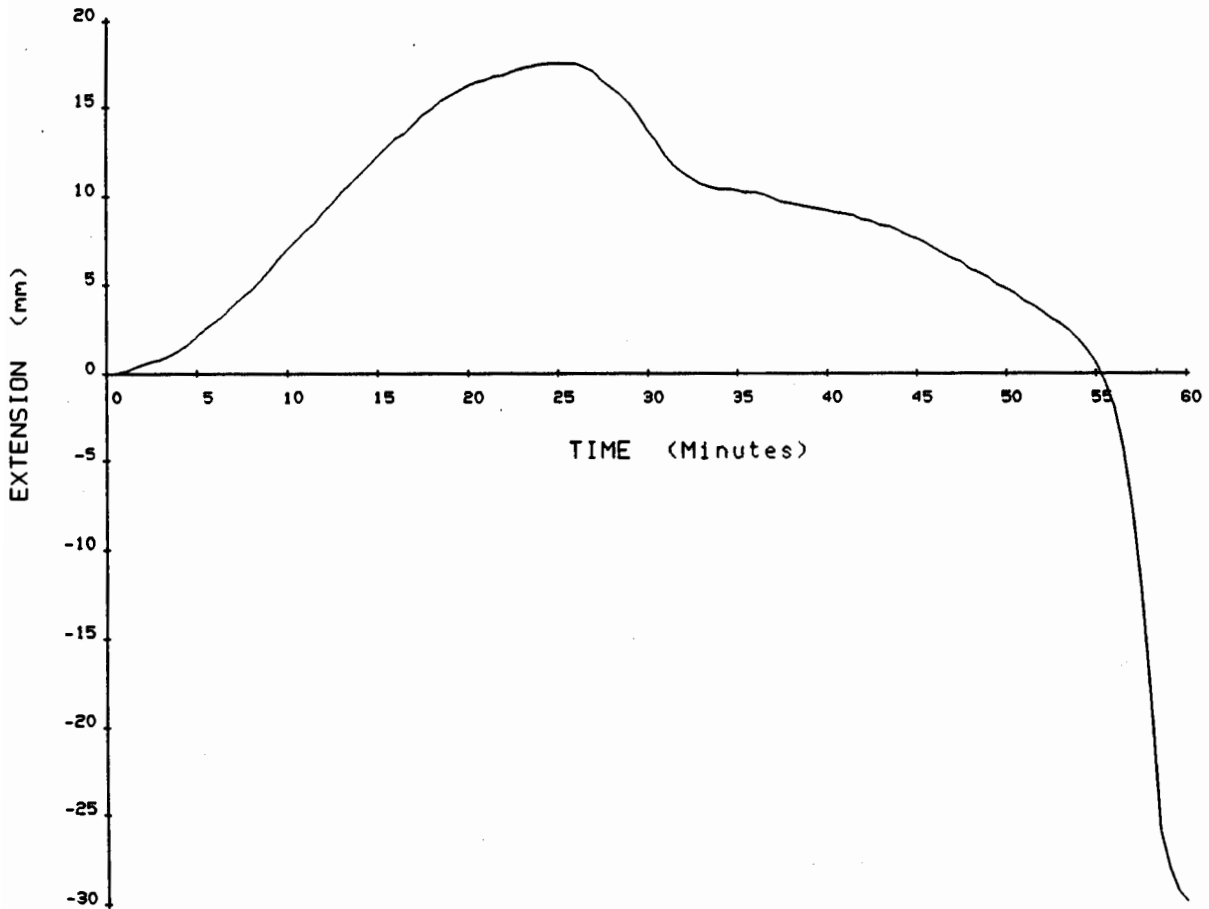


FIG. A2.10 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{1}{4}$ DIAMETER POSITION - LEVEL C
TEST NO. LPC 81441
(244.5 mm O/D \times 6.3 mm WALL CHS)



**FIG. A2.11 TEMPERATURES RECORDED AT THE CONCRETE CORE POSITION
 TEST NO. LPC 81441
 (244.5 mm O/D × 6.3 mm WALL CHS)**

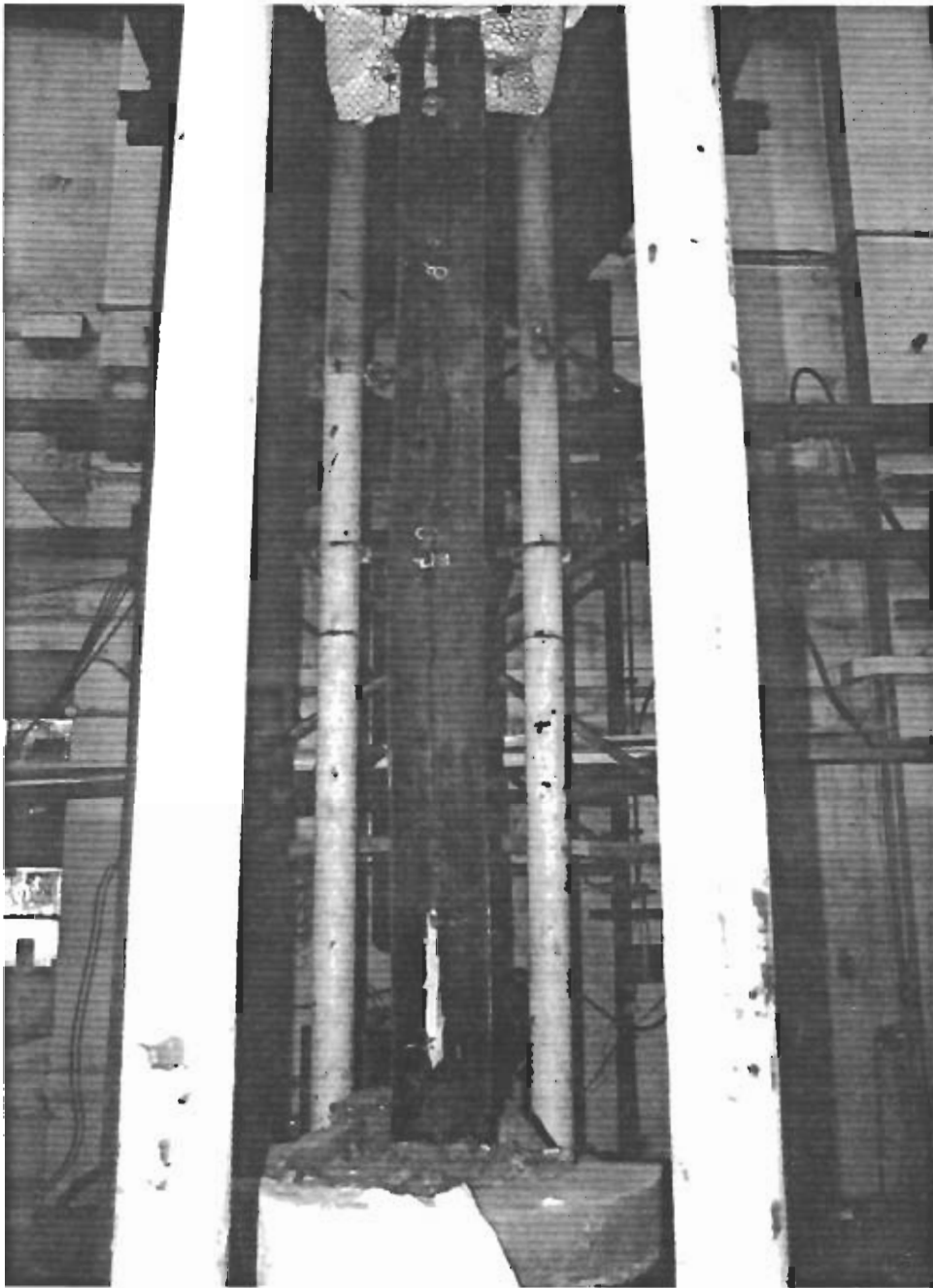


**FIG. A2.12 VERTICAL EXTENSION OF THE COLUMN
RECORDED DURING TEST NO. LPC 81441
(244.5 mm O/D × 6.3 mm WALL CHS)**



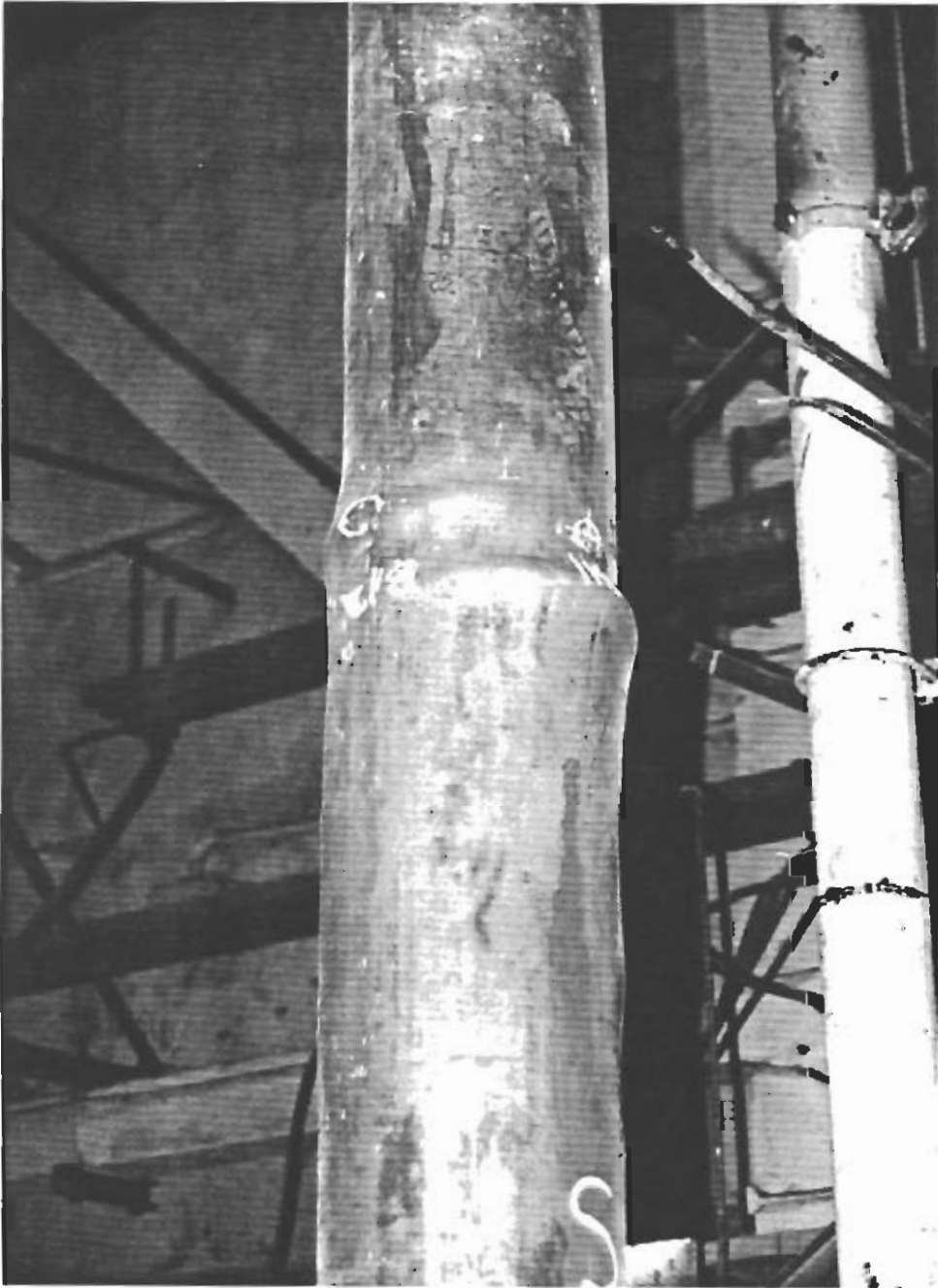
Test No. LPC 81441

**FIG. A2.13 244.5 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE SOUTH EAST POSITION**



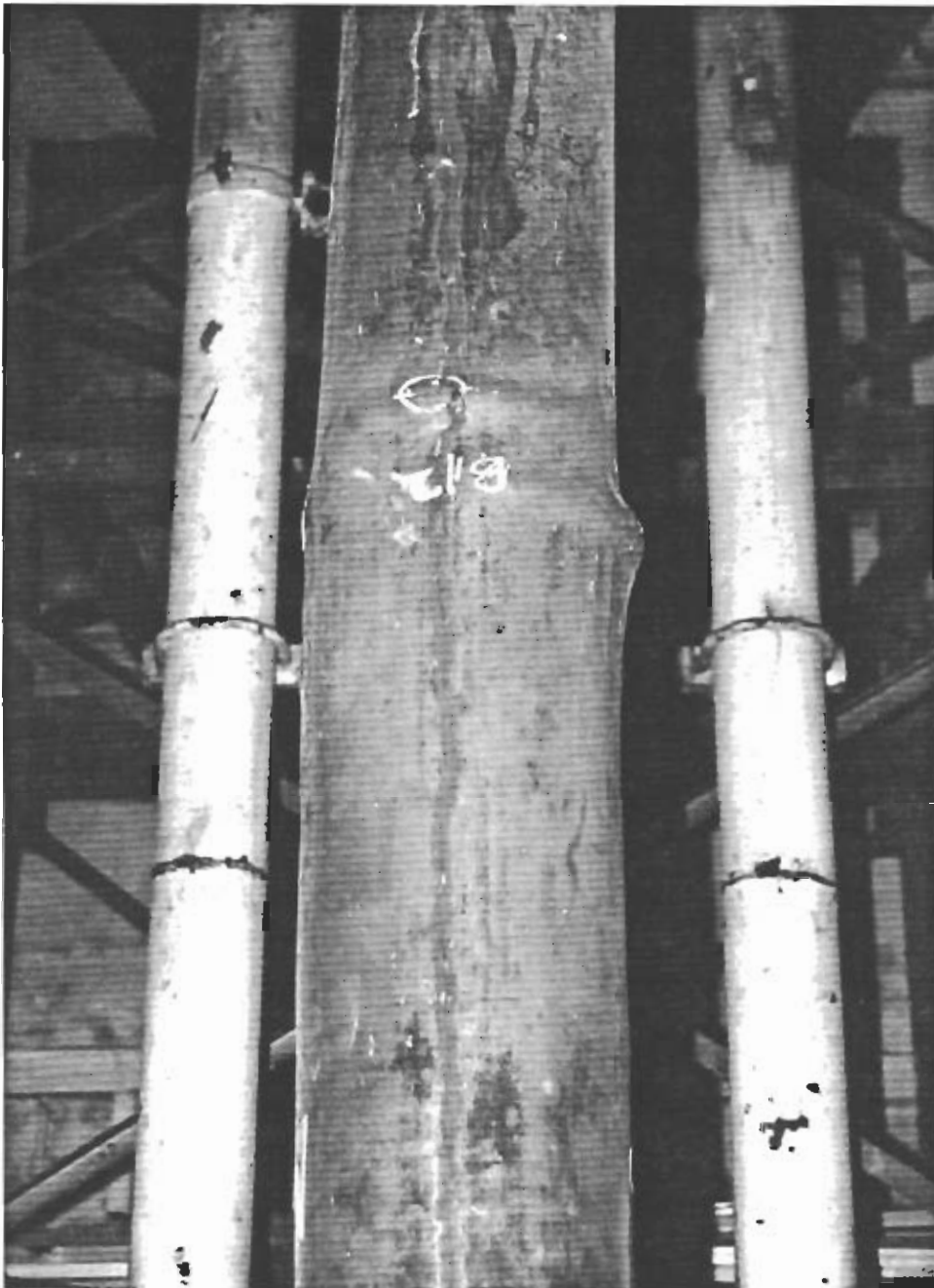
Test No. LPC 81441

**FIG. A2.14 244.5 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE WEST POSITION**



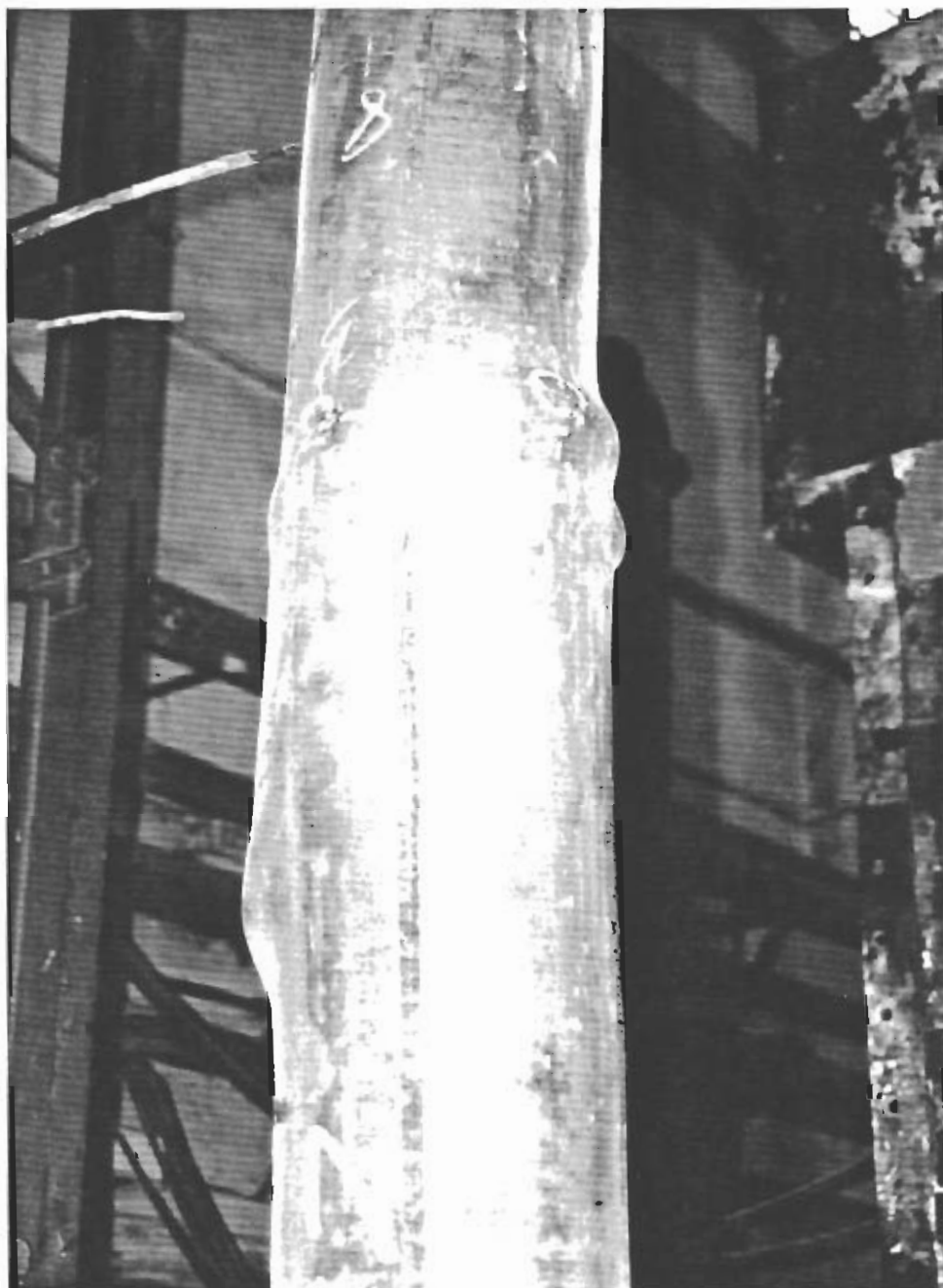
Test No. LPC 81441

**FIG. A2.15 244.5 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE SOUTH WEST POSITION**



Test No. LPC 81441

**FIG. A2.16 244.5 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE WEST POSITION**



Test No. LPC 81441

**FIG. A2.17 244.5 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE NORTH WEST POSITION**



Test No. LPC 81441

**FIG. A2.18 244.5 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE NORTH EAST POSITION**

APPENDIX 3**DETAILED EXPERIMENTAL RESULTS - 2ND COLUMN TEST****A3.1 TEST NO. LPC 81442 (323.9 MM O/D × 6.3 MM THICK WALL CHS)**

The test was carried out in accordance with Section 6 of BS476:Part 21:1987 at the LPC, Borehamwood, on 12th November 1991.

The full test load of 1686 kN was supported by the column for a period of 45.5 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 time of 50 minutes. In accordance with the provisions of BS476:Part 21 the fire resistance rating of the test assembly was 45 minutes.

A3.1.1 Temperature Measurements

The temperatures recorded by the six thermocouples monitoring the furnace atmosphere are presented in Table A3.1. The table also gives the mean furnace atmosphere temperatures and the corresponding BS476 standard heating curve values. The temperature data from the twelve thermocouples embedded in the steelwork are presented in Table A3.2, together with the average temperatures at the three measurement planes. Similarly, the temperatures recorded in the concrete at the $\frac{3}{8}$ diameter, $\frac{1}{4}$ diameter and central positions are presented in Tables A3.3, A3.4 and A3.5 respectively.

The average furnace atmosphere temperature is compared with the BS476 time/temperature curve in Fig. A3.1. This shows a very similar pattern of events to those described for the first test, (see A2.1.1). As before a much closer agreement between the average and aim values was noted after about 30-35 minutes. The plot provided by the LPC again indicates that the furnace atmosphere temperature was controlled more accurately than is suggested by Fig. A3.1.

The data presented in Table A3.2 for the steelwork are shown graphically in Figs. A3.2, A3.3 and A3.4. Similarly, Figs. A3.5 to A3.10 are plots of the data presented in Tables A3.3 and A3.4 for the concrete infill at the $\frac{3}{8}$ and $\frac{1}{4}$ diameter positions. Finally, Fig. A3.11 is a plot of the data in Table A3.5 for the concrete core temperatures at the three measurement levels.

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 A2.6, and is shown plotted in Fig. A3.12. The maximum extension under load was 4.2 mm. This occurred 13 minutes after the commencement of the test and was maintained until 14.5 minutes had elapsed, after which time the column began to contract. The column regained its original length after 31.5 minutes.

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/s	Event
-15.00	Load of 1686 kN applied to the column. Displacement transducer set to zero.
00.00	Test commenced
13.00	Column extension reaches a maximum value of 4.2 mm
14.30	Column begins to contract
18.00	Sound of steam issuing from the vent holes becoming noticeable
19.00	Bulge starts to form in the column approximately mid-way between the A and B thermocouple positions. Estimated to be protruding about 20 mm from the tube wall. Appears to go all the way round the tube.
23.00	Steam emission now vigorous.
26.00	No significant change to bulge condition
30.00	No significant change to bulge condition. Steam emission continues. Concrete plugs in lower vent holes appear to have been ejected.
31.30	Column length at its original value
33.30	No significant changes since 30.0 minutes
37.30	No change from conditions previously noted
43.00	No changes noted
45.30	Column unable to support the load. No deformation of the column noted. Load reduced to a pinch value.
50.00	Test terminated

A3.1.3.2 Subsequent to the Test

On opening up the furnace it was noted that there was a region at the bottom of the column which appeared to be darker, and therefore presumably cooler, than the remainder. The effect was identical to that observed on the previous test, (see A2.1.3.2), but on this occasion the top of the cooler region was about 150 mm below the level of the vent holes. As before, there did not appear to be a corresponding region at the top of the column. Steam continued to be emitted vigorously from all the vent holes for a period of about 30 minutes after the test. However, about one hour after opening the furnace the pressure had subsided sufficiently for any further escape of steam to be generally inaudible.

A detailed examination of the column was carried out on 13.11.91 after it had been allowed to cool over night. The column appeared to have suffered no overall lateral distortion, remaining visibly unbowed over its entire length. The upper half of the column also appeared to be free of any defects such as bulging of the tube wall.

Figures A3.13-A3.18 are a series of photographs taken from the NW, NE, E, SE, S and SW positions respectively. The bulge, which was observed to have formed 19 minutes into the test, can be clearly seen in

all six views, which effectively give a pictorial circumnavigation of the column. These views confirm the impression gained during the test, that the bulge was continuous around the tube circumference and that it was located roughly mid-way between the A and B thermocouple positions. The protrusion of the bulge from the tube wall was in the region of 25-30 mm.

Several other irregularly shaped bulges, situated at various positions around the column, were also noted. In order to overcome the problems inherent in representing three dimensional features in two dimensional photographs, the boundaries of the bulged areas were outlined on the steel tube. Also, for ease of reference, points on the tube wall were assigned code numbers. The distances of these points from the bottom of the tube are given in the following table.

Position Code No.	Distance to Base of Column mm	Position Code No.	Distance to Base of Column mm
1	565	10	1180
2	650	11	1180
3	745	12	1180
4	805	13	1170
5	1220	14	1170
6	1150	15	1395
7	1160	16	1510
8	1180	17	1470
9	1180		

The principal areas where bulging had occurred were as follows:-

(1) **North and North West Aspects**

A fairly large flattish area with two raised bumps, coded 1 and 2, and shown in Figs. A3.13 and A3.14.

(2) **West Aspect**

Two relatively small raised areas, coded 4 and 5, also shown in Fig. A3.13.

(3) **North East Aspect**

A small area coded 3, shown in Figs. A3.14 and A3.15.

(4) **East, SE, S and SW Aspects**

This was the largest single area of deformation anywhere on the column. It was situated wholly above the circumferential bulge and, as may be seen in Figs. A3.15-A3.18, covered an area extending from the East to the South West positions. The three points of greatest protrusion from the tube wall were coded 15, 16 and 17.

There were also a few areas consisting principally of small ripples and general unevenness. These were concentrated mainly on the SE face of the column, just below the A level of thermocouples. Points on the circumferential bulge were coded 6-14.

TABLE A3.1
FURNACE ATMOSPHERE TEMPERATURE DATA - LPC 81442
(323.9 mm OD × 6.3 mm THICK WALL CHS)

TIME MINS	ISO TEMP	ATM 1	ATM 2	ATM 3	ATM 4	ATM 5	ATM 6	ATM AVE
0	20	85	80	80	85	100	103	89
1	349	454	387	254	391	425	228	357
2	445	475	442	340	422	457	302	406
3	502	504	510	436	422	490	370	455
4	544	552	577	567	450	522	433	517
5	576	568	596	623	468	553	485	549
6	603	594	626	637	491	578	490	569
7	626	605	637	645	510	577	523	583
8	645	640	671	671	537	605	563	615
9	663	689	703	692	586	636	583	648
10	678	703	718	711	613	664	613	670
11	693	715	725	711	611	691	643	683
12	705	717	727	716	614	692	666	689
13	717	732	737	723	615	720	686	702
14	728	738	745	731	630	731	683	710
15	739	747	754	737	637	736	682	716
16	748	748	759	752	648	734	703	724
17	757	756	770	767	650	742	714	733
18	766	753	777	775	643	750	724	737
19	774	763	785	784	689	776	727	754
20	781	771	789	794	715	789	739	766
21	789	781	796	805	724	803	749	776
22	796	784	801	813	740	804	764	784
23	802	785	804	813	744	809	773	788
24	809	785	811	809	759	810	782	793
25	815	789	815	813	770	814	790	799
26	820	797	816	811	765	820	797	801
27	826	803	824	817	769	815	808	806
28	832	804	824	820	779	816	796	807
29	837	829	839	832	792	820	794	818
30	842	845	834	843	794	824	756	816
31	847	847	850	860	794	833	757	824
32	851	845	857	868	803	853	777	834
33	856	864	867	889	821	874	792	851
34	860	871	874	891	828	878	794	856
35	865	880	883	896	833	884	803	863
36	869	885	885	895	832	885	804	864
37	873	884	881	889	838	902	859	876
38	877	890	885	905	854	909	852	883
39	881	889	880	870	860	903	860	877
40	885	894	890	872	852	905	842	876
41	888	894	890	866	871	906	856	881
42	892	895	896	875	875	910	866	886
43	896	904	897	885	882	913	863	891
44	899	913	904	884	882	919	865	895
45	902	918	911	887	883	920	866	898
46	906	914	913	882	884	931	882	901
47	909	924	927	887	883	934	879	906
48	912	932	934	899	891	934	885	913
49	915	937	938	896	896	940	888	916
50	918	933	941	897	896	935	883	914

TABLE A3.2
TEMPERATURES RECORDED IN THE STEELWORK - LPC 81442
(323.9 mm OD × 6.3 THICK WALL CHS)

TIME MINS	A10	A11	A12	A13	A AVE	B10	B11	B12	B13	B AVE	C10	C11	C12	C13	C AVE
0	15	15	15	15	15	15	15	*	15	15	16	16	*	16	16
1	33	31	27	25	29	39	37	*	37	38	33	44	*	43	40
2	52	47	40	39	45	57	51	*	49	52	55	51	*	57	54
3	77	64	52	59	63	78	67	*	61	69	76	59	*	69	68
4	109	87	71	92	90	103	86	*	85	91	98	69	*	89	85
5	140	115	93	132	120	127	107	*	110	115	121	81	*	110	104
6	172	144	111	174	150	153	130	*	141	141	145	93	*	135	124
7	201	172	131	214	180	177	153	*	172	167	169	105	*	156	143
8	234	206	157	253	213	208	180	*	201	196	194	118	*	185	166
9	274	243	188	291	249	227	219	*	234	227	227	135	*	223	195
10	314	279	229	327	287	266	259	*	272	266	259	157	*	267	228
11	346	313	272	352	321	301	297	*	307	302	290	177	*	306	258
12	370	341	317	372	350	341	327	*	332	333	321	200	*	337	286
13	384	363	359	394	375	372	351	*	366	363	347	210	*	362	306
14	399	381	397	416	398	391	372	*	405	389	373	220	*	388	327
15	417	396	427	437	419	400	392	*	437	410	396	243	*	411	350
16	436	411	451	459	439	419	411	*	465	432	411	269	*	433	371
17	463	426	474	482	461	444	432	*	488	455	425	293	*	450	389
18	487	440	501	502	483	467	445	*	506	473	436	314	*	464	405
19	514	452	523	517	502	491	461	*	522	491	455	347	*	469	424
20	531	463	545	531	518	511	470	*	539	507	487	405	*	470	454
21	544	475	563	551	533	528	475	*	553	519	507	449	*	470	475
22	556	486	568	573	546	544	478	*	566	529	524	480	*	479	494
23	568	497	577	593	559	559	483	*	577	540	538	500	*	493	510
24	579	509	588	609	571	573	494	*	592	553	550	508	*	504	521
25	590	523	599	619	583	584	506	*	606	565	560	515	*	514	530
26	603	535	603	625	592	597	519	*	611	576	564	535	*	531	543
27	614	548	611	630	601	604	528	*	622	585	572	543	*	543	553
28	623	562	620	636	610	618	538	*	627	594	581	557	*	557	565
29	631	574	628	642	619	627	547	*	640	605	600	566	*	575	580
30	639	589	638	655	630	639	564	*	645	616	611	577	*	588	592
31	649	603	644	664	640	652	583	*	653	629	620	592	*	602	605
32	669	618	651	675	653	663	602	*	661	642	630	605	*	616	617
33	685	640	663	685	668	675	614	*	670	653	644	625	*	639	636
34	701	659	676	696	683	686	627	*	681	665	657	642	*	660	653
35	717	675	689	707	697	694	637	*	693	675	666	655	*	677	666
36	728	689	698	718	708	702	651	*	704	686	676	667	*	694	679
37	732	695	706	731	716	709	665	*	713	696	688	672	*	711	690
38	735	703	715	740	723	716	679	*	723	706	699	682	*	720	700
39	736	707	724	746	728	721	691	*	729	714	704	688	*	729	707
40	737	710	730	755	733	729	701	*	733	721	709	700	*	738	716
41	738	715	736	761	738	733	709	*	737	726	713	710	*	746	723
42	740	722	740	766	742	734	720	*	739	731	722	720	*	751	731
43	744	727	746	774	748	739	729	*	742	737	732	730	*	759	740
44	748	732	753	781	754	745	736	*	750	744	742	741	*	770	751
45	743	738	761	788	758	755	743	*	758	752	750	749	*	784	761
46	738	742	773	792	761	763	751	*	765	760	761	758	*	797	772
47	746	748	779	795	767	772	759	*	774	768	774	769	*	812	785
48	756	755	787	804	776	779	768	*	786	778	786	780	*	819	795
49	764	763	794	810	783	792	780	*	796	789	797	791	*	826	805
50	773	769	799	816	789	804	790	*	805	800	804	801	*	827	811

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

TABLE A3.3
TEMPERATURES RECORDED AT $\frac{3}{8}$ DIAMETER FROM CENTRE OF CONCRETE
- LPC 81442
(323.9 mm OD \times 6.3 mm THICK WALL CHS)

TIME MINS	A1	A3	A5	A7	A AVE	B1	B3	B5	B7	B AVE	C1	C3	C5	C7	C AVE
0	15	15	15	15	15	16	16	15	15	16	16	16	16	16	16
1	15	15	15	15	15	16	16	15	15	16	16	16	16	16	16
2	15	15	15	15	15	16	16	15	15	16	16	16	16	16	16
3	15	15	15	15	15	16	16	15	15	16	16	16	16	16	16
4	15	15	15	15	15	16	16	15	15	16	16	16	16	16	16
5	15	15	15	17	16	16	16	15	15	16	16	16	16	16	16
6	15	15	18	19	17	16	16	15	15	16	16	16	16	16	16
7	17	17	22	23	20	16	17	16	16	16	17	19	16	16	17
8	19	19	26	27	23	17	19	17	17	18	19	21	17	17	19
9	21	22	31	33	27	18	22	20	20	20	22	24	18	18	21
10	25	25	35	38	31	20	24	22	22	22	25	27	20	21	23
11	28	29	40	43	35	22	27	25	25	25	28	30	23	23	26
12	32	32	45	49	40	25	30	29	28	28	32	33	25	27	29
13	35	35	50	55	44	28	33	33	30	31	36	37	28	30	33
14	39	39	55	63	49	31	36	37	34	35	40	40	31	33	36
15	42	42	60	71	54	35	39	41	37	38	43	44	33	36	39
16	46	46	65	79	59	38	42	46	40	42	48	47	37	39	43
17	50	49	70	87	64	42	46	50	44	46	52	50	40	42	46
18	53	53	76	96	70	46	50	54	49	50	57	53	44	45	50
19	57	57	82	104	75	50	54	58	51	53	62	57	48	49	54
20	62	61	88	110	80	54	59	62	54	57	67	61	53	53	59
21	66	65	95	116	86	60	65	68	60	63	72	65	58	57	63
22	71	72	101	121	91	65	71	72	68	69	76	70	64	63	68
23	76	81	108	126	98	71	77	78	77	76	81	75	71	68	74
24	81	91	113	130	104	77	82	83	89	83	86	80	79	73	80
25	87	98	119	132	109	82	86	88	102	90	91	84	84	78	84
26	93	104	125	133	114	87	90	92	119	97	96	88	88	82	89
27	99	109	132	135	119	92	93	96	134	104	101	93	91	87	93
28	106	112	135	138	123	101	96	100	138	109	107	97	93	92	97
29	114	114	137	141	127	110	99	105	136	113	114	101	95	96	102
30	123	116	139	145	131	116	103	109	137	116	127	105	97	100	107
31	130	118	141	150	135	121	106	115	135	119	130	110	99	103	111
32	131	120	144	155	138	124	108	121	134	122	132	114	100	105	113
33	131	122	147	163	141	125	111	126	133	124	132	118	102	107	115
34	131	125	151	170	144	125	113	128	132	125	132	121	104	109	117
35	132	127	156	178	148	126	116	130	131	126	132	125	106	110	118
36	134	127	162	185	152	127	118	130	131	127	132	126	108	112	120
37	136	127	168	193	156	126	120	129	133	127	133	125	109	113	120
38	140	128	175	200	161	126	123	130	135	129	137	125	110	115	122
39	145	128	181	209	166	126	125	132	137	130	145	126	111	117	125
40	150	129	190	218	172	127	128	135	139	132	154	127	114	120	129
41	156	130	198	226	178	128	129	138	142	134	162	128	116	125	133
42	162	132	205	235	184	129	130	140	145	136	167	130	118	130	136
43	168	134	213	242	189	130	132	143	149	139	173	131	120	134	140
44	174	135	218	246	193	134	136	146	153	142	179	132	122	139	143
45	181	139	*	242	187	140	140	151	159	148	*	*	*	*	*
46	187	145	*	*	166	144	144	*	165	151	*	*	*	*	*
47	193	155	*	*	174	147	148	*	170	155	*	*	*	*	*
48	*	163	*	*	163	150	151	*	178	160	*	*	*	*	*
49	*	169	*	*	169	153	156	*	183	164	*	*	*	*	*
50	*	175	*	*	175	157	160	*	188	168	*	*	*	*	*

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

TABLE A3.4
TEMPERATURES RECORDED AT 1/4 DIAMETER FROM CENTRE OF CONCRETE
- LPC 81442
(323.9 mm OD x 6.3 mm THICK WALL CHS)

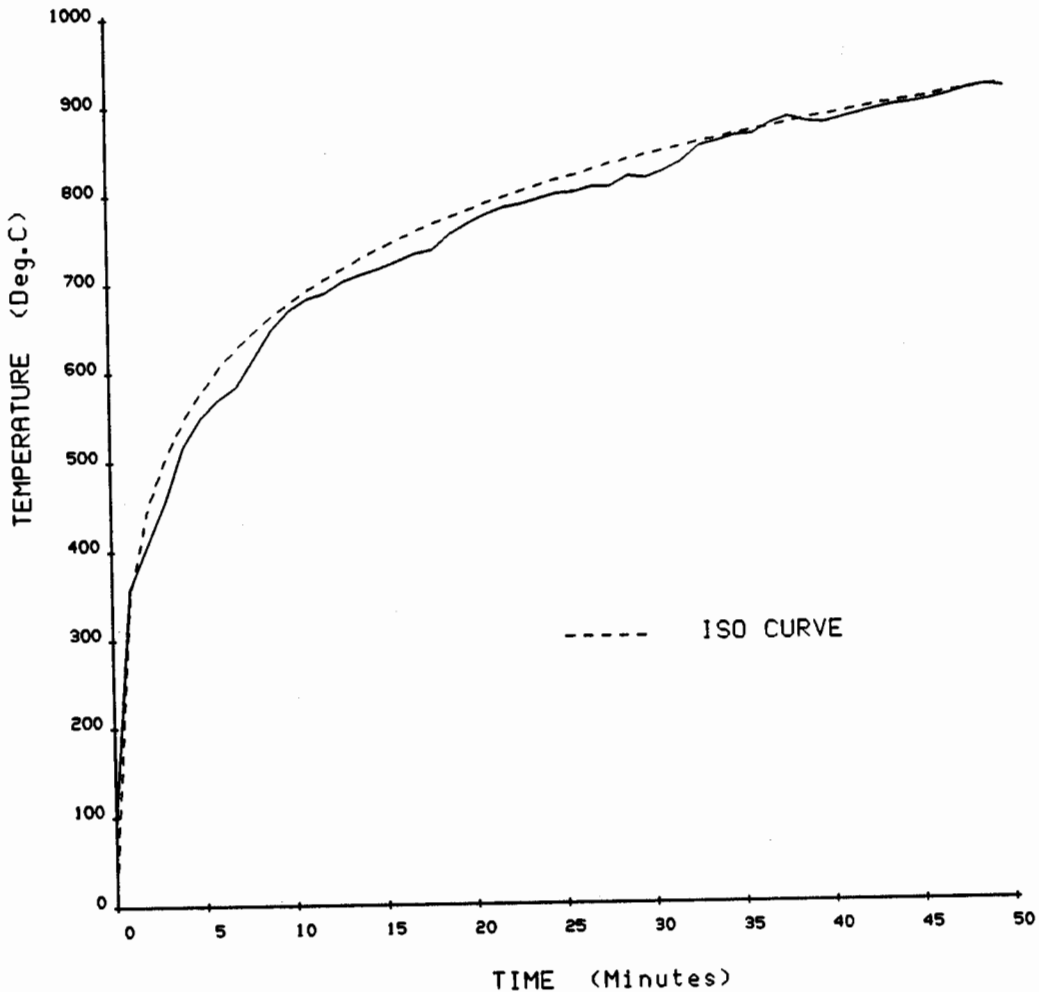
TIME MINS	A2	A4	A6	A8	A AVE	B2	B4	B6	B8	B AVE	C2	C4	C6	C8	C AVE
0	15	15	15	15	15	16	15	15	15	15	16	16	16	16	16
1	15	15	15	15	15	16	15	15	15	15	16	16	16	16	16
2	15	15	15	15	15	16	15	15	15	15	16	16	16	16	16
3	15	15	15	15	15	16	15	15	15	15	16	16	16	16	16
4	15	15	15	15	15	16	15	15	15	15	16	16	16	16	16
5	15	15	15	15	15	16	15	15	15	15	16	16	16	16	16
6	15	15	15	15	15	16	15	15	15	15	16	16	16	16	16
7	15	15	15	16	15	16	15	15	15	15	16	16	16	16	16
8	15	15	15	16	15	17	15	15	15	16	17	17	17	17	17
9	15	15	15	16	15	17	15	15	15	16	17	17	17	17	17
10	15	15	15	16	15	17	15	15	15	16	17	17	17	17	17
11	16	16	16	16	16	17	16	16	16	16	17	17	17	17	17
12	16	16	16	16	16	17	16	16	20	17	17	17	17	17	17
13	16	16	17	16	16	17	16	17	26	19	17	17	17	17	17
14	16	16	19	17	17	17	16	18	33	21	17	17	17	17	17
15	16	18	21	18	18	17	16	20	41	24	17	17	17	17	17
16	17	19	23	20	20	18	17	22	49	27	17	18	17	18	18
17	18	21	25	22	22	19	19	24	56	30	18	19	17	19	18
18	20	23	28	24	24	20	20	27	65	33	20	21	17	21	20
19	21	25	31	26	26	21	22	28	22	23	21	22	18	22	21
20	23	26	33	28	28	28	24	31	23	27	23	24	19	24	23
21	24	28	36	31	30	72	27	34	25	40	25	25	21	25	24
22	26	30	41	34	33	95	30	37	27	47	27	26	22	27	26
23	28	32	45	37	36	90	33	41	29	48	29	28	24	29	28
24	30	34	50	41	39	94	36	46	32	52	31	29	26	31	29
25	32	36	55	46	42	92	39	50	35	54	34	31	28	33	32
26	34	39	59	51	46	92	43	55	39	57	36	33	30	36	34
27	37	42	64	58	50	92	47	59	44	61	39	35	33	38	36
28	39	46	69	65	55	96	50	64	50	65	40	37	34	40	38
29	41	51	72	72	59	96	53	70	56	69	44	39	37	43	41
30	44	57	76	78	64	99	57	76	59	73	47	42	40	46	44
31	47	64	79	84	69	97	60	81	64	76	49	44	43	49	46
32	50	71	83	89	73	97	63	86	66	78	52	46	45	51	49
33	53	77	85	92	77	98	66	89	67	80	55	49	49	54	52
34	56	82	88	94	80	97	69	92	68	82	58	52	52	58	55
35	60	86	90	96	83	91	71	94	71	82	61	54	54	61	58
36	63	90	93	97	86	88	74	96	72	83	63	56	56	63	60
37	67	92	94	98	88	85	76	98	75	84	65	59	58	66	62
38	70	94	97	99	90	87	78	101	83	87	67	61	60	68	64
39	73	96	100	102	93	87	80	103	93	91	70	64	62	71	67
40	76	101	104	107	97	88	82	106	108	96	73	67	64	74	70
41	79	106	108	111	101	86	84	109	112	98	75	71	66	76	72
42	82	112	114	114	106	87	87	113	115	101	77	75	68	79	75
43	84	115	121	115	109	87	89	116	117	102	79	77	69	82	77
44	85	116	124	111	109	89	91	120	119	105	81	80	70	84	79
45	90	119	128	112	112	109	94	124	121	112	*	*	*	*	*
46	94	118	129	117	115	*	96	*	*	*	*	*	*	*	*
47	*	*	131	*	*	*	98	*	*	*	*	*	*	*	*
48	*	*	132	*	*	*	100	*	*	*	*	*	*	*	*
49	*	*	132	*	*	*	103	*	*	*	*	*	*	*	*
50	*	*	132	*	*	*	106	*	*	*	*	*	*	*	*

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

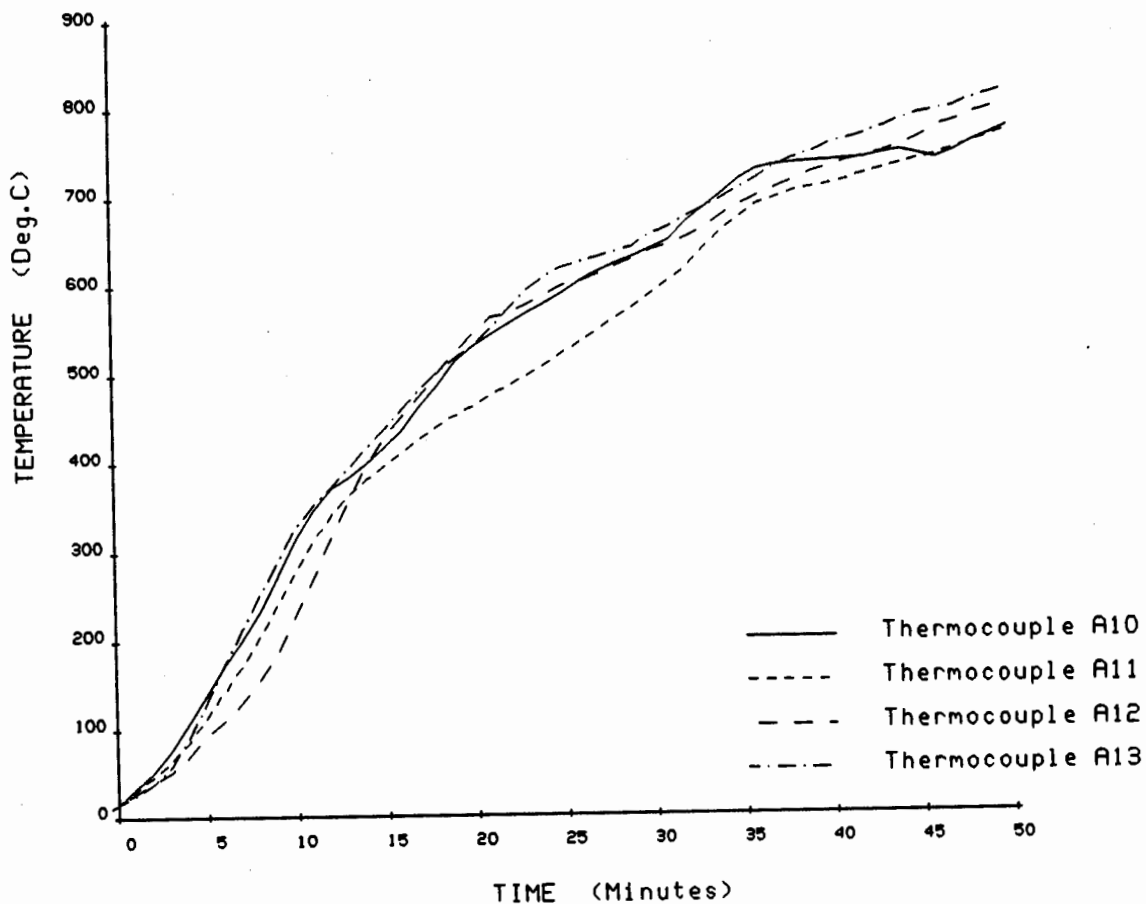
TABLE A3.5
TEMPERATURES RECORDED AT THE CENTRE OF THE CONCRETE - LPC 81442
(323.9 mm OD × 6.3 mm THICK WALL)

TIME MINS	A9	B9	C9
0	15	15	*
1	15	15	16
2	15	15	16
3	15	15	16
4	15	15	*
5	15	15	*
6	15	15	*
7	16	15	*
8	16	15	*
9	16	15	*
10	16	15	*
11	16	16	17
12	16	16	17
13	16	16	17
14	16	16	17
15	16	16	17
16	16	16	17
17	16	16	17
18	16	16	17
19	16	16	18
20	16	16	18
21	17	17	18
22	17	18	18
23	17	20	18
24	17	21	18
25	17	21	18
26	17	21	18
27	17	22	19
28	18	23	20
29	19	24	21
30	20	24	23
31	21	26	24
32	23	27	25
33	24	29	26
34	26	30	27
35	28	31	28
36	31	33	29
37	33	35	30
38	35	37	32
39	38	40	34
40	41	45	35
41	43	50	36
42	46	56	38
43	50	61	38
44	52	65	40
45	57	70	*
46	62	74	*
47	197	77	*
48	246	80	*
49	276	83	*
50	356	85	*

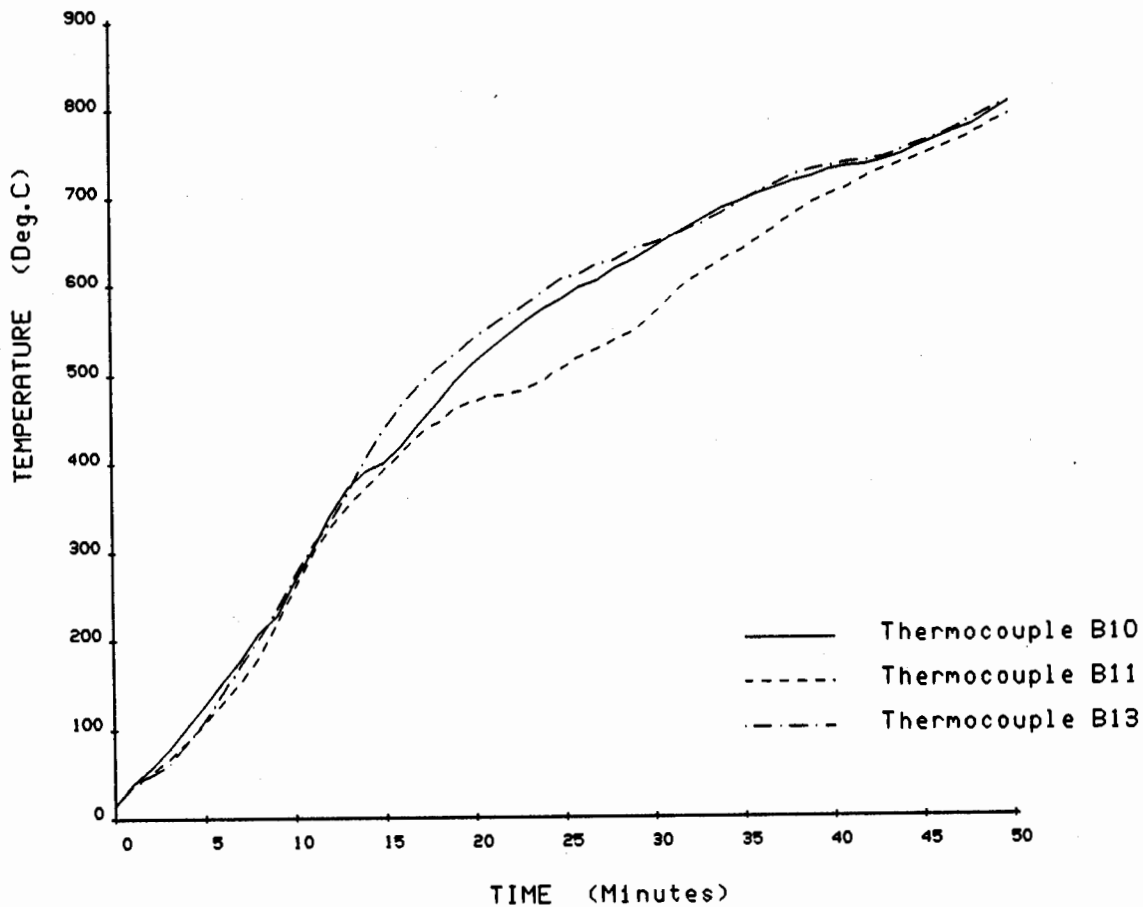
Note that an * indicates that the temperature measurement was known or thought to be incorrect.



**FIG. A3.1 COMPARISON OF AVERAGE FURNACE ATMOSPHERE TEMPERATURE
AND THE STANDARD TEMPERATURE/TIME CURVE
TEST NO. LPC 81442
(323.9 mm O/D × 6.3 mm WALL CHS)**



**FIG. A3.2 TEMPERATURES RECORDED IN THE STEELWORK AT THE A POSITION
TEST NO. LPC 81442
(323.9 mm O/D × 6.3 mm WALL CHS)**



**FIG. A3.3 TEMPERATURES RECORDED IN THE STEELWORK AT THE B POSITION
TEST NO. LPC 81442
(323.9 mm O/D × 6.3 mm WALL CHS)**

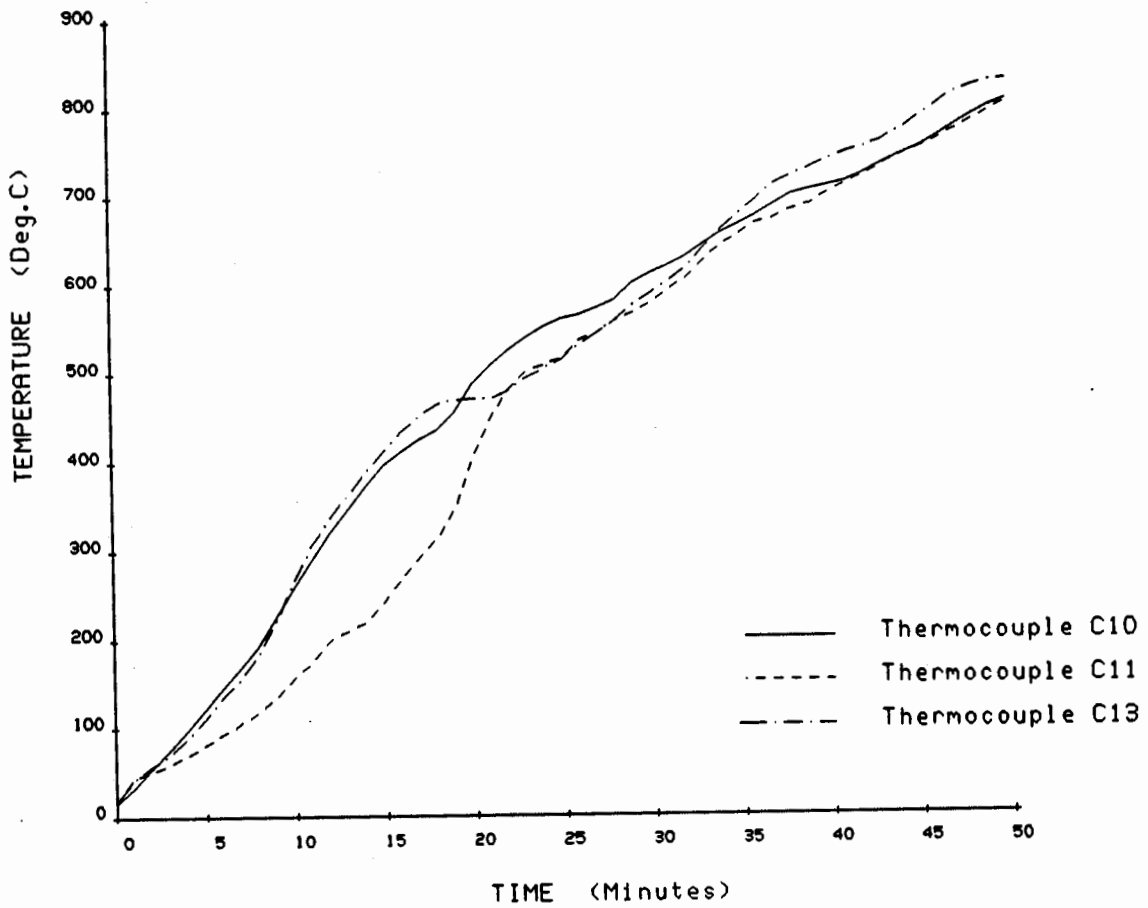
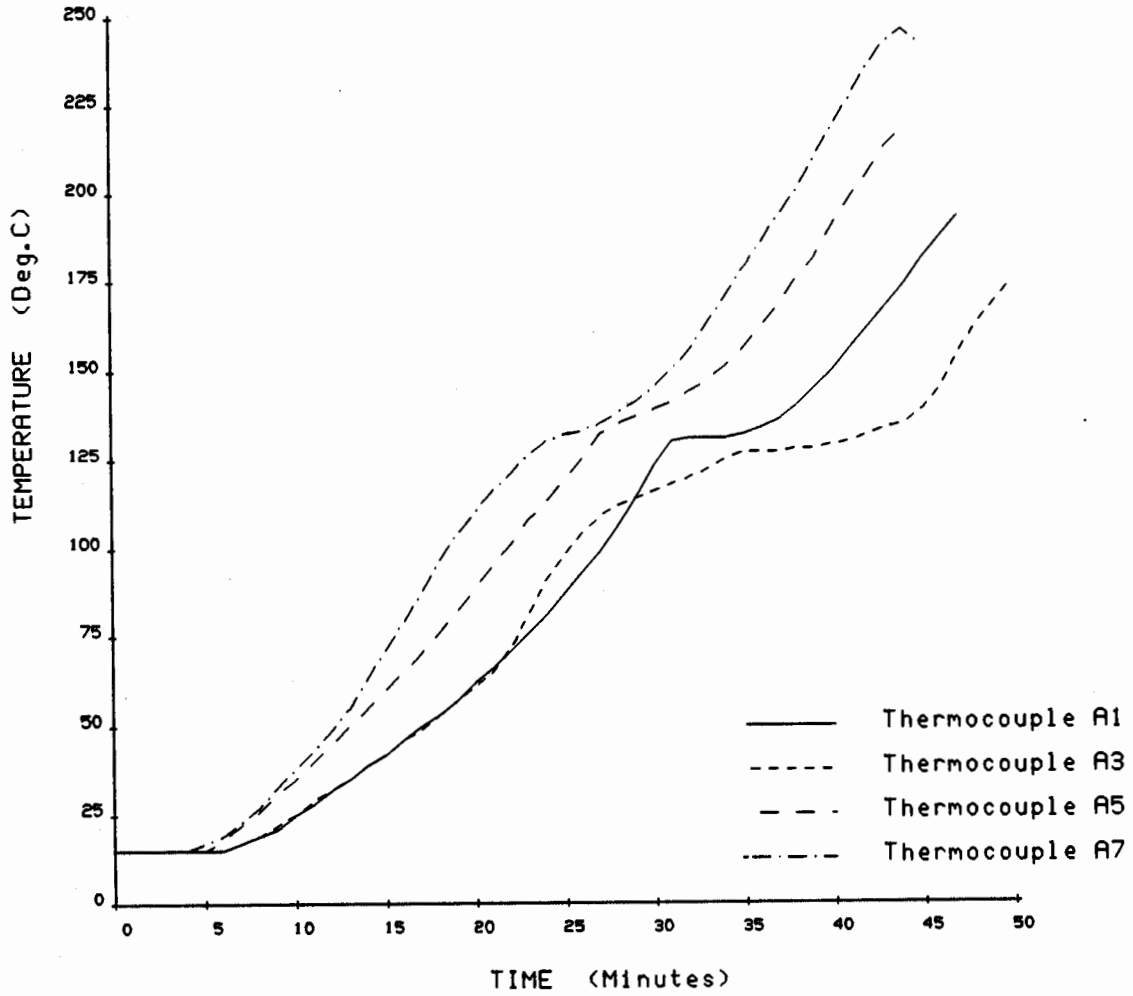


FIG. A3.4 **TEMPERATURES RECORDED IN THE STEELWORK AT THE C POSITION**
TEST NO. LPC 81442
(323.9 mm O/D × 6.3 mm WALL CHS)



**FIG. A3.5 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{3}{8}$ DIAMETER POSITION - LEVEL A
 TEST NO. LPC 81442
 (323.9 mm O/D \times 6.3 mm WALL CHS)**

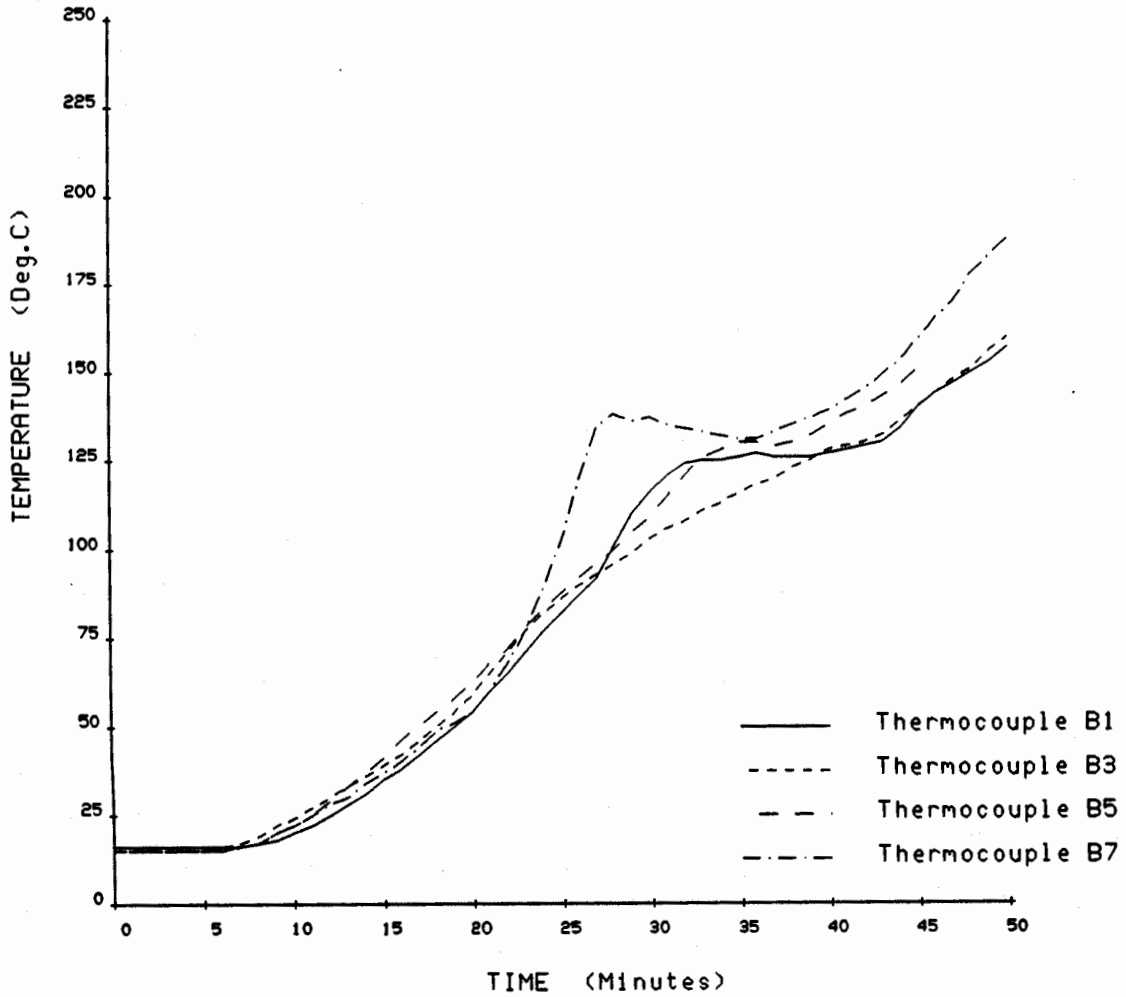


FIG. A3.6 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{3}{8}$ DIAMETER POSITION - LEVEL B
 TEST NO. LPC 81442
 (323.9 mm O/D \times 6.3 mm WALL CHS)

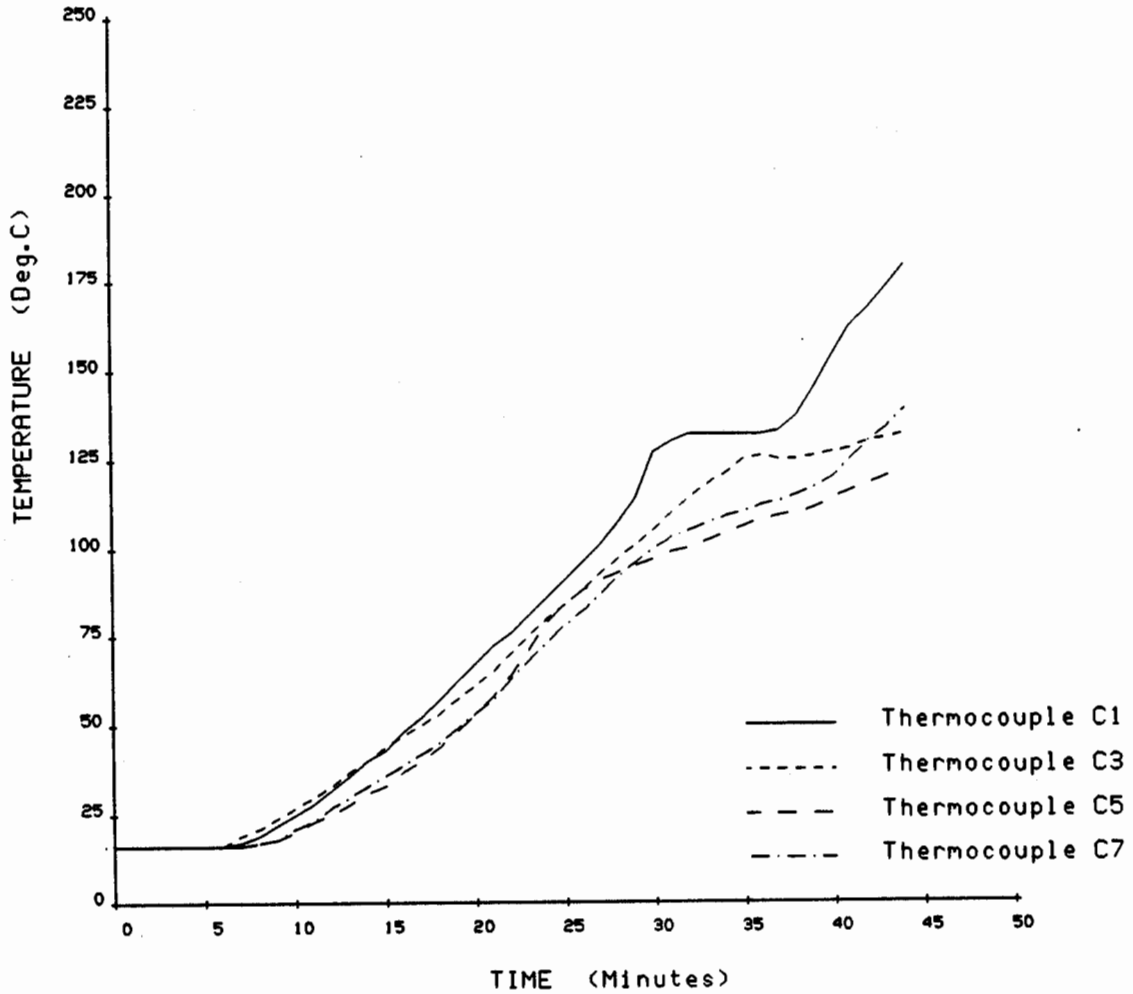


FIG. A3.7 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{3}{8}$ DIAMETER POSITION - LEVEL C
TEST NO. LPC 81442
(323.9 mm O/D \times 6.3 mm WALL CHS)

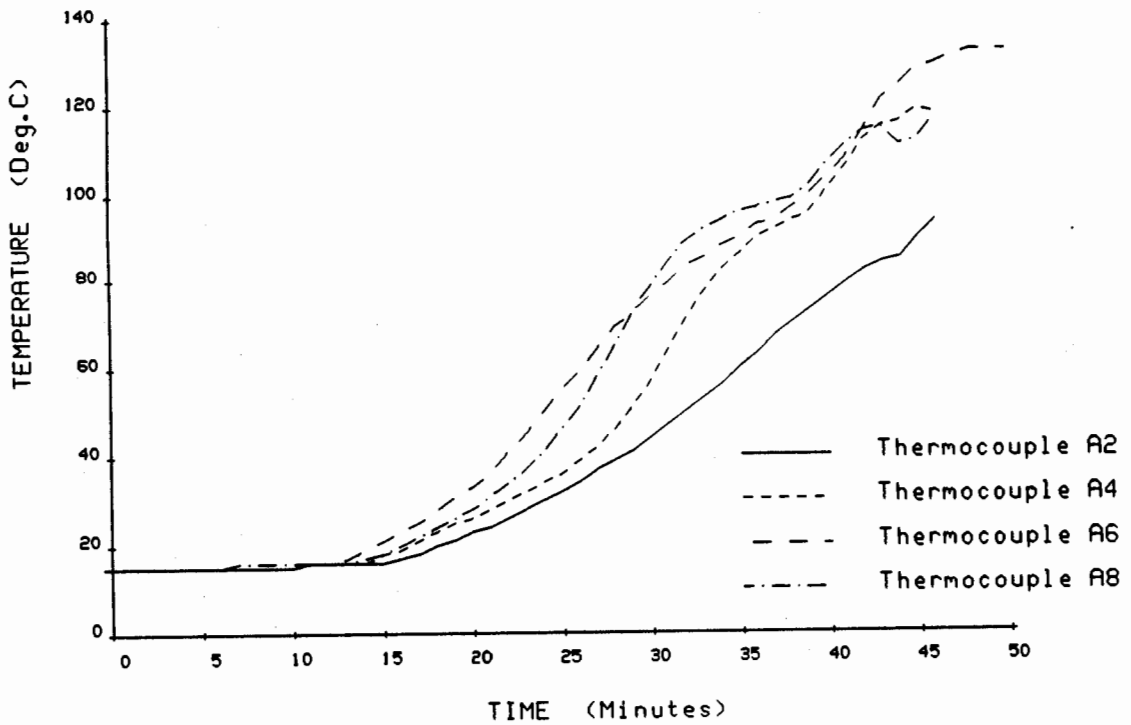


FIG. A3.8 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{1}{4}$ DIAMETER POSITION - LEVEL A
TEST NO. LPC 81442
(323.9 mm O/D \times 6.3 mm WALL CHS)

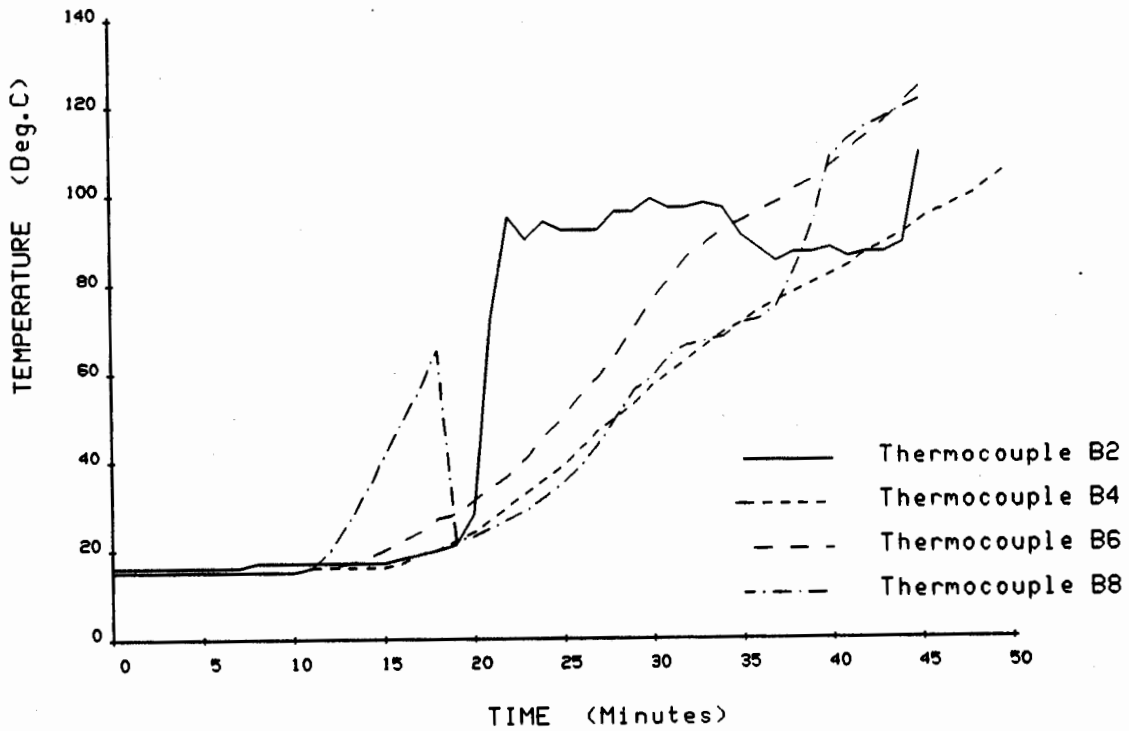


FIG. A3.9 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{1}{4}$ DIAMETER POSITION - LEVEL B
 TEST NO. LPC 81442
 (323.9 mm O/D \times 6.3 mm WALL CHS)

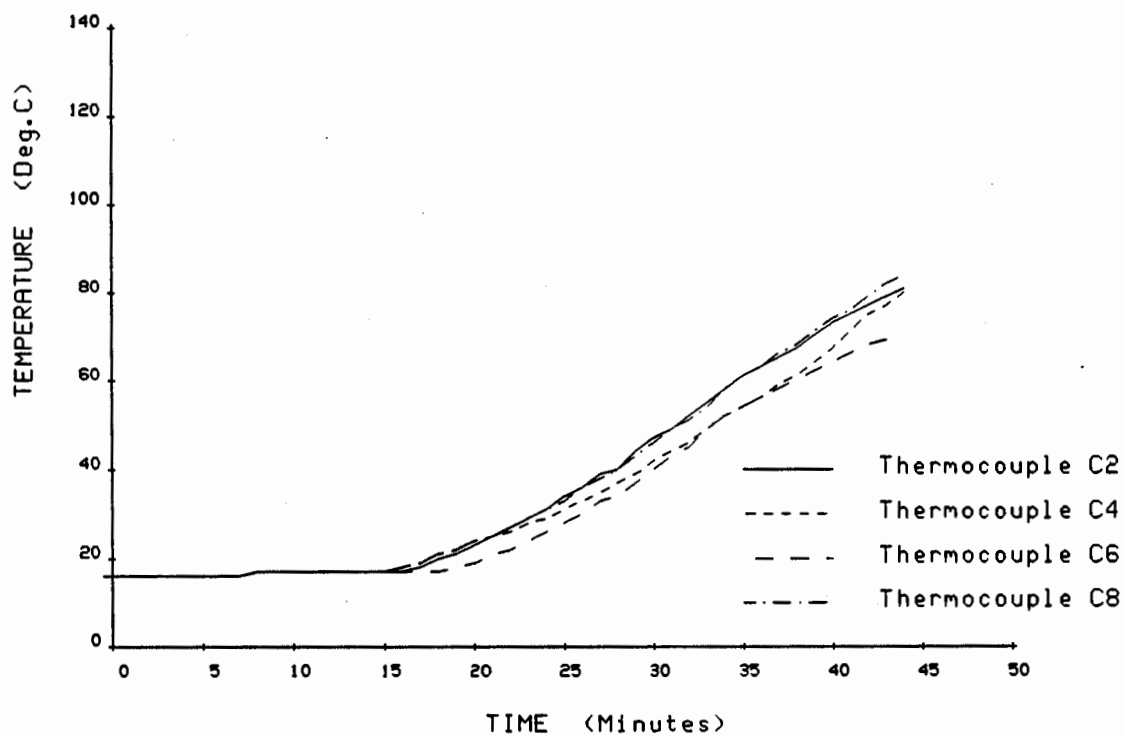


FIG. A3.10 TEMPERATURES RECORDED IN THE CONCRETE AT THE
 $\frac{1}{4}$ DIAMETER POSITION - LEVEL C
TEST NO. LPC 81442
(323.9 mm O/D \times 6.3 mm WALL CHS)

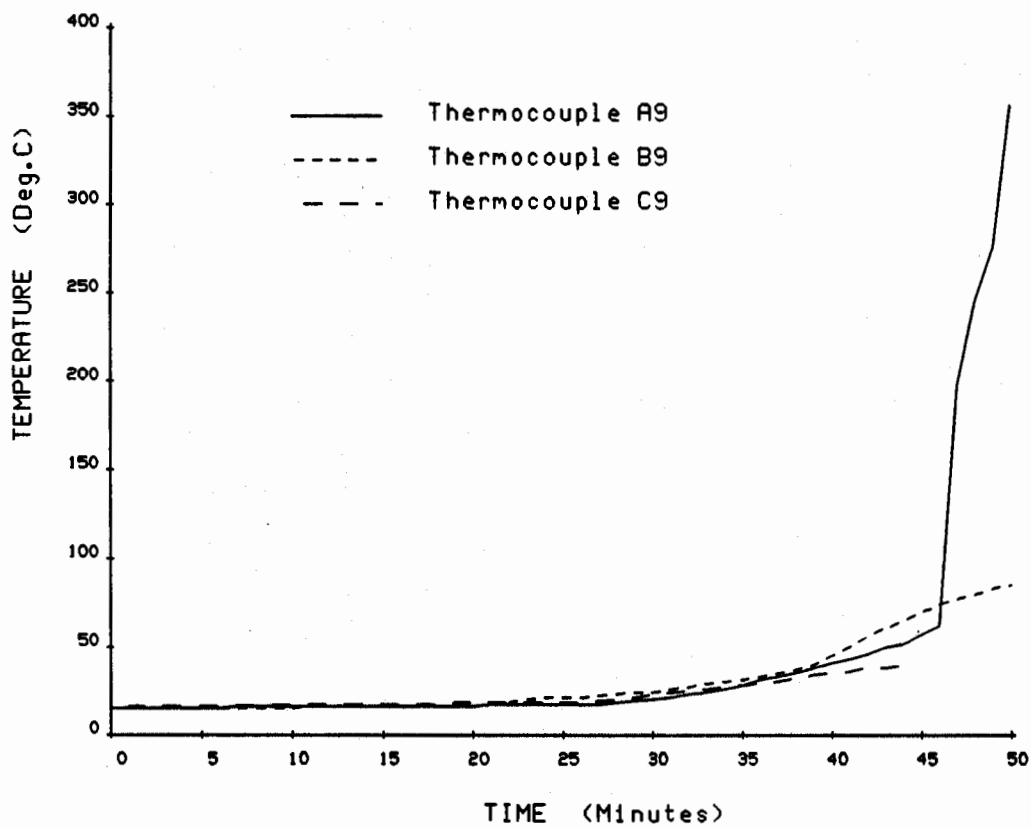
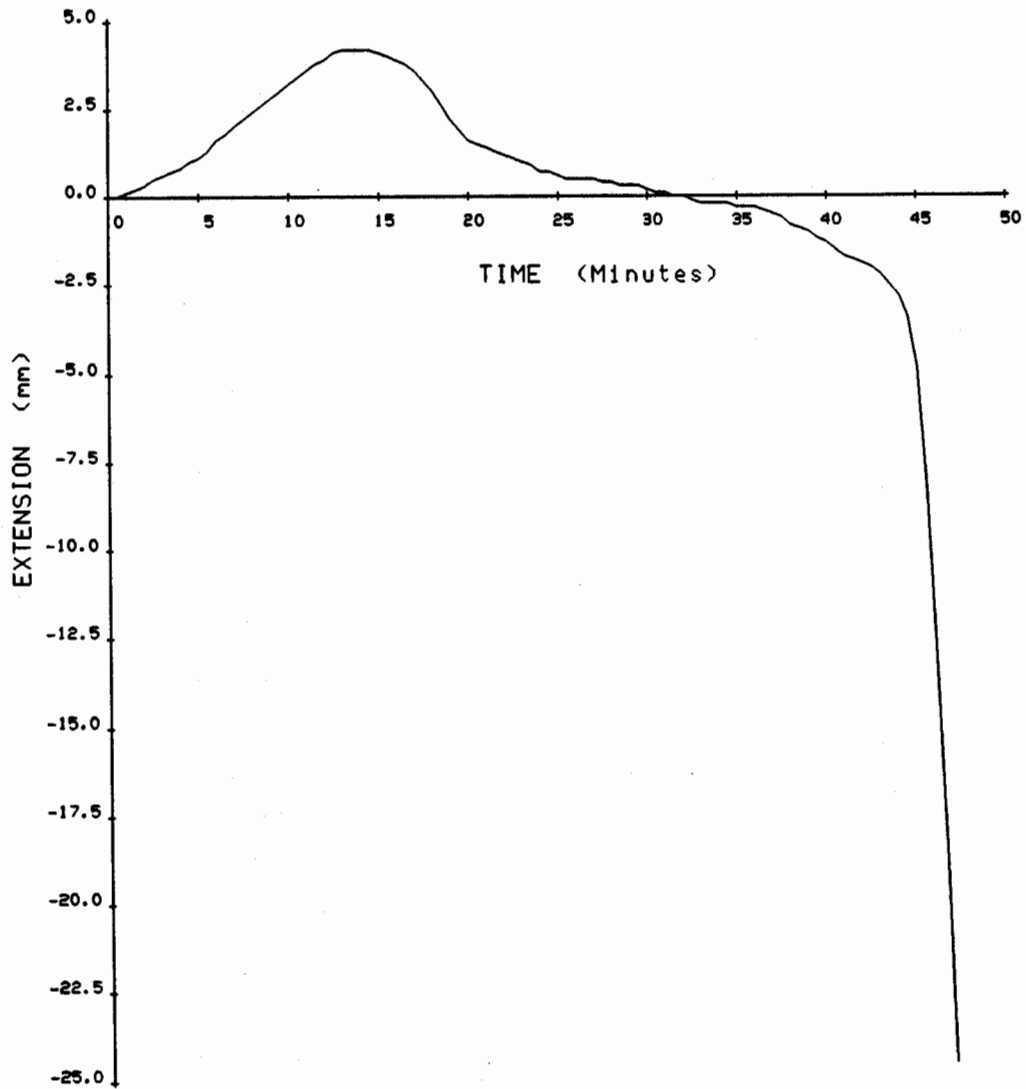
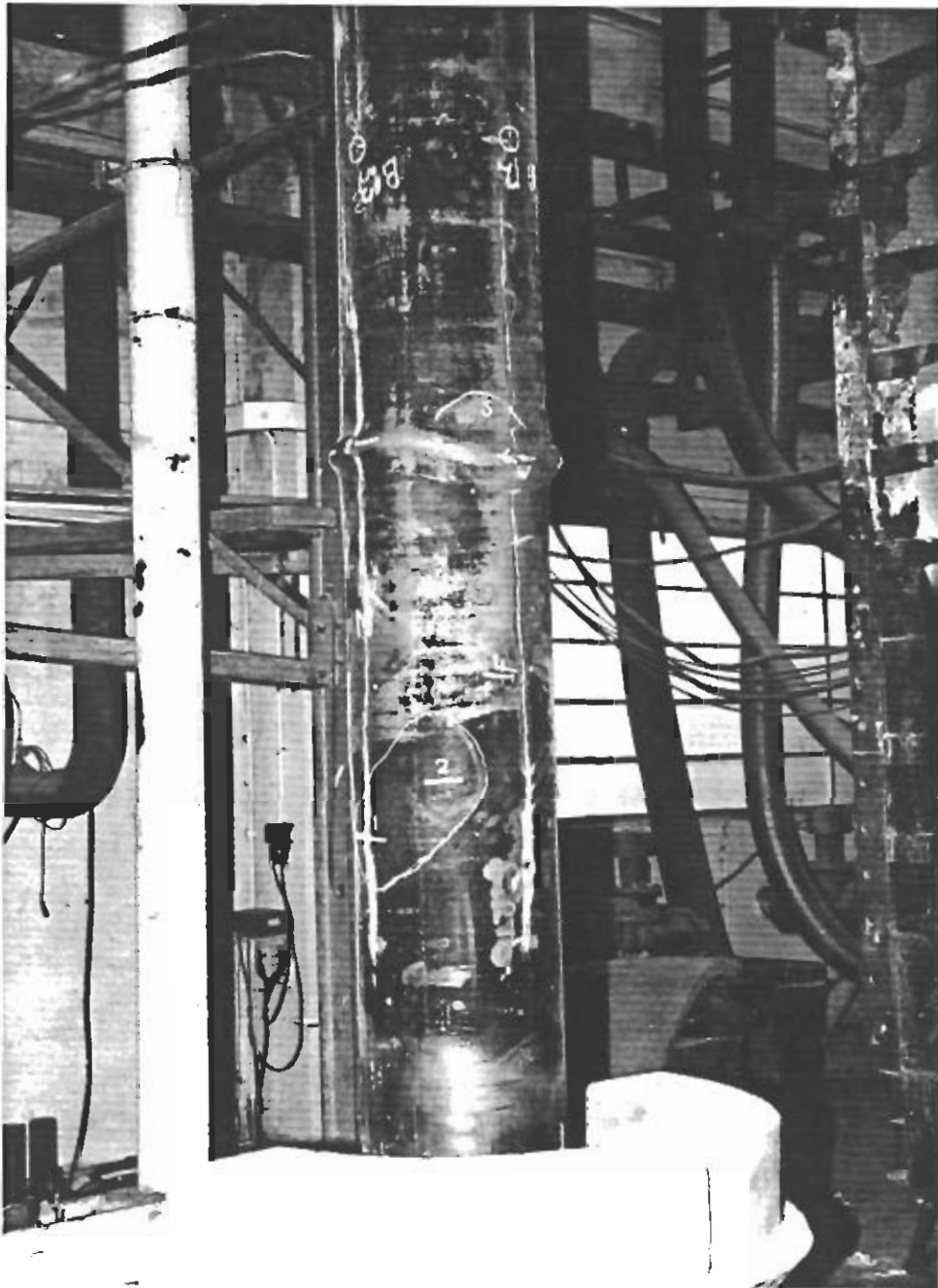


FIG. A3.11 **TEMPERATURES RECORDED AT THE CONCRETE CORE POSITION**
TEST NO. LPC 81442
(323.9 mm O/D × 6.3 mm WALL CHS)

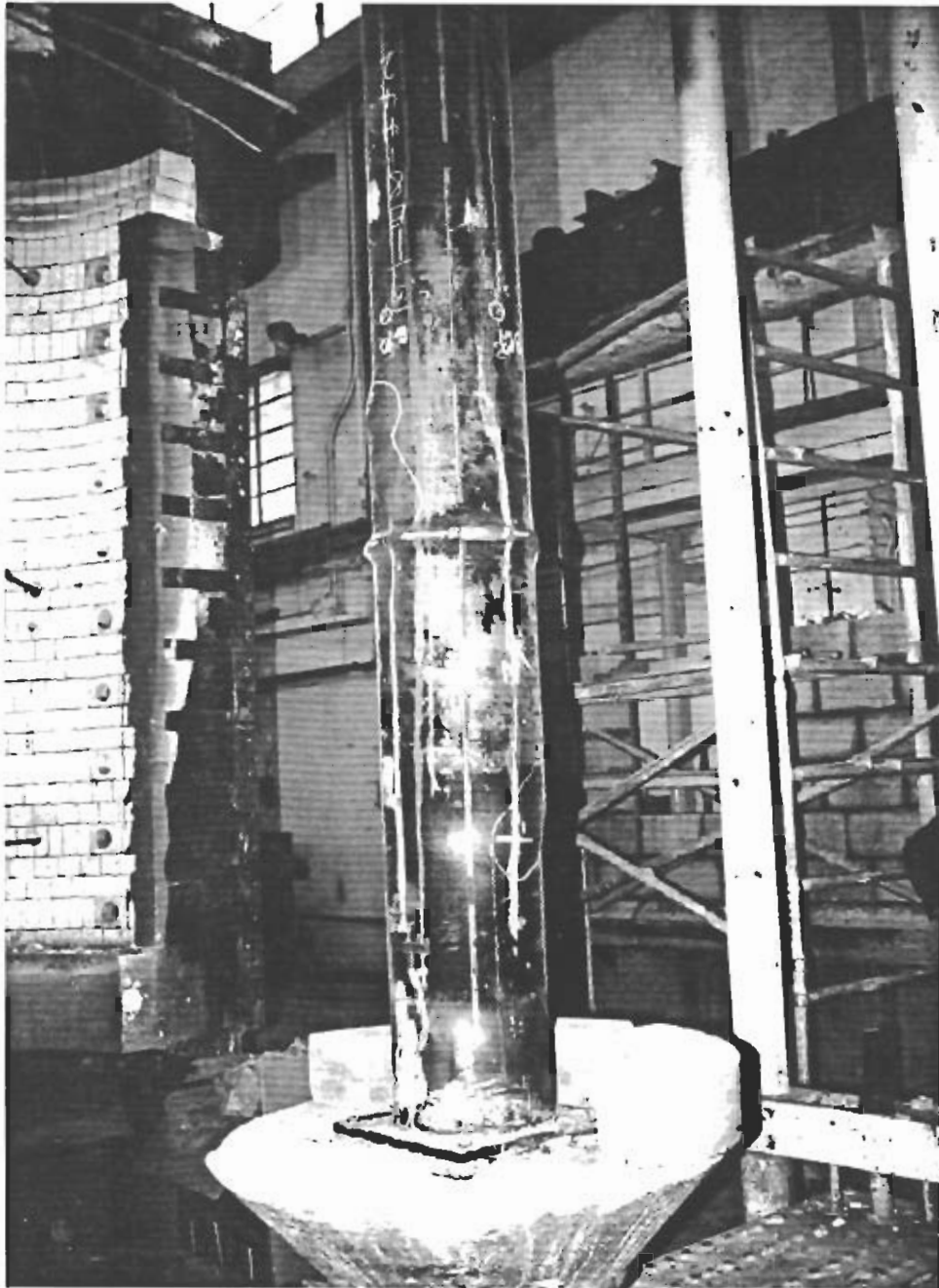


**FIG. A3.12 VERTICAL EXTENSION OF THE COLUMN
RECORDED DURING TEST NO. LPC 81442
(323.9 mm O/D × 6.3 mm WALL CHS)**

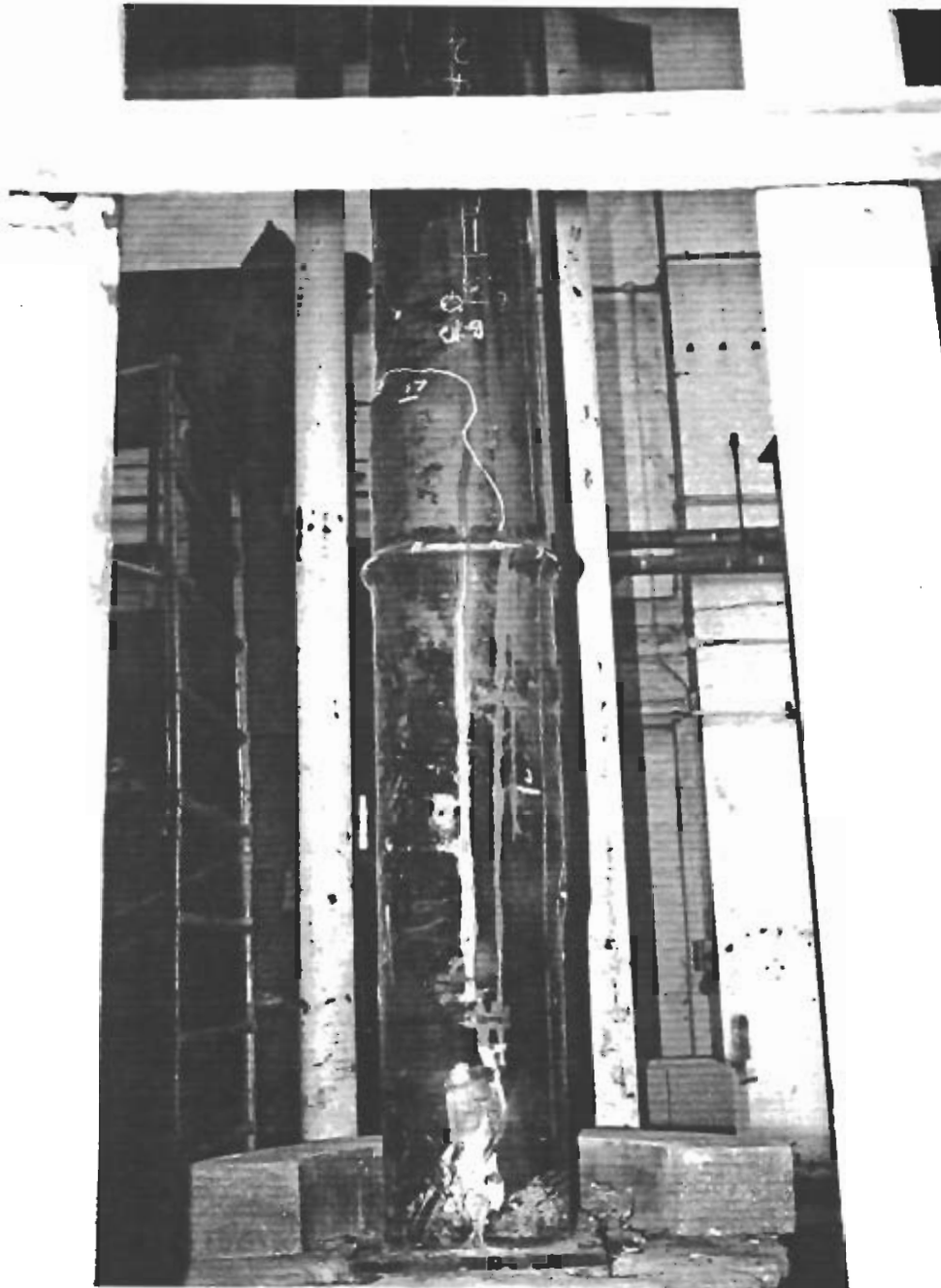


Test No. LPC 81442

**FIG. A3.13 323.9 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE NORTH WEST POSITION**

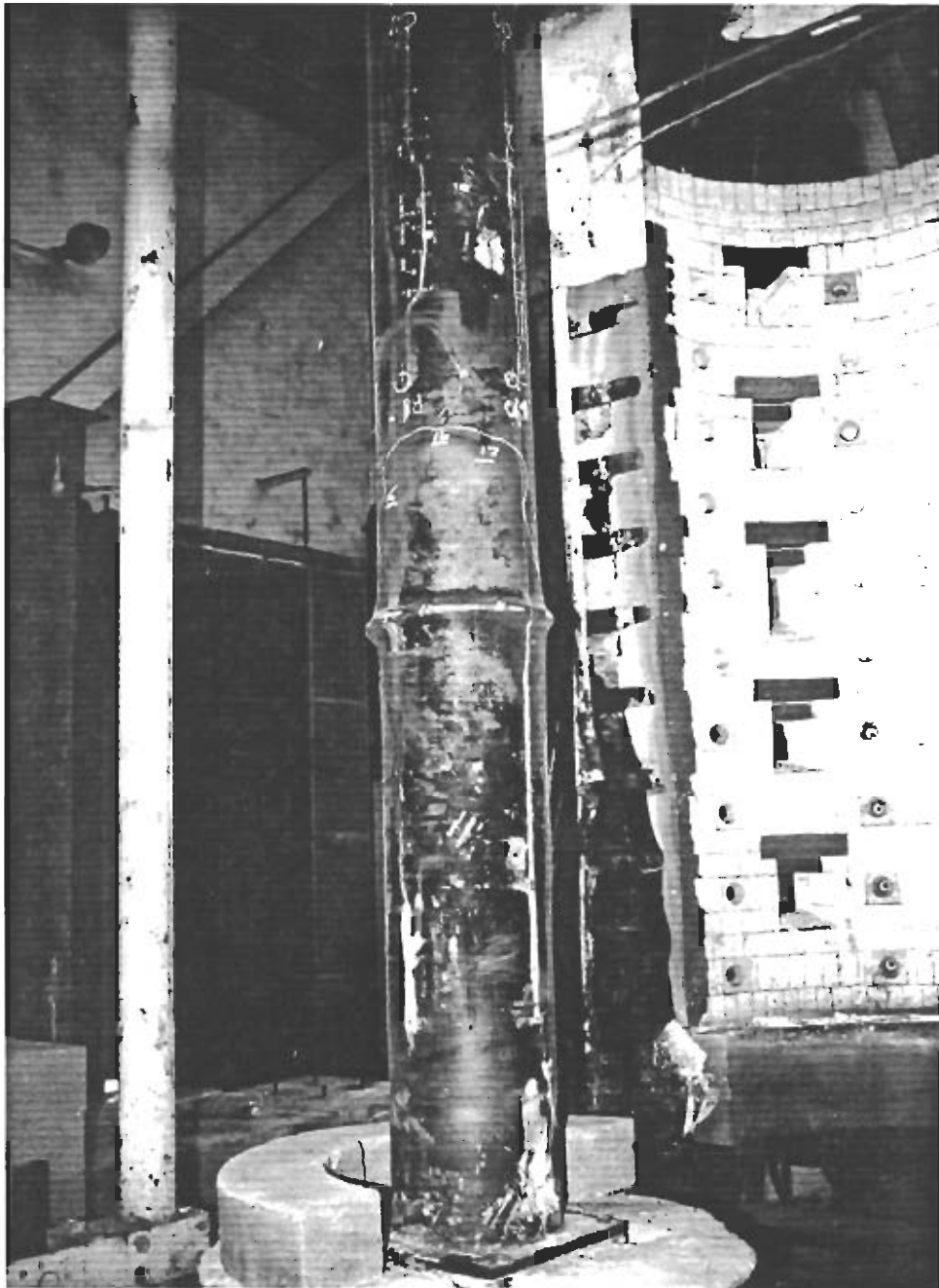


**FIG. A3.14 323.9 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE NORTH EAST POSITION**



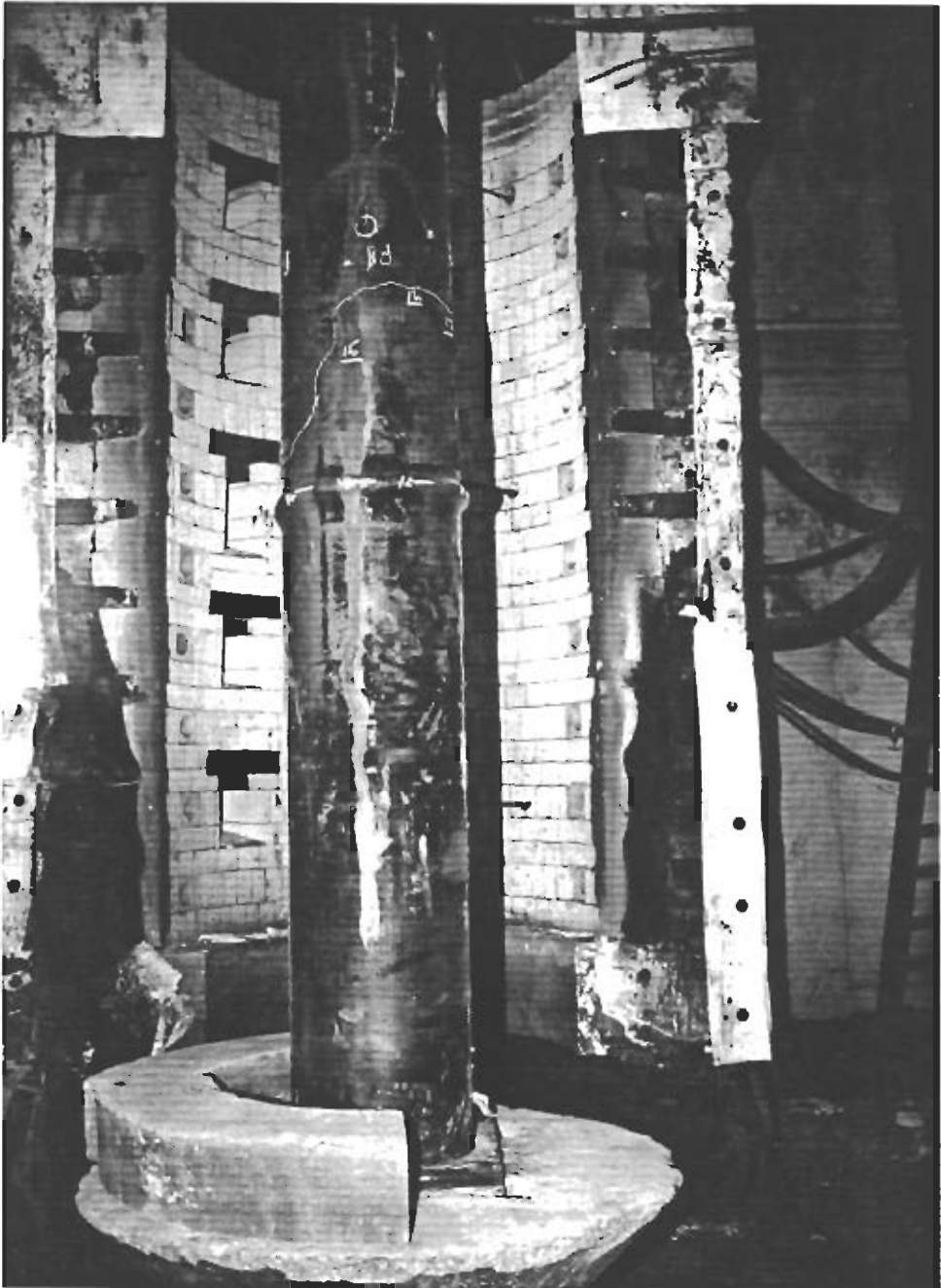
Test No. LPC 81442

**FIG. A3.15 323.9 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE EAST POSITION**



Test No. LPC 81442

**FIG. A3.16 323.9 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE SOUTH EAST POSITION**



Test No. LPC 81442

**FIG. A3.17 323.9 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE SOUTH POSITION**



Test No. LPC 81442

**FIG. A3.18 323.9 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE SOUTH WEST POSITION**

APPENDIX 4

DETAILED EXPERIMENTAL RESULTS - 3RD COLUMN TEST

A4.1 TEST NO. LPC 81443 (355.6 MM O/D × 9.5 MM THICK WALL CHS)

The test was carried out in accordance with Section 6 of BS476:Part 21:1987 at the LPC, Borehamwood, on 26th November 1991.

The column supported the full test load of 900 kN for a period of 142.5 minutes, at which time the load was reduced to a pinch value. The test was terminated after a total heating period of 143 minutes. In accordance with the provisions of BS476:Part 21 the fire resistance rating of the test assembly was 142 minutes.

A4.1.1 Temperature Measurements

The temperatures recorded by the six thermocouples monitoring the furnace atmosphere are presented in Table A4.1. The table also gives the mean furnace atmosphere temperatures and the corresponding BS476 standard heating curve values. The temperature data from the twelve thermocouples embedded in the steelwork are presented in Table A4.2, together with the average temperatures at the three measurements planes. Similarly, the temperatures recorded in the concrete at the $\frac{3}{8}$ diameter, $\frac{1}{4}$ diameter and central positions are presented in Tables A4.3, A4.4 and A4.5 respectively.

In Fig. A4.1 the average furnace atmosphere temperature is compared with the BS476 time/temperature curve. Apart from during the first few minutes, the average temperature remained below the aim value throughout the entire test. There was a momentary loss of control after 32 minutes, and this is also evident in the plot provided by the LPC. As before, the LPC plot indicates a higher degree of control being exercised than is suggested by Fig. A4.1.

The data presented in Table A4.2 for the steelwork are shown graphically in Figs. A4.2, A4.3 and A4.4. Similarly, Figs. A4.5 to A4.10 are plots of the data presented in Tables A4.3 and A4.4 for the concrete infill at the $\frac{3}{8}$ and $\frac{1}{4}$ diameter positions. Finally, Fig. A4.11 is a plot of the data in Table A4.5 for the concrete core temperatures at the three measurement levels.

A4.1.2 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 A2.6 and is shown plotted in Fig. A4.12. The maximum extension under load was 20.2 mm which occurred 27.5 minutes from the commencement of the test. Thereafter the column length contracted, it regaining its original value after 119 minutes of heating.

A4.1.3 General Observations

A4.1.3.1 During the Test

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

Time min/s	Event
-15.00	Load of 900 kN applied to the column. Displacement transducer set to zero.
00.00	Test commenced
24.00	No evidence of any deformation of the column
24.30	Sound of steam issuing from the vent holes becomes apparent
27.30	Column extension reaches a maximum value of 20.2 mm
30.00	Steam emission now very apparent (visually and audibly)
32.00	Concrete plugs in lower vent holes audibly ejected. Steam issuing from the top half of the joint between the furnace shells on the West side.
36.00	Steam emission continues vigorously. Obvious as a dense plume of spray, particularly from the West and North lower vent holes. Now issuing from the furnace joints on both sides (E and W).
40.00	South facing vent is now the most active of the lower group
41.30	No apparent deformation of the column
45.30	Emission of steam from between the furnace shells has ceased
60.00	No apparent deformation of the column. Steam emission into the furnace still continues vigorously
75.00	No significant change from 60.0 minutes
108.00	Still no significant changes
119.00	Column length at its original value
125.30	No apparent deformation of the column
142.30	Column unable to support the load. No deformation of the column noted. Load reduced to a pinch value
143.00	Test terminated

A4.1.3.2 Subsequent to the Test

Figure A4.13 is a photograph of the column taken a few minutes after opening up the furnace at the conclusion of the test. In contrast to the previous two tests, there was no evidence on this occasion of any darker/cooler region at the bottom end. As before, steam continued to be emitted from all the vent holes, though less vigorously than had been noted previously. The absence of any cooler region and the reduced pressure of the post test steam emission were almost certainly attributable to the considerably longer test duration.

Figures A4.14 and A4.15 are general views of the column, after cooling, taken from the SW and NW positions respectively. From these it can be seen that no lateral distortion, (bowing), of the tube had occurred during the test. A detailed examination of the column was carried out on 27.11.91. This revealed two areas of bulging, neither of which had been apparent during the course of the test. As before, the boundaries of the affected areas were marked on the tube wall to aid identification.

The first of these areas was situated just above the mid-height of the column, and extended from the SE to the NW positions. Its height, measured from the B level of thermocouples, was typically 250 mm and the maximum protrusion from the tube wall was about 30 mm. The bulged area can be seen generally in Figs. A4.14 and A4.15, and is shown in greater detail in Figs. A4.16 and A4.17.

The second area was located much higher up the column and covered a region which extended from the NW to the E positions. The part of the tube most badly affected was situated between the N and E positions, and this is shown in Fig. A4.18. The bulged surface was generally undulating with no specific high points being observed. The protrusion from the tube wall was variable within the range 10-30 mm. The upper boundary was approximately 100 mm above the C level of thermocouples. The lower boundary was more difficult to define, but was typically 250 mm and 500 mm below the C13 and C10 thermocouple positions respectively.

TABLE A4.1
FURNACE ATMOSPHERE TEMPERATURE DATA - LPC 81443
(355.6 mm OD × 9.5 mm THICK WALL CHS)

TIME MINS	ISO TEMP	ATM 1	ATM 2	ATM 3	ATM 4	ATM 5	ATM 6	ATM AVE
0	20	115	113	86	147	138	47	108
1	349	563	506	281	511	492	20	396
2	445	481	488	315	411	485	297	413
3	502	547	586	522	443	567	504	528
4	544	554	591	515	452	566	495	529
5	576	566	601	514	467	572	507	538
6	603	593	624	591	548	594	568	586
7	626	587	633	622	567	622	581	602
8	645	632	636	660	582	643	613	628
9	663	661	649	670	600	656	625	644
10	678	676	654	684	610	669	639	655
11	693	683	685	696	632	701	654	675
12	705	695	690	703	647	708	663	684
13	717	702	701	711	646	722	669	692
14	728	708	706	720	656	724	675	698
15	739	705	714	724	670	726	683	704
16	748	725	724	724	674	739	698	714
17	757	730	729	731	683	747	708	721
18	766	742	731	736	690	751	718	728
19	774	750	750	755	723	763	725	744
20	781	735	761	764	740	784	740	754
21	789	742	770	758	743	783	746	757
22	796	753	773	771	748	792	752	765
23	802	783	774	776	757	801	765	776
24	809	812	786	771	772	802	775	786
25	815	808	802	771	776	806	786	792
26	820	801	790	776	801	812	795	796
27	826	805	791	780	810	808	793	798
28	832	810	801	783	813	823	797	805
29	837	822	806	783	821	832	799	811
30	842	831	803	794	822	835	804	815
31	847	821	801	810	841	834	835	824
32	851	819	803	774	825	792	768	797
33	856	837	827	774	834	811	785	811
34	860	852	838	793	840	847	816	831
35	865	861	853	807	842	860	840	844
36	869	870	874	816	834	854	857	851
37	873	886	889	834	847	840	860	859
38	877	892	892	839	856	841	877	866
39	881	901	901	848	866	837	891	874
40	885	901	898	848	878	845	888	876
41	888	906	904	856	880	860	891	883
42	892	896	906	856	877	871	892	883
43	896	898	911	856	879	869	911	887
44	899	899	914	861	884	867	923	891
45	902	895	905	851	878	893	886	885
46	906	895	912	859	878	901	887	889
47	909	883	917	864	873	898	892	888
48	912	877	915	879	880	921	890	894
49	915	887	920	898	873	923	893	899
50	918	888	921	900	879	930	895	902
51	921	893	917	890	881	932	899	902
52	924	897	919	889	886	933	904	905
53	927	896	921	893	896	928	905	907
54	930	901	921	901	917	934	891	911
55	932	912	927	914	919	936	889	916
56	935	915	925	911	922	939	897	918
57	938	919	926	907	924	944	897	920
58	940	920	930	907	927	946	905	923
59	943	925	930	912	929	946	902	924
60	945	928	934	910	931	955	904	927
61	948	931	936	910	932	957	910	929
62	950	933	940	915	935	952	915	932
63	953	934	941	915	938	959	914	934
64	955	938	943	913	940	962	918	936
65	957	939	947	914	943	961	924	938
66	960	942	948	921	945	963	923	940
67	962	945	950	924	947	964	929	943
68	964	949	953	927	950	965	929	946
69	966	952	955	930	952	969	929	948
70	968	954	958	937	955	972	939	953

TABLE A4.1
(CONTINUED))

TIME MINS	ISO TEMP	ATM 1	ATM 2	ATM 3	ATM 4	ATM 5	ATM 6	ATM AVE
71	971	957	962	939	958	973	943	955
72	973	961	965	945	960	976	944	959
73	975	963	967	947	963	975	946	960
74	977	965	969	948	966	981	950	963
75	979	968	973	950	968	983	952	966
76	981	970	976	955	970	982	957	968
77	983	972	978	954	971	986	961	970
78	985	973	981	957	975	986	963	973
79	986	976	983	958	979	993	966	976
80	988	976	985	960	978	994	969	977
81	990	978	988	964	981	996	970	980
82	992	980	990	968	984	997	973	982
83	994	981	994	968	983	999	976	984
84	996	984	996	972	985	1003	977	986
85	997	989	998	974	990	1003	980	989
86	999	988	1000	977	990	1006	982	991
87	1001	989	1003	983	991	1008	983	993
88	1003	992	1005	981	994	1011	983	994
89	1004	995	1008	986	995	1013	984	997
90	1006	995	1010	988	999	1014	988	999
91	1008	997	1011	989	1001	1018	985	1000
92	1009	1000	1013	990	1003	1020	990	1003
93	1011	1000	1015	990	1002	1017	986	1002
94	1012	998	1015	992	1005	1017	988	1003
95	1014	1001	1017	992	1006	1017	991	1004
96	1016	1001	1016	992	1007	1019	990	1004
97	1017	1003	1017	994	1008	1021	994	1006
98	1019	1004	1018	995	1012	1021	991	1007
99	1020	1005	1020	997	1009	1025	993	1008
100	1022	1006	1021	998	1014	1027	997	1011
101	1023	1007	1023	997	1013	1027	998	1011
102	1025	1008	1024	1000	1015	1029	1000	1013
103	1026	1010	1025	1002	1017	1032	1001	1015
104	1028	1011	1028	1000	1018	1031	1002	1015
105	1029	1013	1027	1005	1017	1033	1003	1016
106	1030	1014	1030	1005	1019	1034	1008	1018
107	1032	1016	1030	1007	1018	1035	1010	1019
108	1033	1017	1032	1007	1020	1037	1011	1021
109	1035	1019	1034	1010	1022	1040	1013	1023
110	1036	1019	1036	1010	1024	1041	1012	1024
111	1037	1021	1036	1012	1023	1043	1018	1026
112	1039	1021	1039	1014	1025	1044	1019	1027
113	1040	1025	1039	1015	1028	1047	1018	1029
114	1041	1026	1042	1017	1026	1046	1020	1030
115	1043	1027	1044	1018	1028	1048	1023	1031
116	1044	1029	1044	1019	1025	1052	1024	1032
117	1045	1030	1047	1021	1029	1050	1024	1034
118	1047	1033	1048	1023	1029	1053	1027	1036
119	1048	1033	1050	1024	1031	1055	1028	1037
120	1049	1035	1053	1025	1032	1055	1027	1038
121	1050	1036	1054	1026	1033	1058	1030	1040
122	1052	1038	1056	1027	1033	1060	1031	1041
123	1053	1041	1058	1030	1036	1062	1033	1043
124	1054	1041	1060	1030	1038	1060	1036	1044
125	1055	1042	1062	1030	1040	1063	1037	1046
126	1056	1045	1063	1033	1043	1063	1038	1048
127	1058	1045	1065	1032	1043	1065	1041	1049
128	1059	1047	1067	1034	1043	1066	1041	1050
129	1060	1048	1068	1035	1043	1066	1042	1050
130	1061	1051	1072	1034	1047	1065	1041	1052
131	1062	1053	1073	1033	1047	1068	1042	1053
132	1063	1054	1074	1034	1047	1070	1042	1054
133	1064	1055	1076	1035	1048	1068	1042	1054
134	1066	1058	1076	1034	1049	1071	1047	1056
135	1067	1060	1077	1033	1049	1072	1048	1057
136	1068	1060	1078	1034	1048	1071	1051	1057
137	1069	1061	1079	1033	1050	1075	1054	1059
138	1070	1063	1080	1032	1049	1074	1053	1059
139	1071	1066	1081	1029	1051	1076	1052	1059
140	1072	1067	1082	1029	1050	1077	1053	1060
141	1073	1068	1082	1027	1052	1078	1056	1061
142	1074	1070	1083	1027	1051	1080	1053	1061

TABLE A4.2
TEMPERATURES RECORDED IN THE STEELWORK - LPC 81443
(355.6 mm OD × 9.5 mm THICK WALL CHS)

TIME MINS	A10	A11	A12	A13	A AVE	B10	B11	B12	B13	B AVE	C10	C11	C12	C13	C AVE
0	20	20	20	20	20	20	20	20	20	20	22	22	*	22	22
1	53	64	41	42	50	41	40	35	35	38	56	74	*	59	63
2	59	63	48	51	55	56	55	49	50	53	61	67	*	63	64
3	94	95	72	77	85	77	76	68	70	73	73	75	*	81	76
4	119	116	95	96	107	97	98	90	90	94	86	84	*	100	90
5	146	135	117	115	128	117	120	107	110	114	98	94	*	118	103
6	178	159	143	140	155	139	143	125	130	134	115	122	*	137	125
7	209	183	168	163	181	163	165	144	151	156	139	151	*	154	148
8	240	210	198	193	210	184	189	166	173	178	173	188	*	177	179
9	268	234	226	220	237	206	196	189	194	196	210	221	*	208	213
10	294	256	254	245	262	223	142	209	211	196	248	247	*	238	244
11	317	277	280	269	286	239	185	238	215	219	281	279	*	264	275
12	339	300	306	291	309	246	265	267	219	249	311	312	*	290	304
13	360	319	330	311	330	272	313	293	228	277	339	340	*	311	330
14	380	335	352	329	349	308	351	318	253	308	362	363	*	331	352
15	396	353	371	349	367	336	380	341	280	334	382	386	*	348	372
16	411	372	389	369	385	362	407	363	305	359	401	406	*	366	391
17	426	391	408	387	403	384	429	384	326	381	416	426	*	382	408
18	440	411	423	407	420	397	450	404	344	399	433	446	*	408	429
19	458	429	440	426	438	408	470	425	359	416	447	469	*	425	447
20	477	448	457	445	457	421	484	446	381	433	463	493	*	443	466
21	495	464	469	461	472	430	496	466	407	450	474	514	*	459	482
22	508	480	481	480	487	434	509	484	415	461	484	532	*	476	497
23	518	493	492	499	501	438	524	500	415	469	496	548	*	493	512
24	527	507	502	516	513	441	540	516	402	475	511	564	*	516	530
25	539	520	508	530	524	441	554	530	409	484	524	575	*	544	548
26	548	532	516	545	535	441	572	544	415	493	536	586	*	552	558
27	554	541	520	556	543	443	586	556	423	502	549	596	*	561	569
28	562	550	521	564	549	443	599	568	440	513	563	606	*	570	580
29	570	560	522	573	556	448	612	578	454	523	575	615	*	579	590
30	579	572	525	582	565	453	624	587	470	534	586	626	*	591	601
31	583	584	528	590	571	469	634	595	483	545	594	635	*	601	610
32	586	589	529	597	575	483	637	600	486	552	602	637	*	614	618
33	594	594	512	605	576	471	623	602	513	552	614	633	*	631	626
34	609	606	523	616	589	499	625	611	543	570	629	637	*	648	638
35	622	618	557	631	607	518	630	619	574	585	643	639	*	660	647
36	632	628	583	646	622	530	636	626	603	599	655	650	*	673	659
37	640	638	604	662	636	539	641	635	627	611	666	665	*	684	672
38	647	647	628	675	649	558	643	642	647	623	677	679	*	692	683
39	658	656	650	689	663	578	646	651	664	635	689	693	*	701	694
40	669	665	668	700	676	597	650	659	677	646	700	703	*	711	705
41	681	675	685	709	688	612	657	669	687	656	712	714	*	723	716
42	693	684	698	718	698	625	665	680	697	667	720	722	*	731	724
43	704	693	711	726	709	638	673	689	705	676	726	727	*	737	730
44	713	700	722	733	717	649	681	697	713	685	732	732	*	741	735
45	720	706	727	735	722	658	687	704	720	692	737	735	*	742	738
46	727	709	728	737	725	668	696	711	726	700	741	739	*	745	742
47	732	713	728	740	728	677	704	716	732	707	745	743	*	749	746
48	736	716	731	746	732	687	713	723	737	715	748	746	*	752	749
49	740	719	741	755	739	697	723	732	742	724	753	748	*	757	753
50	745	724	750	766	746	707	732	739	748	732	758	751	*	762	757
51	749	731	761	777	755	715	738	745	755	738	762	755	*	765	761
52	751	738	772	784	761	722	743	750	761	744	766	759	*	770	765
53	756	742	781	792	768	729	750	754	769	751	772	765	*	775	771
54	760	745	786	797	772	734	758	757	774	756	777	768	*	781	775
55	771	752	786	800	777	738	765	760	780	761	786	776	*	787	783
56	778	758	786	804	782	739	772	763	783	764	792	783	*	791	789
57	784	765	789	808	787	742	778	768	786	769	799	792	*	795	795
58	787	770	794	812	791	744	784	774	789	773	804	797	*	801	801
59	792	776	797	816	795	747	790	780	792	777	810	804	*	806	807
60	793	782	801	820	799	750	795	787	796	782	815	809	*	811	812
61	795	788	805	824	803	753	800	795	799	787	820	816	*	815	817
62	799	792	811	828	808	755	805	803	802	791	825	821	*	821	822
63	802	797	814	833	812	758	810	811	806	796	830	826	*	825	827
64	805	803	819	837	816	760	815	818	810	801	834	832	*	829	832
65	807	808	824	841	820	762	819	824	814	805	839	837	*	834	837
66	811	813	829	845	825	764	824	831	819	810	844	842	*	838	841
67	816	817	833	850	829	765	829	837	824	814	849	847	*	843	846
68	821	821	838	855	834	766	834	844	829	818	853	853	*	847	851
69	826	825	843	860	839	767	838	850	834	822	858	858	*	852	856
70	833	831	849	865	845	769	843	856	840	827	864	865	*	857	862

TABLE A4.2
(CONTINUED)

TIME MINS	A10	A11	A12	A13	A AVE	B10	B11	B12	B13	B AVE	C10	C11	C12	C13	C AVE
71	839	836	855	871	850	771	848	862	846	832	868	871	*	862	867
72	845	842	861	877	856	774	854	868	853	837	874	876	*	868	873
73	851	847	867	882	862	776	860	874	859	842	878	882	*	872	877
74	857	852	873	887	867	780	865	879	866	848	883	886	*	877	882
75	862	857	878	892	872	783	870	884	872	852	888	891	*	883	887
76	867	862	884	896	877	787	876	889	879	858	893	894	*	888	892
77	871	867	889	901	882	790	881	893	884	862	896	899	*	893	896
78	875	872	893	906	887	794	887	897	889	867	901	902	*	898	900
79	877	877	898	909	890	798	891	901	895	871	904	906	*	902	904
80	879	882	901	913	894	802	896	905	899	876	909	909	*	906	908
81	884	886	904	917	898	806	901	909	904	880	913	913	*	910	912
82	888	890	908	920	902	811	905	912	909	884	916	916	*	915	916
83	891	894	910	924	905	816	909	915	914	889	920	918	*	918	919
84	894	898	914	927	908	820	913	919	918	893	923	922	*	922	922
85	898	901	918	931	912	824	916	922	923	896	926	924	*	927	926
86	902	904	922	935	916	828	919	926	927	900	930	927	*	930	929
87	906	908	925	938	919	832	922	929	932	904	933	930	*	935	933
88	908	911	929	942	923	837	926	932	936	908	936	932	*	938	935
89	912	914	932	945	926	840	929	935	940	911	940	935	*	942	939
90	915	917	935	949	929	845	932	938	944	915	941	937	*	946	941
91	917	920	938	951	932	849	934	941	947	918	944	940	*	948	944
92	919	922	941	953	934	853	937	944	951	921	947	943	*	952	947
93	919	924	944	956	936	855	939	946	953	923	947	943	*	954	948
94	919	924	946	958	937	857	939	948	955	925	948	943	*	956	949
95	919	925	947	959	938	860	941	950	957	927	948	945	*	959	951
96	919	926	949	961	939	862	943	951	958	929	950	946	*	960	952
97	920	927	952	962	940	865	944	953	961	931	952	949	*	962	954
98	921	928	953	965	942	868	946	955	963	933	954	949	*	965	956
99	922	930	955	966	943	871	948	957	965	935	956	952	*	967	958
100	924	932	956	968	945	874	950	959	967	938	957	954	*	968	960
101	925	933	959	970	947	878	951	961	969	940	959	956	*	970	962
102	926	935	960	971	948	882	953	963	971	942	961	957	*	973	964
103	928	937	962	973	950	886	955	965	974	945	962	960	*	975	966
104	930	939	964	975	952	889	957	967	975	947	965	962	*	977	968
105	931	941	966	977	954	893	959	969	977	950	967	964	*	978	970
106	932	943	968	979	956	896	961	971	979	952	967	967	*	981	972
107	934	945	971	981	958	900	963	973	981	954	970	968	*	983	974
108	936	947	972	983	960	903	965	975	983	957	971	971	*	985	976
109	938	949	974	984	961	907	967	977	986	959	973	974	*	988	978
110	940	951	976	985	963	911	969	979	987	962	975	975	*	989	980
111	943	953	978	987	965	915	971	981	989	964	978	978	*	991	982
112	944	955	980	988	967	918	973	983	992	967	979	979	*	993	984
113	946	956	981	990	968	922	975	985	994	969	980	981	*	995	985
114	948	958	982	991	970	925	977	987	996	971	983	983	*	998	988
115	950	960	984	993	972	929	979	988	998	974	984	985	*	1000	990
116	952	962	987	995	974	932	981	991	1000	976	986	987	*	1002	992
117	954	963	989	997	976	936	983	992	1002	978	988	988	*	1004	993
118	956	965	990	998	977	939	985	994	1004	981	991	991	*	1005	996
119	958	967	992	1000	979	942	987	996	1006	983	992	993	*	1008	998
120	960	968	993	1003	981	946	989	998	1008	985	994	994	*	1010	999
121	962	970	996	1005	983	949	991	1000	1011	988	997	996	*	1013	1002
122	964	971	997	1007	985	952	993	1001	1012	990	998	998	*	1015	1004
123	966	973	999	1009	987	956	994	1004	1015	992	1001	1001	*	1017	1006
124	968	976	1001	1011	989	959	997	1006	1017	995	1002	1002	*	1019	1008
125	971	977	1002	1015	991	962	999	1008	1019	997	1005	1005	*	1022	1011
126	973	979	1005	1017	994	965	1001	1010	1021	999	1007	1006	*	1023	1012
127	975	981	1006	1019	995	968	1003	1011	1023	1001	1009	1008	*	1025	1014
128	976	982	1008	1021	997	971	1004	1013	1024	1003	1010	1010	*	1027	1016
129	979	985	1010	1023	999	973	1006	1015	1026	1005	1011	1011	*	1029	1017
130	981	986	1011	1023	1000	976	1008	1016	1028	1007	1013	1013	*	1031	1019
131	983	987	1011	1022	1001	979	1009	1018	1030	1009	1016	1014	*	1033	1021
132	985	989	1013	1024	1003	981	1010	1019	1032	1011	1016	1016	*	1034	1022
133	987	990	1014	1024	1004	983	1011	1020	1033	1012	1018	1017	*	1037	1024
134	989	992	1015	1025	1005	985	1013	1021	1034	1013	1019	1019	*	1038	1025
135	990	993	1016	1026	1006	987	1014	1023	1036	1015	1020	1020	*	1040	1027
136	991	994	1018	1028	1008	989	1016	1024	1037	1017	1022	1021	*	1041	1028
137	992	996	1020	1029	1009	990	1017	1025	1038	1018	1024	1023	*	1043	1030
138	994	997	1022	1030	1011	992	1019	1026	1039	1019	1025	1024	*	1044	1031
139	995	999	1023	1031	1012	993	1020	1028	1042	1021	1027	1025	*	1046	1033
140	995	1000	1025	1031	1013	993	1023	1029	1042	1022	1028	1026	*	1048	1034
141	996	1002	1027	1032	1014	995	1025	1031	1044	1024	1029	1027	*	1048	1035
142	997	1002	1029	1034	1016	997	1027	1033	1046	1026	1031	1028	*	1051	1037

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

TABLE A4.3
TEMPERATURES RECORDED AT $\frac{3}{8}$ DIAMETER FROM CENTRE OF CONCRETE
- LPC 81443
(355.6 mm OD \times 9.5 mm THICK WALL CHS)

TIME MINS	A1	A3	A5	A7	A AVE	B1	B3	B5	B7	B AVE	C1	C3	C5	C7	C AVE
0	20	20	20	20	20	22	22	20	20	21	22	22	22	22	22
1	20	20	20	20	20	22	22	20	20	21	22	22	22	22	22
2	20	20	20	20	20	22	22	20	20	21	22	22	22	22	22
3	20	20	20	20	20	22	22	20	20	21	22	22	22	22	22
4	20	20	20	20	20	22	22	20	20	21	22	22	22	22	22
5	20	20	20	21	20	22	22	20	20	21	22	22	22	22	22
6	20	20	20	21	20	22	22	20	20	21	22	22	22	22	22
7	21	21	21	22	21	22	22	21	21	22	22	22	22	22	22
8	21	22	22	25	23	22	22	21	21	22	22	22	22	22	22
9	89	24	26	61	50	22	25	21	23	23	22	22	22	22	22
10	95	32	47	76	63	22	94	60	41	54	22	24	24	22	23
11	102	43	85	99	82	22	99	79	52	63	24	36	28	24	28
12	105	54	98	102	90	100	102	90	60	88	29	58	35	25	37
13	108	81	104	106	100	104	106	93	67	93	36	68	41	27	43
14	110	80	107	108	101	106	108	94	72	95	44	75	45	29	48
15	112	106	110	110	110	108	110	104	77	100	91	80	49	32	63
16	114	109	113	112	112	111	112	103	81	102	100	85	54	34	68
17	117	113	115	115	115	113	115	104	86	105	113	89	58	36	74
18	120	117	118	119	119	117	119	113	89	110	117	94	63	40	79
19	123	115	122	122	121	120	122	112	94	112	121	99	69	43	83
20	127	115	125	126	123	124	126	117	98	116	117	103	75	47	86
21	128	113	125	128	124	127	129	122	102	120	117	108	81	51	89
22	133	113	128	132	127	131	133	126	106	124	124	110	86	56	94
23	137	114	131	137	130	135	137	132	111	129	127	113	91	61	98
24	141	117	132	141	133	140	142	134	116	133	128	114	97	66	101
25	145	124	133	144	137	144	146	137	121	137	138	115	102	72	107
26	148	130	124	148	138	148	149	140	127	141	147	115	107	78	112
27	149	143	136	149	144	151	151	142	133	144	154	116	114	87	118
28	150	148	125	151	144	154	153	143	138	147	156	115	120	97	122
29	152	150	125	152	145	156	155	144	143	150	157	113	126	106	126
30	154	150	130	154	147	158	157	146	147	152	161	111	131	119	131
31	154	149	124	154	145	158	157	148	150	153	162	110	137	144	138
32	147	137	145	147	144	150	150	144	151	149	156	107	140	152	139
33	136	136	136	141	137	139	139	138	142	140	146	108	142	148	136
34	130	130	130	141	133	133	133	132	136	134	139	120	142	142	136
35	126	126	126	148	132	129	129	128	132	130	136	126	140	137	135
36	124	124	124	154	132	127	126	126	129	127	137	129	139	135	135
37	123	124	123	160	133	126	125	125	128	126	136	130	139	134	135
38	124	124	124	165	134	126	126	125	127	126	134	130	139	132	134
39	125	125	125	171	137	126	126	125	127	126	133	128	140	130	133
40	126	126	126	175	138	126	126	126	127	126	134	129	142	131	134
41	126	127	126	179	140	127	127	126	127	127	136	130	144	130	135
42	127	127	126	184	141	127	127	127	127	127	136	130	146	130	136
43	127	127	127	189	143	128	128	127	128	128	137	130	149	132	137
44	129	128	128	194	145	129	129	128	129	129	138	130	153	133	139
45	132	129	129	200	148	130	130	129	129	130	138	131	157	135	140
46	136	132	130	206	151	132	132	131	131	132	138	132	161	137	142
47	140	133	132	213	155	135	134	132	133	134	139	133	166	138	144
48	144	136	133	219	158	138	137	134	134	136	141	135	170	141	147
49	149	138	135	226	162	141	142	136	136	139	144	138	175	143	150
50	155	141	137	232	166	145	147	138	138	142	148	141	179	145	153
51	161	144	139	238	171	149	152	140	140	145	153	143	183	147	157
52	168	150	140	244	176	152	159	141	142	149	159	146	186	149	160
53	174	162	142	250	182	156	165	143	145	152	165	149	190	151	164
54	180	170	144	255	187	160	171	145	148	156	173	154	193	153	168
55	185	178	148	261	193	164	176	146	151	159	180	159	197	155	173
56	191	184	155	267	199	167	181	148	154	163	186	164	200	157	177
57	197	191	165	272	206	170	185	149	156	165	193	168	204	161	182
58	202	197	174	278	213	173	189	151	158	168	203	172	207	165	187
59	207	204	184	283	220	176	193	152	161	171	215	176	211	171	193
60	213	209	192	289	226	179	196	153	163	173	226	180	215	176	199
61	218	215	200	296	232	181	200	153	166	175	236	184	218	181	205
62	223	219	207	303	238	184	204	154	168	178	245	188	222	186	210
63	229	224	214	312	245	187	209	155	171	181	253	191	226	192	216
64	235	230	223	325	253	189	213	155	174	183	260	196	230	199	221
65	241	237	233	339	263	193	218	156	177	186	267	200	234	206	227
66	248	248	245	356	274	196	223	156	181	189	275	205	238	213	233
67	255	261	261	374	288	200	229	157	184	193	284	210	243	221	240
68	266	279	279	394	305	204	235	158	188	196	294	216	249	230	247
69	278	300	300	414	323	208	241	159	192	200	304	222	255	239	255
70	293	324	323	435	344	212	249	159	197	204	316	229	262	250	264

TABLE A4.3
(CONTINUED)

TIME MINS	A1	A3	A5	A7	A AVE	B1	B3	B5	B7	B AVE	C1	C3	C5	C7	C AVE
71	310	349	346	454	365	217	257	161	202	209	329	237	271	261	275
72	328	375	369	472	386	222	265	162	208	214	344	246	280	273	286
73	348	401	392	489	408	226	274	164	213	219	361	257	290	285	298
74	369	426	415	506	429	231	284	168	219	226	379	268	303	296	312
75	391	451	437	521	450	236	294	173	225	232	399	282	317	306	326
76	414	475	459	536	471	241	305	178	230	239	419	296	333	315	341
77	436	498	479	552	491	245	317	183	235	245	440	311	350	323	356
78	459	520	499	567	511	250	328	188	241	252	461	328	369	331	372
79	481	542	518	581	531	255	340	193	247	259	482	346	388	339	389
80	502	561	536	595	549	276	351	198	254	270	502	364	407	348	405
81	521	579	552	608	565	281	362	203	259	276	521	383	427	357	422
82	540	596	568	621	581	285	373	208	266	283	539	401	447	366	438
83	557	612	583	634	597	289	383	212	273	289	556	420	466	376	455
84	573	627	597	645	611	293	394	217	279	296	571	439	485	385	470
85	589	641	610	657	624	297	403	222	286	302	585	458	503	396	486
86	602	654	622	666	636	301	413	226	293	308	599	476	521	406	501
87	616	666	633	675	648	304	422	231	300	314	611	493	539	416	515
88	628	677	644	684	658	309	431	236	307	321	623	510	555	427	529
89	639	688	653	692	668	313	440	240	315	327	635	527	571	437	543
90	649	697	662	699	677	317	448	245	322	333	646	543	585	447	555
91	659	706	672	706	686	321	456	249	329	339	657	558	599	457	568
92	669	714	680	712	694	323	464	253	336	344	667	574	612	467	580
93	677	721	687	718	701	328	470	257	343	350	677	589	626	477	592
94	685	728	694	723	708	333	477	261	350	355	686	603	638	487	604
95	693	734	700	727	714	337	483	265	356	360	696	615	650	497	615
96	700	740	706	730	719	341	489	269	363	366	705	628	662	506	625
97	709	747	713	735	726	345	495	272	369	370	713	641	672	516	636
98	717	754	720	740	733	349	501	275	376	375	722	652	683	527	646
99	724	760	725	744	738	353	505	279	382	380	730	663	694	537	656
100	731	766	730	748	744	357	510	282	387	384	738	674	704	547	666
101	738	770	735	751	749	361	514	286	393	389	745	684	713	557	675
102	743	773	749	754	755	365	519	289	398	393	752	694	722	567	684
103	748	776	753	756	758	369	522	292	402	396	760	703	730	576	692
104	752	779	753	757	760	373	526	295	406	400	766	712	738	586	701
105	756	781	755	758	763	376	529	297	411	403	772	720	745	595	708
106	759	783	757	759	765	380	533	300	415	407	778	728	752	605	716
107	763	785	757	760	766	383	535	303	419	410	783	736	759	614	723
108	766	787	757	760	768	386	538	305	422	413	789	743	765	623	730
109	769	788	756	758	768	389	541	308	425	416	794	750	770	632	737
110	770	789	756	756	768	392	543	310	428	418	798	757	775	640	743
111	771	789	752	753	766	395	545	313	431	421	802	763	780	648	748
112	771	787	747	749	764	397	547	315	434	423	805	768	784	657	754
113	770	785	742	745	761	400	549	317	436	426	809	773	789	663	759
114	769	783	737	741	758	402	551	320	439	428	812	777	793	670	763
115	766	781	731	735	753	404	553	323	440	430	815	782	796	678	768
116	762	779	725	729	749	407	554	325	443	432	817	786	800	685	772
117	756	774	715	742	747	409	556	328	445	435	819	790	803	691	776
118	752	772	682	737	736	411	557	330	446	436	822	794	806	698	780
119	747	764	677	736	731	413	559	333	448	438	824	798	808	703	783
120	742	762	670	734	727	416	560	335	450	440	826	801	810	709	787
121	738	753	660	731	721	417	562	338	452	442	828	804	813	715	790
122	734	748	653	728	716	419	563	340	453	444	829	807	814	721	793
123	730	740	646	729	711	421	564	342	455	446	831	809	817	726	796
124	725	736	638	720	705	423	565	345	457	448	832	811	818	732	798
125	721	732	632	721	702	425	566	347	458	449	833	814	820	737	801
126	718	732	630	694	694	427	567	349	459	451	833	815	822	742	803
127	716	727	627	693	691	429	568	351	461	452	833	817	823	746	805
128	710	721	624	719	694	431	570	353	463	454	833	818	824	750	806
129	712	719	652	705	697	433	571	355	464	456	832	818	824	753	807
130	708	723	649	723	701	436	572	357	466	458	831	819	825	756	808
131	704	727	650	734	704	438	573	359	467	459	831	818	824	758	808
132	700	724	649	738	703	440	574	361	469	461	830	816	823	759	807
133	700	720	647	737	701	443	575	362	471	463	829	815	823	761	807
134	696	718	622	734	693	445	575	364	473	464	829	814	821	762	807
135	687	715	627	729	690	447	575	366	475	466	827	813	820	762	806
136	685	710	632	726	688	449	576	368	477	468	824	812	818	763	804
137	686	709	635	730	690	451	576	370	479	469	822	809	817	764	803
138	684	711	640	733	692	454	575	371	481	470	819	807	815	764	801
139	681	713	644	733	693	457	574	373	484	472	815	805	811	762	798
140	680	717	646	726	692	460	*	374	486	440	811	804	806	761	796
141	678	718	652	731	695	462	*	376	488	442	811	804	802	753	793
142	680	722	654	742	700	464	*	378	491	444	*	*	*	*	*

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

TABLE A4.4
TEMPERATURES RECORDED AT 1/4 DIAMETER FROM CENTRE OF CONCRETE
- LPC 81443
(355.6 mm OD x 9.5 mm THICK WALL CHS)

TIME MINS	A2	A4	A6	A8	A AVE	B2	B4	B6	B8	B AVE	C2	C4	C6	C8	C AVE
0	20	20	20	20	20	22	20	20	20	21	22	22	22	22	22
1	20	20	20	20	20	22	20	20	20	21	22	22	22	22	22
2	20	20	20	20	20	22	20	20	20	21	22	22	22	22	22
3	20	20	20	20	20	22	20	20	20	21	22	22	22	22	22
4	20	20	20	20	20	22	20	20	20	21	22	22	22	22	22
5	20	20	20	21	20	22	20	20	20	21	22	22	22	22	22
6	20	20	20	21	20	22	20	20	20	21	22	22	22	22	22
7	21	21	21	21	21	22	21	21	21	21	22	22	22	22	22
8	21	21	21	21	21	22	21	21	21	21	22	22	22	22	22
9	21	21	21	21	21	22	21	21	21	21	22	22	22	22	22
10	21	21	21	21	21	100	28	22	31	45	22	22	22	22	22
11	21	21	24	22	22	102	49	31	73	64	22	22	22	22	22
12	33	21	55	37	37	105	98	81	83	92	22	22	22	22	22
13	61	21	94	51	57	109	104	95	90	100	40	22	22	22	27
14	78	21	104	62	66	111	107	100	95	103	63	27	22	22	34
15	82	30	106	68	72	113	109	103	98	106	108	32	23	23	47
16	83	31	109	73	74	115	111	106	101	108	113	48	23	23	52
17	81	37	112	76	77	118	114	109	104	111	116	63	23	23	56
18	82	51	116	78	82	121	117	112	106	114	119	76	23	23	60
19	84	54	119	81	85	124	120	116	109	117	122	86	23	23	64
20	87	56	122	85	88	128	123	120	113	121	122	91	24	23	65
21	86	54	124	87	88	129	125	123	115	123	111	89	27	26	63
22	83	53	128	89	88	133	130	127	119	127	110	84	30	28	63
23	83	50	131	89	88	137	133	131	124	131	111	81	32	31	64
24	89	49	135	91	91	141	135	134	129	135	108	78	34	34	64
25	98	49	139	94	95	144	138	131	133	137	104	77	38	36	64
26	104	51	141	98	99	147	136	130	137	138	102	75	42	39	65
27	116	53	138	102	102	149	139	134	141	141	110	75	45	44	69
28	118	54	134	108	104	151	137	137	145	143	117	76	50	48	73
29	121	56	142	113	108	153	143	138	147	145	120	75	54	52	75
30	120	57	144	117	110	155	143	140	150	147	140	73	59	56	82
31	120	59	145	119	111	155	144	144	150	148	162	76	63	62	91
32	124	60	145	121	113	149	140	146	145	145	147	84	76	70	94
33	125	99	135	123	121	138	136	137	137	137	154	96	123	92	116
34	123	116	130	121	123	132	131	131	132	132	147	108	139	102	124
35	123	117	126	119	121	128	127	127	128	128	143	114	136	107	125
36	124	117	123	118	121	126	125	124	125	125	140	117	134	110	125
37	123	118	123	117	120	125	124	123	124	124	143	118	133	112	127
38	122	120	124	117	121	125	124	124	124	124	138	118	133	112	125
39	123	121	124	117	121	126	125	124	124	125	133	118	132	112	124
40	123	123	125	118	122	126	125	124	124	125	134	119	134	113	125
41	123	124	126	118	123	127	126	125	125	126	133	120	135	115	126
42	125	124	126	119	124	127	126	126	125	126	131	121	135	116	126
43	125	125	127	120	124	128	127	126	125	127	131	120	136	117	126
44	126	126	128	121	125	129	128	127	126	128	130	120	136	118	126
45	127	127	129	122	126	130	129	128	128	129	131	120	136	118	126
46	127	129	130	122	127	132	131	129	129	130	132	119	137	119	127
47	128	130	131	122	128	134	132	131	131	132	132	120	137	120	127
48	130	129	133	123	129	135	134	133	133	134	134	120	137	121	128
49	131	129	134	123	129	137	136	134	135	136	135	120	138	122	129
50	131	129	136	123	130	139	138	137	137	138	137	120	140	123	130
51	133	131	138	124	132	141	140	138	140	140	138	121	140	123	131
52	134	131	140	125	133	143	141	140	141	141	139	121	136	124	130
53	135	132	141	126	134	145	143	142	143	143	140	122	134	125	130
54	137	132	143	127	135	146	145	144	144	145	142	122	134	125	131
55	138	133	145	128	136	148	146	145	146	146	143	122	134	126	131
56	139	134	146	130	137	150	148	147	148	148	144	122	135	127	132
57	140	135	147	131	138	151	149	148	149	149	145	123	136	128	133
58	141	136	148	133	140	152	150	150	150	151	146	124	137	129	134
59	142	137	149	135	141	154	151	152	151	152	147	125	138	130	135
60	143	139	150	137	142	155	152	154	151	153	148	126	138	132	136
61	144	141	152	141	145	156	153	156	153	155	148	127	140	133	137
62	145	145	153	148	148	157	154	159	154	156	150	128	141	135	139
63	147	152	157	159	154	158	155	162	156	158	152	129	142	137	140
64	149	163	162	176	163	160	156	168	160	161	152	130	143	139	141
65	152	176	169	196	173	162	157	175	163	164	154	132	144	143	143
66	157	195	180	220	188	165	159	183	167	169	156	134	145	146	145
67	165	217	195	247	206	168	161	191	170	173	156	135	146	149	147
68	175	243	213	275	227	172	164	200	174	178	162	138	148	152	150
69	189	270	233	303	249	176	166	210	177	182	167	140	149	156	153
70	206	298	256	329	272	182	169	219	181	188	173	143	151	160	157

TABLE A4.4
(CONTINUED)

TIME MINS	A2	A4	A6	A8	A AVE	B2	B4	B6	B8	B AVE	C2	C4	C6	C8	C AVE
71	225	325	278	353	295	188	173	229	184	194	180	145	153	165	161
72	246	351	300	375	318	194	177	237	187	199	189	149	156	172	167
73	268	375	321	396	340	200	181	246	191	205	197	153	158	179	172
74	291	398	342	414	361	206	185	253	195	210	209	158	162	188	179
75	314	420	364	431	382	212	190	261	199	216	222	163	165	198	187
76	337	441	384	447	402	217	195	267	198	219	238	170	169	210	197
77	361	462	403	464	423	222	200	273	202	224	255	178	174	223	208
78	383	481	422	480	442	227	205	278	207	229	270	186	181	238	219
79	405	501	439	496	460	231	210	283	211	234	285	196	188	254	231
80	426	519	456	512	478	236	214	287	219	239	301	206	198	271	244
81	445	536	473	526	495	240	218	290	222	243	318	217	208	288	258
82	463	551	489	539	511	244	222	292	225	246	334	228	220	305	272
83	480	566	504	550	525	248	226	294	228	249	350	241	234	322	287
84	496	579	518	561	539	251	229	295	230	251	367	255	248	339	302
85	511	592	532	572	552	254	233	295	231	253	384	270	264	356	319
86	525	604	544	581	564	256	236	294	233	255	401	284	280	373	335
87	538	614	555	589	574	259	238	293	235	256	418	300	297	390	351
88	550	624	566	597	584	261	241	292	236	258	435	315	315	407	368
89	560	633	575	602	593	263	243	290	237	258	452	331	333	422	385
90	571	640	583	608	601	265	245	288	238	259	469	348	350	438	401
91	580	648	592	612	608	266	247	286	239	260	485	364	369	454	418
92	589	654	599	616	615	267	248	284	239	260	501	380	387	469	434
93	597	659	606	618	620	268	249	283	240	260	518	397	405	483	451
94	604	662	613	618	624	268	250	282	240	260	534	414	423	498	467
95	611	664	620	619	629	269	251	280	240	260	549	429	441	511	483
96	617	667	625	619	632	269	251	278	240	260	565	446	459	525	499
97	625	671	631	622	637	269	252	277	241	260	580	462	478	538	515
98	633	675	638	625	643	270	252	277	241	260	596	479	497	552	531
99	640	678	644	626	647	271	252	275	242	260	610	496	516	566	547
100	646	679	648	627	650	271	253	274	242	260	624	513	533	579	562
101	653	681	651	627	653	272	253	273	243	260	637	529	550	591	577
102	660	680	654	627	655	272	253	272	243	260	650	544	566	603	591
103	664	676	655	625	655	273	252	271	244	260	662	559	582	615	605
104	666	673	654	617	653	273	252	270	245	260	673	573	596	626	617
105	668	667	653	612	650	273	252	269	246	260	683	587	609	636	629
106	670	666	652	605	648	274	252	267	247	260	693	600	622	646	640
107	671	663	651	601	647	274	252	266	248	260	701	613	634	656	651
108	671	661	649	592	643	274	251	265	248	260	710	624	645	665	661
109	668	653	645	578	636	274	251	263	250	260	717	636	655	674	671
110	666	650	641	566	631	275	251	262	251	260	724	646	664	681	679
111	663	641	636	546	622	275	251	261	252	260	730	656	673	688	687
112	657	624	629	533	611	275	250	259	253	259	736	664	681	695	694
113	651	610	616	527	601	275	250	259	255	260	742	673	689	701	701
114	643	594	603	513	588	276	250	259	255	260	747	681	696	706	708
115	635	581	592	497	576	276	250	259	256	260	751	688	702	712	713
116	625	570	582	487	566	277	250	259	258	261	756	695	709	716	719
117	609	560	584	477	558	278	250	259	259	262	759	701	714	721	724
118	595	544	576	472	547	278	250	259	261	262	763	707	720	725	729
119	585	535	567	474	540	279	250	260	262	263	767	713	726	728	734
120	574	524	553	462	528	280	250	261	263	264	771	718	729	732	738
121	564	514	544	458	520	280	251	262	265	265	774	723	734	735	742
122	554	513	534	454	514	281	251	263	267	266	778	727	739	738	746
123	536	505	519	447	502	282	252	264	269	267	780	731	743	741	749
124	524	493	507	443	492	283	252	264	271	268	782	735	747	743	752
125	509	484	499	437	482	285	252	265	273	269	783	739	750	747	755
126	502	480	478	433	473	286	252	267	275	270	786	742	753	750	758
127	496	478	476	429	470	288	253	268	277	272	788	744	755	749	759
128	488	477	490	425	470	289	254	270	281	274	789	746	757	750	761
129	481	468	479	425	463	291	254	271	285	275	791	748	758	750	762
130	469	474	484	423	463	293	255	272	286	277	793	749	755	750	762
131	467	477	490	421	464	294	256	274	290	279	794	749	755	751	762
132	464	477	490	417	462	295	257	276	293	280	790	749	754	750	761
133	461	477	493	416	462	297	258	279	296	283	788	749	753	750	760
134	453	479	493	416	460	298	259	281	298	284	786	748	752	749	759
135	453	482	492	415	461	300	261	283	300	286	783	746	751	747	757
136	449	483	490	415	459	301	262	285	303	288	778	744	749	746	754
137	446	484	494	415	460	303	263	287	306	290	773	741	747	744	751
138	444	483	498	415	460	303	264	290	309	292	769	739	745	742	749
139	445	483	498	412	460	305	265	292	312	294	764	736	741	739	745
140	449	483	492	413	459	306	267	295	315	296	760	733	738	735	742
141	451	488	495	414	462	307	268	297	317	297	*	732	735	731	733
142	452	495	497	414	465	308	270	299	320	299	*	*	*	*	*

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

TABLE A4.5
TEMPERATURES RECORDED AT THE CENTRE OF THE CONCRETE - LPC 81443
(355.6 mm OD × 9.5 mm THICK WALL)

TIME MINS	A9	B9	C9
0	20	20	22
1	20	20	22
2	20	20	22
3	20	20	22
4	20	20	22
5	21	20	22
6	21	20	22
7	21	21	22
8	21	21	22
9	21	21	22
10	21	21	22
11	21	23	22
12	21	58	22
13	21	81	22
14	21	90	22
15	21	97	23
16	21	105	23
17	23	109	27
18	28	113	37
19	33	116	46
20	37	120	50
21	40	122	47
22	41	126	46
23	43	130	45
24	44	133	43
25	45	133	41
26	48	136	40
27	52	140	38
28	55	141	41
29	57	143	44
30	59	143	48
31	60	143	48
32	62	135	62
33	86	132	136
34	97	130	137
35	102	126	135
36	105	124	134
37	106	123	133
38	108	123	132
39	109	123	131
40	110	123	131
41	111	124	131
42	112	125	131
43	113	126	131
44	115	126	125
45	116	128	122
46	116	129	116
47	115	131	112
48	113	133	110
49	112	134	109
50	111	136	110
51	110	138	112
52	109	139	116
53	109	141	119
54	109	143	124
55	108	145	129
56	108	147	134
57	109	150	140
58	110	152	147
59	112	156	154
60	119	159	162
61	128	165	170
62	139	172	177
63	151	181	183
64	166	191	188
65	184	202	193
66	206	212	198
67	231	223	204
68	257	235	211
69	284	247	218
70	311	258	225

**TABLE A4.5
(CONTINUED)**

TIME MINS	A9	B9	C9
71	336	268	233
72	358	278	243
73	379	288	254
74	400	296	266
75	419	304	280
76	438	312	294
77	457	318	310
78	475	324	326
79	493	329	344
80	512	332	362
81	529	334	380
82	545	335	399
83	561	336	417
84	574	335	435
85	587	335	452
86	599	333	469
87	609	332	485
88	619	329	500
89	626	327	515
90	634	325	529
91	640	321	544
92	646	317	557
93	651	313	570
94	654	309	584
95	657	303	596
96	660	299	608
97	663	295	620
98	668	292	632
99	670	289	643
100	673	285	654
101	673	280	664
102	687	277	674
103	687	274	684
104	683	268	693
105	685	264	701
106	682	259	709
107	677	255	717
108	673	251	724
109	666	248	731
110	655	243	737
111	646	240	743
112	635	237	748
113	624	233	753
114	612	230	757
115	595	226	761
116	579	224	765
117	566	222	768
118	495	220	771
119	480	219	773
120	475	217	775
121	462	214	776
122	450	213	778
123	439	212	778
124	427	212	781
125	422	212	779
126	415	212	779
127	411	213	780
128	409	213	779
129	467	213	777
130	455	213	775
131	448	212	773
132	441	212	770
133	438	212	769
134	391	212	766
135	388	212	762
136	382	212	753
137	382	213	751
138	381	213	749
139	381	213	743
140	384	214	733
141	385	214	731
142	382	215	*

Note that an * indicates that the temperature measurement was known or thought to be incorrect.

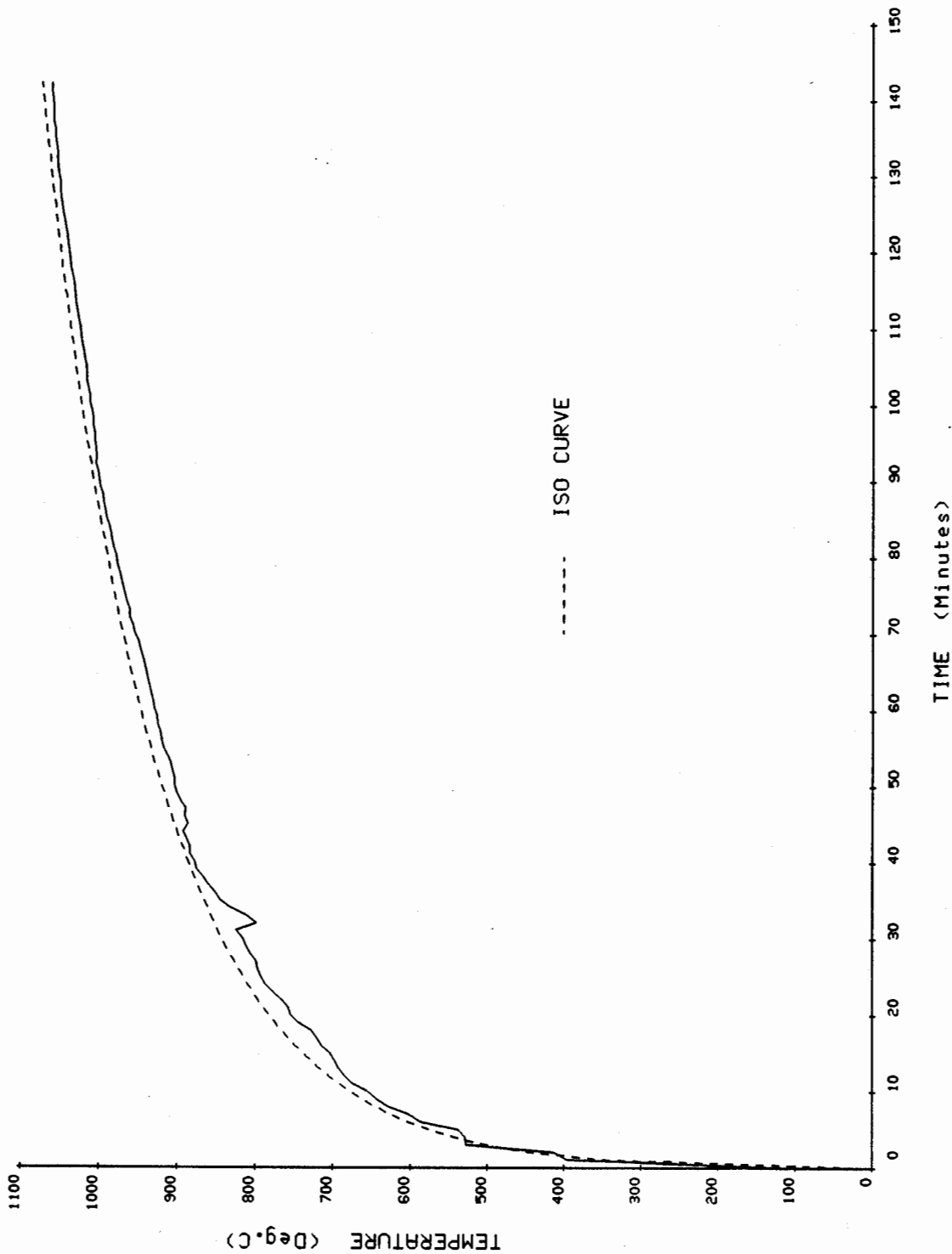


FIG. A4.1 COMPARISON OF AVERAGE FURNACE ATMOSPHERE TEMPERATURE
AND THE STANDARD TEMPERATURE/TIME CURVE
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)

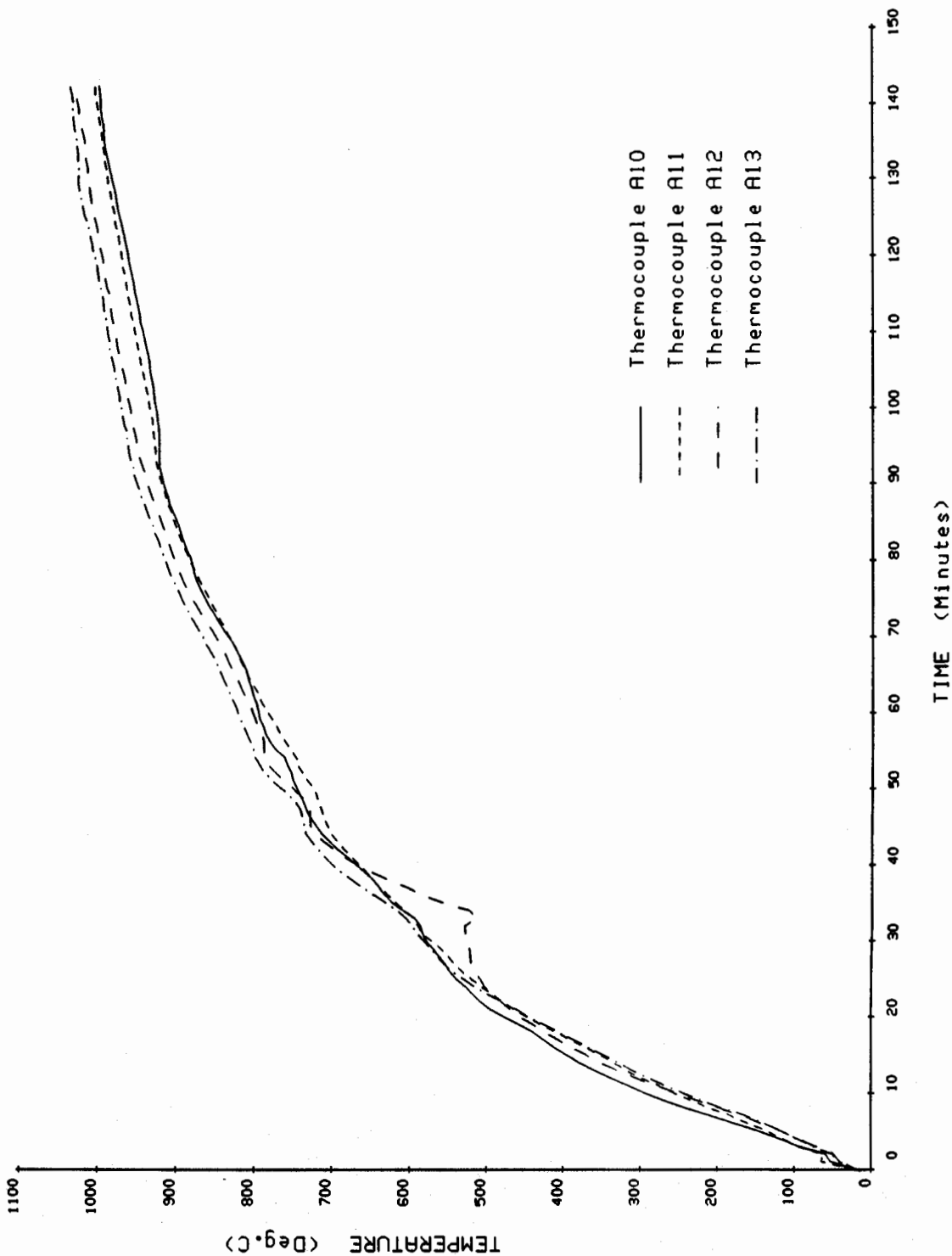


FIG. A.4.2 TEMPERATURES RECORDED IN THE STEELWORK AT THE A POSITION
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)

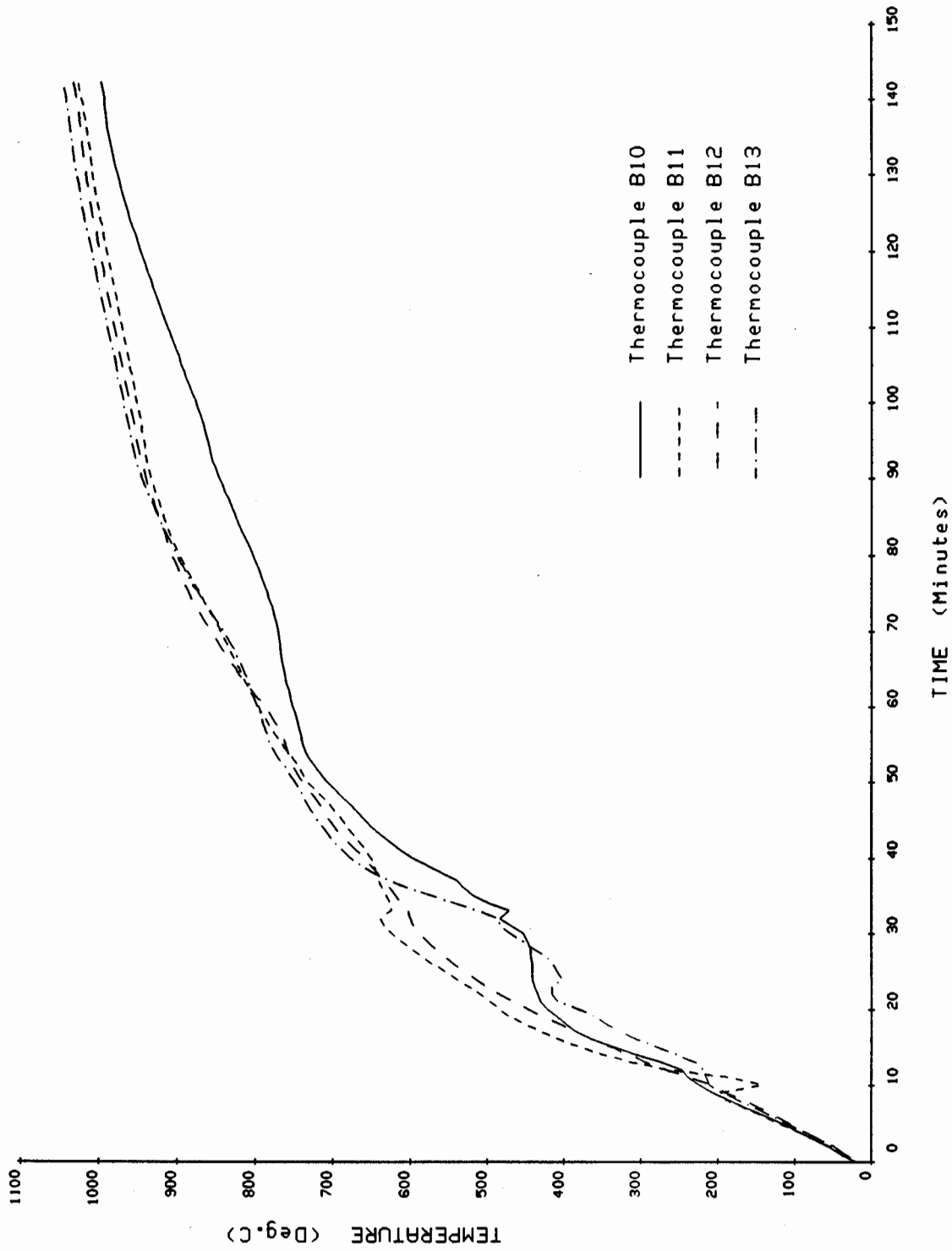


FIG. A.4.3 TEMPERATURES RECORDED IN THE STEELWORK AT THE B POSITION
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)

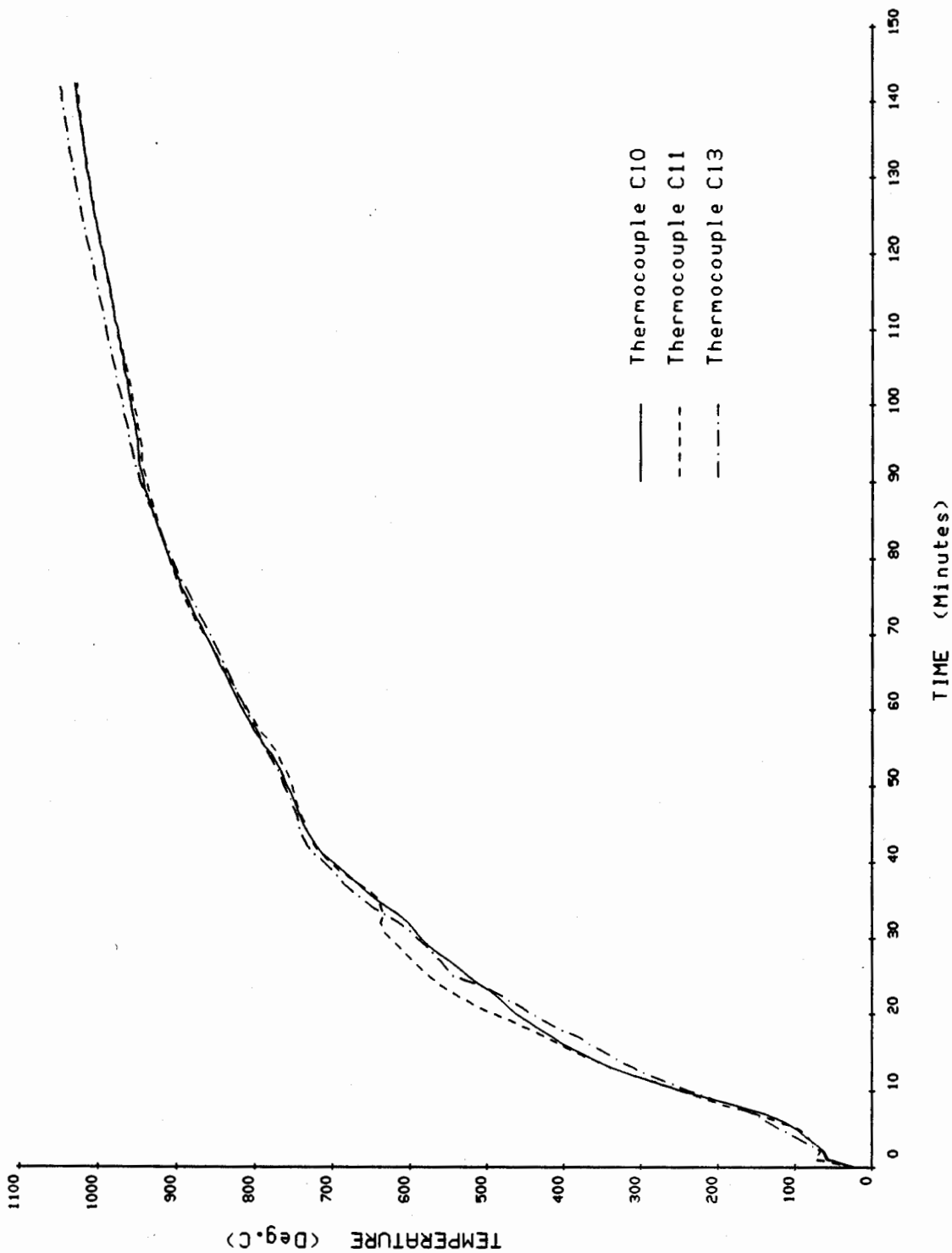


FIG. A4.4 TEMPERATURES RECORDED IN THE STEELWORK AT THE C POSITION
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)

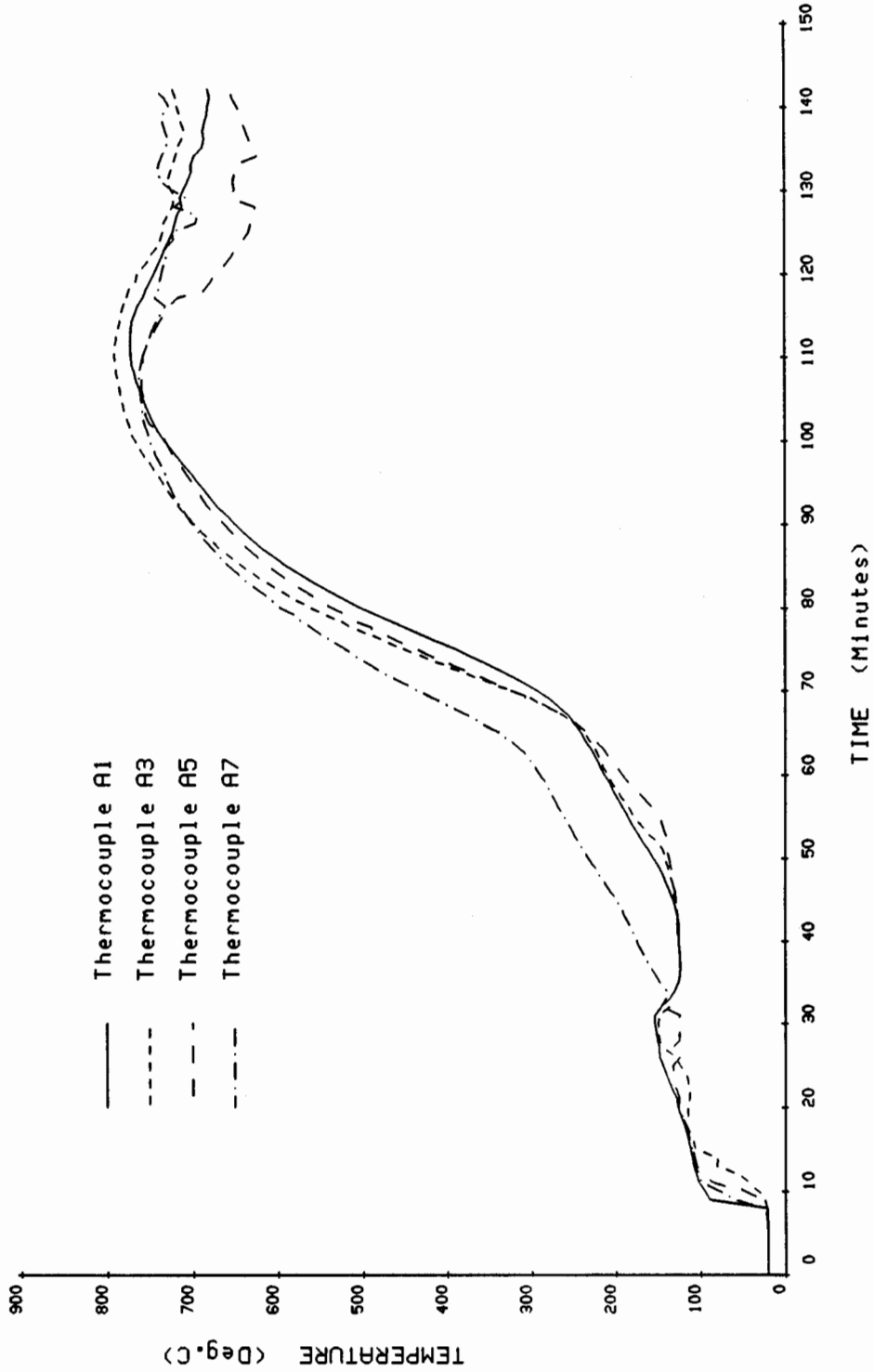


FIG. A4.5 TEMPERATURES RECORDED IN THE CONCRETE AT THE 3/8 DIAMETER POSITION - LEVEL A
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)

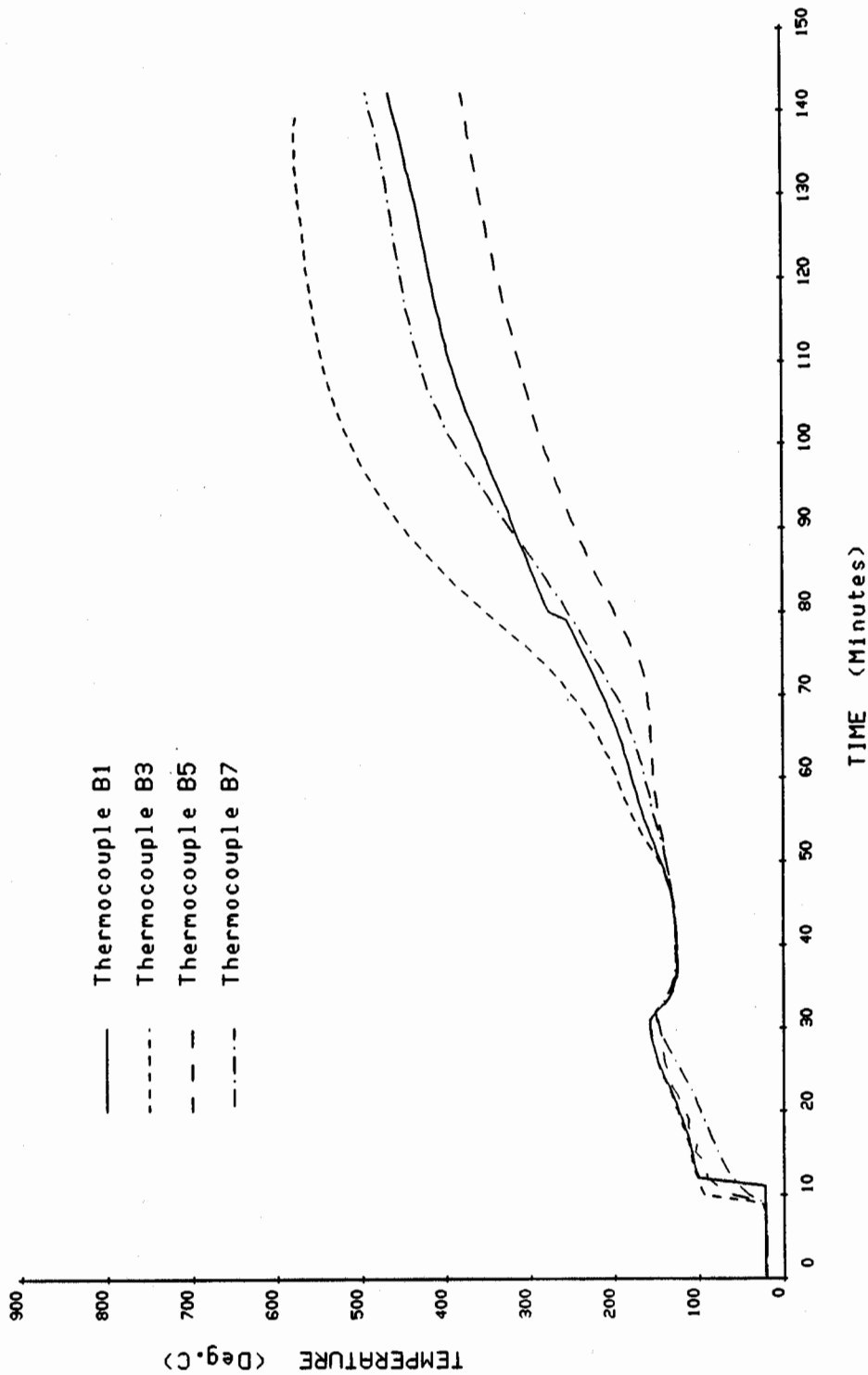
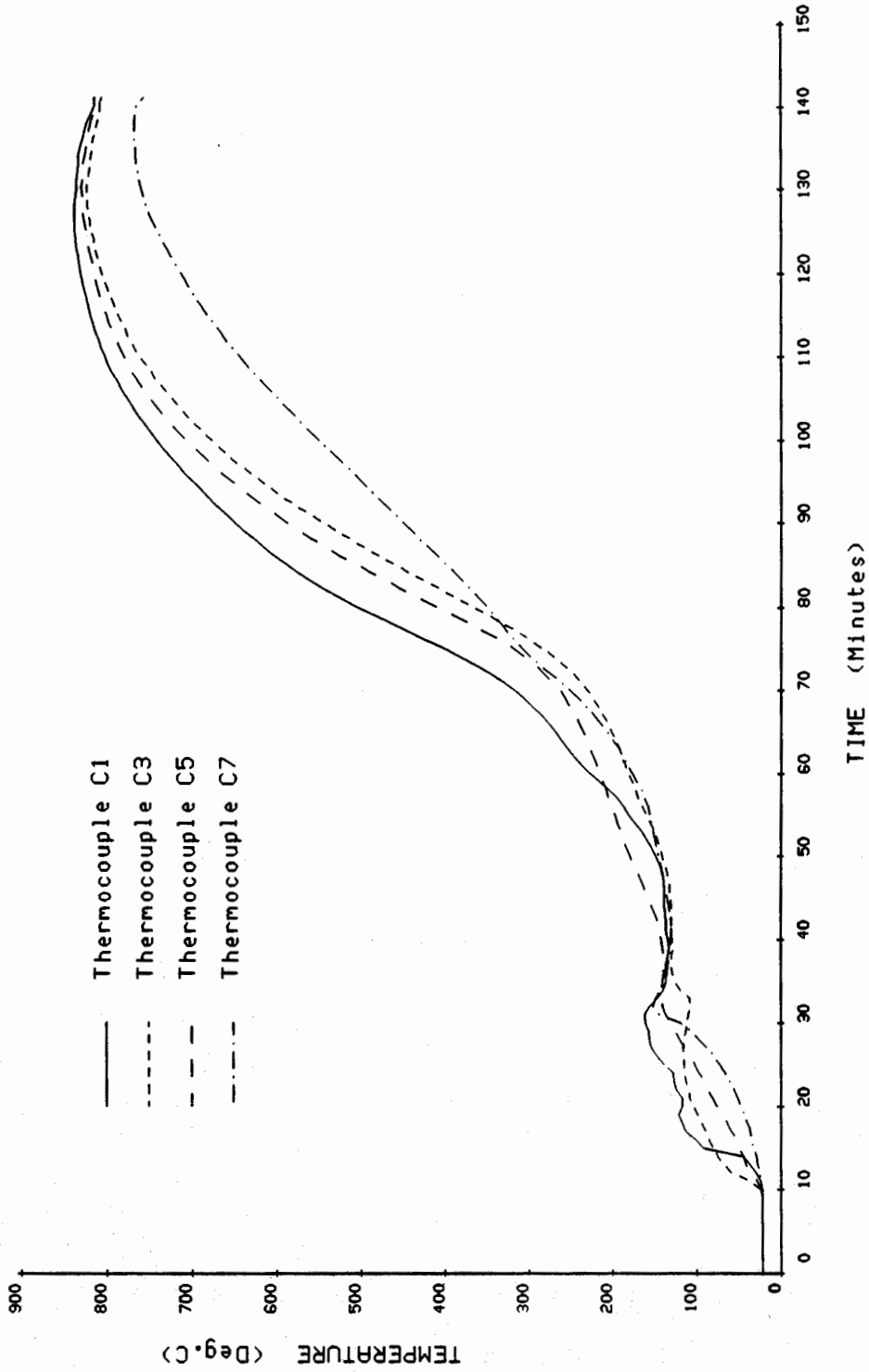


FIG. A4.6 TEMPERATURES RECORDED IN THE CONCRETE AT THE 3/8 DIAMETER POSITION - LEVEL B
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)



**FIG. A4.7 TEMPERATURES RECORDED IN THE CONCRETE AT THE 3/8 DIAMETER POSITION - LEVEL C
 TEST NO. LPC81443
 (355.6 mm O/D x 9.5 mm WALL CHS)**

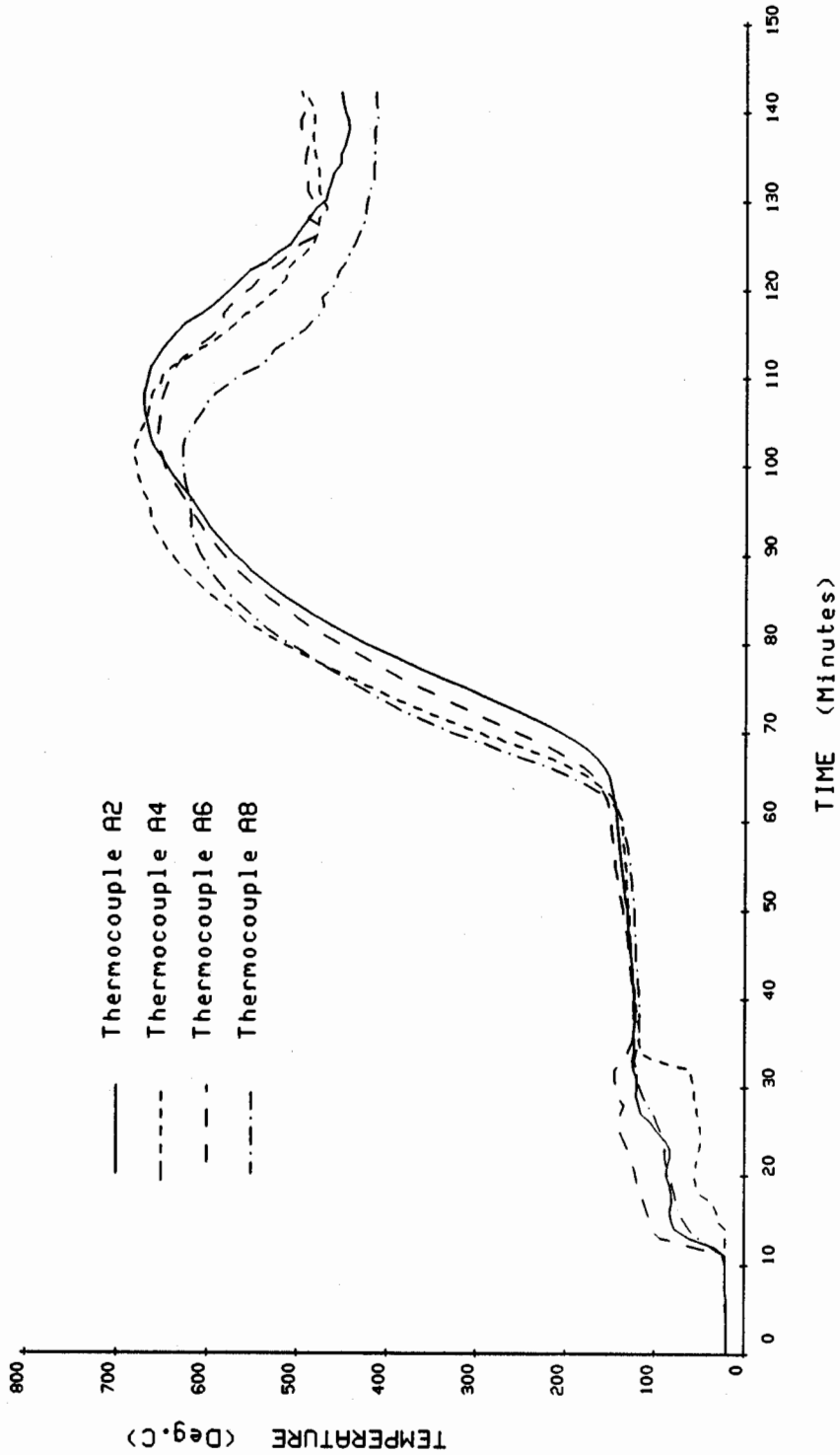


FIG. A4.8 TEMPERATURES RECORDED IN THE CONCRETE AT THE 1/4 DIAMETER POSITION - LEVEL A
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)

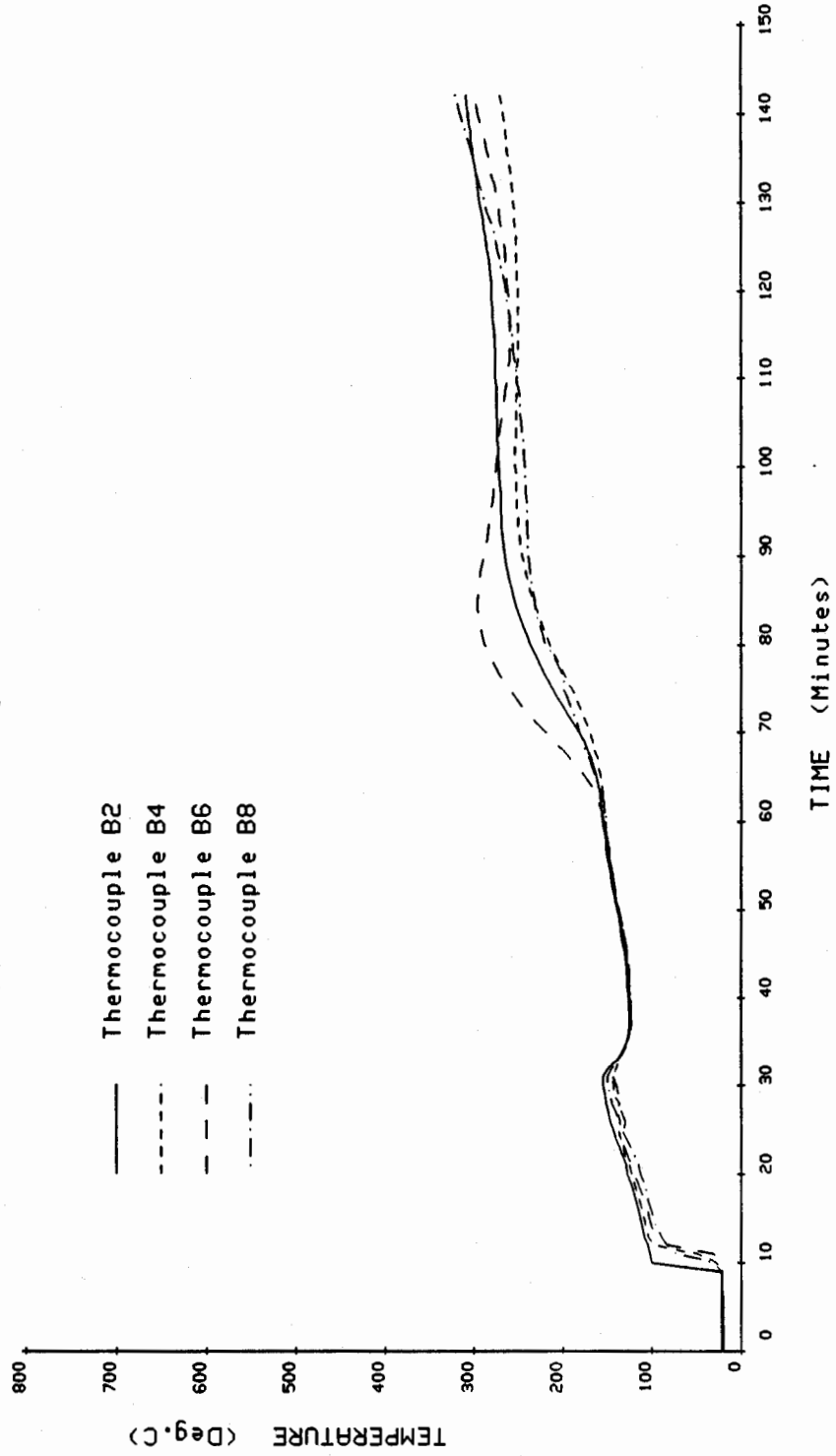


FIG. A4.9 TEMPERATURES RECORDED IN THE CONCRETE AT THE 1/4 DIAMETER POSITION - LEVEL B
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)

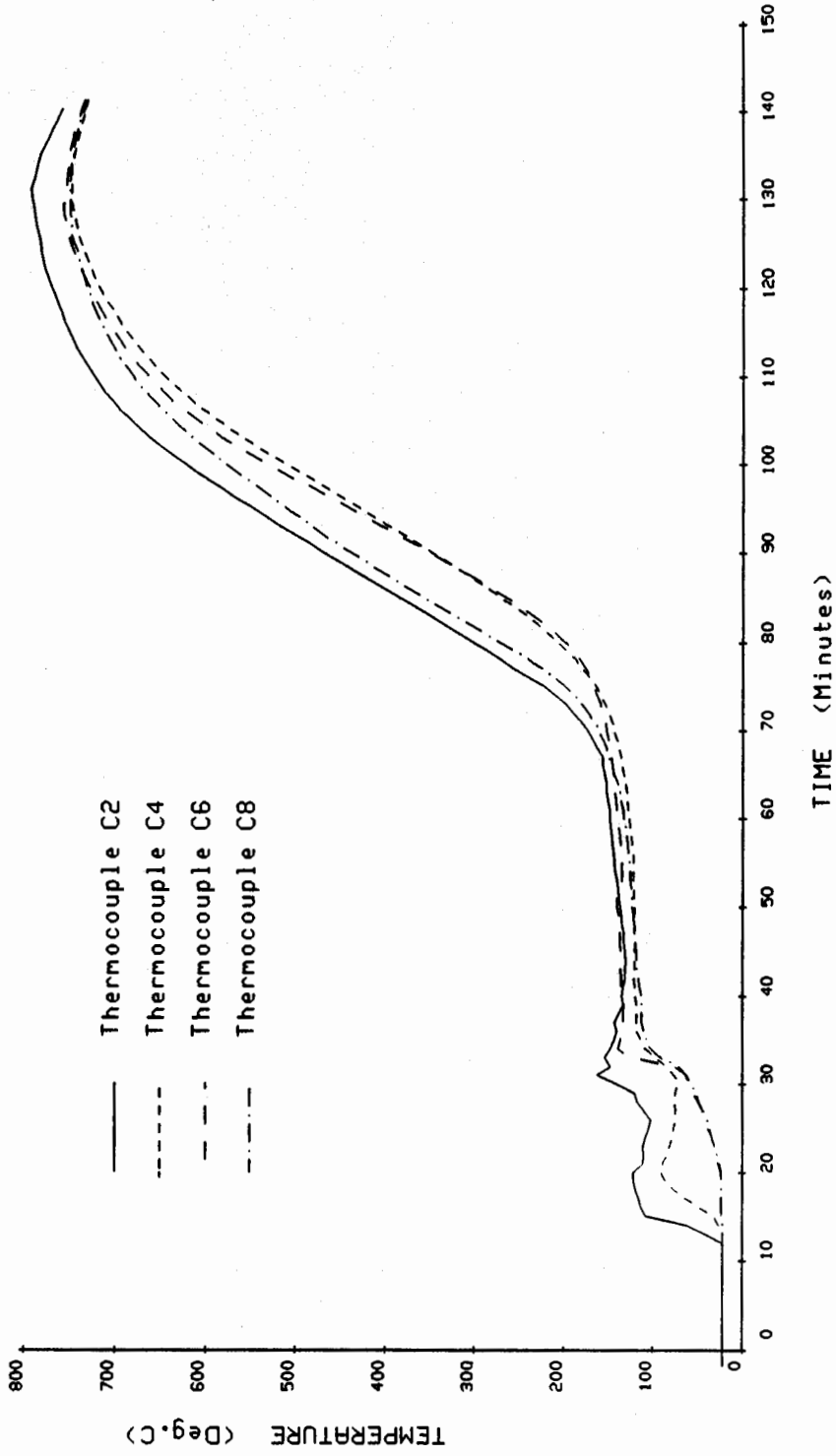


FIG. A4.10 TEMPERATURES RECORDED IN THE CONCRETE AT THE 1/4 DIAMETER POSITION - LEVEL C
TEST NO. LPC81443
(355.6 mm O/D x 9.5 mm WALL CHS)

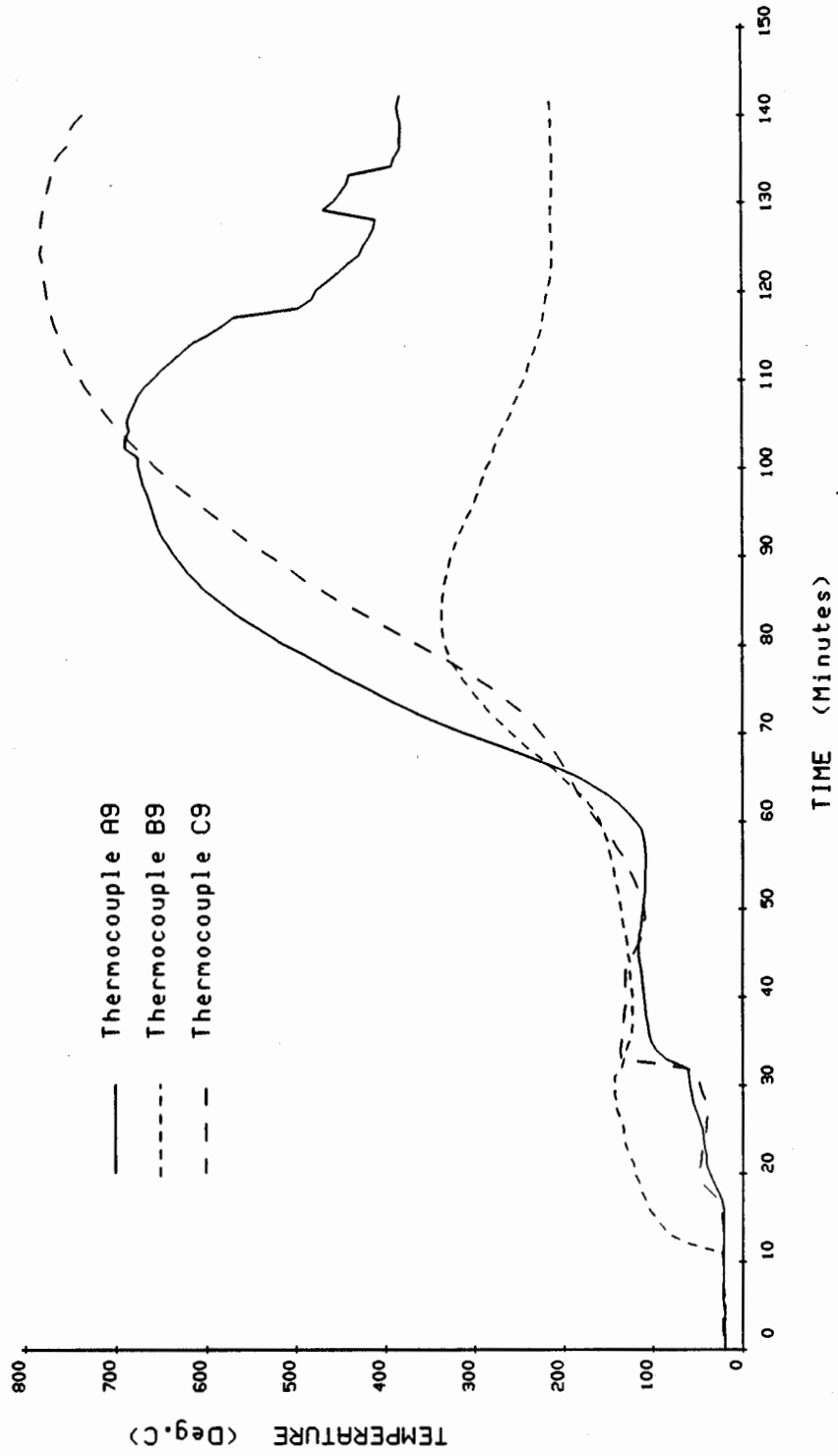
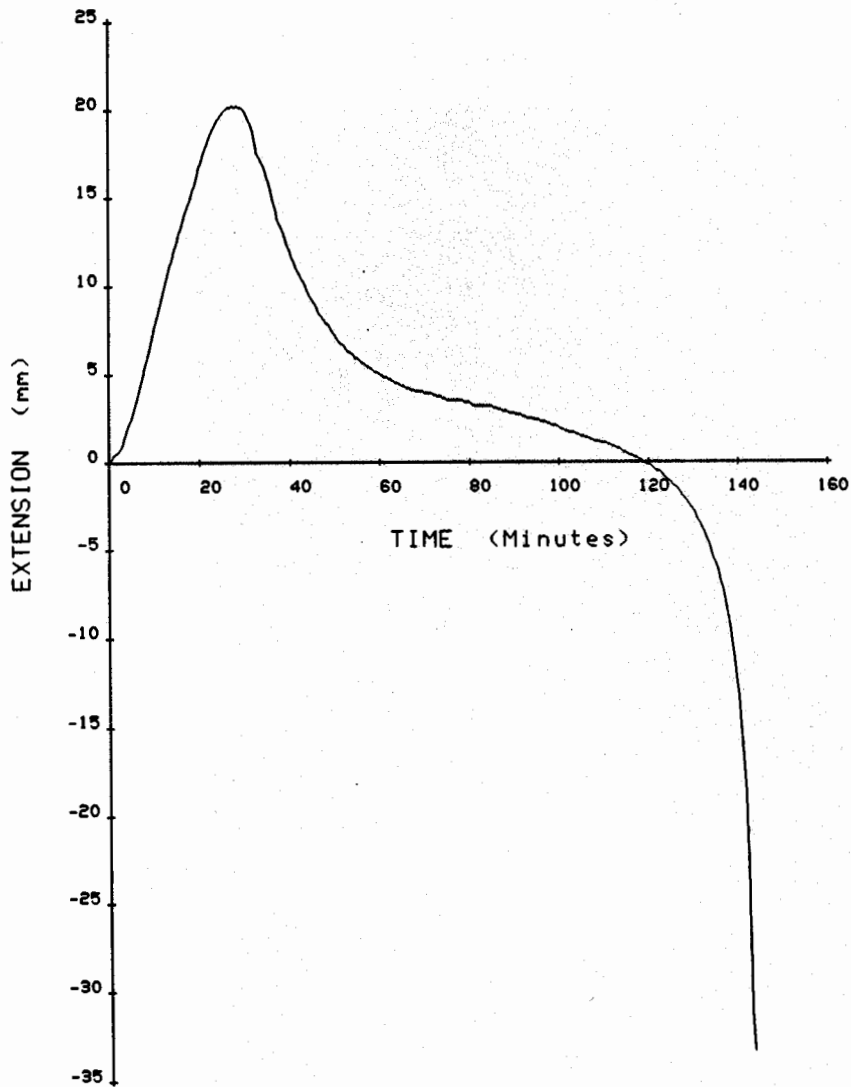
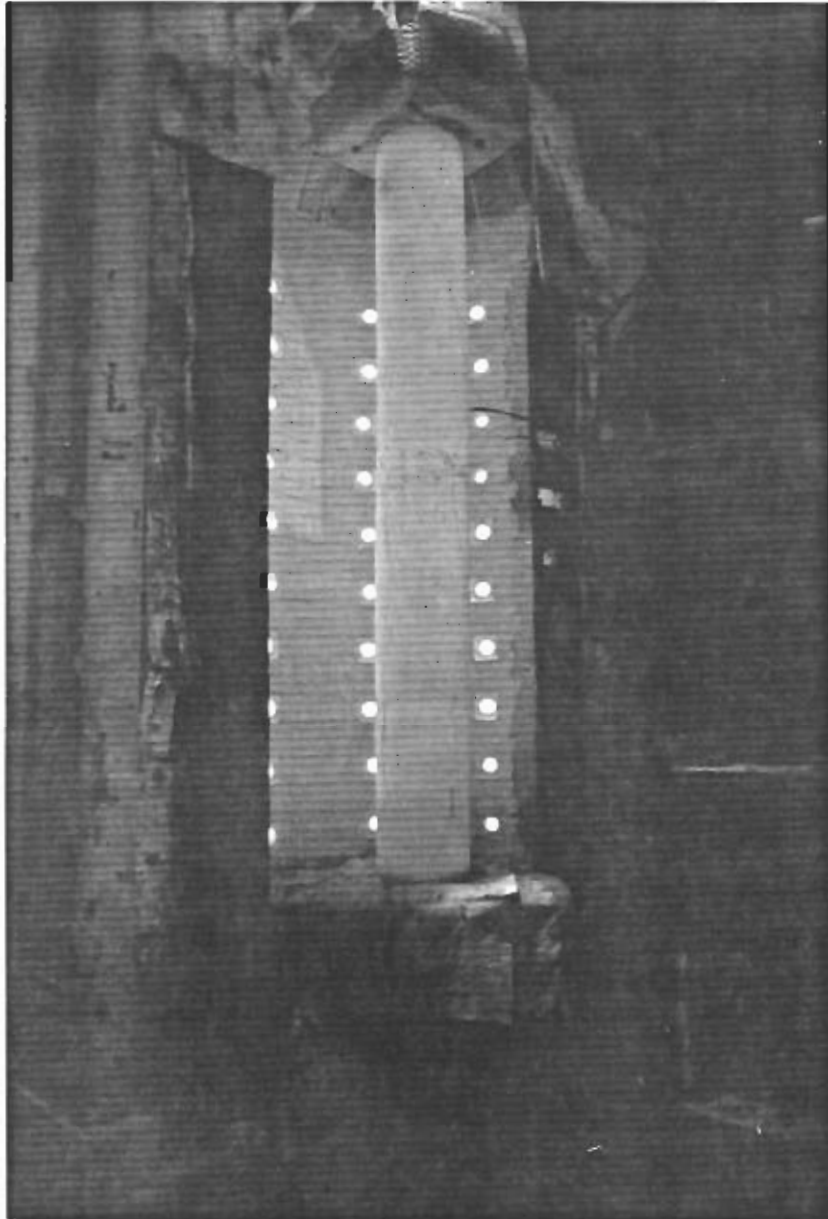


FIG. A4.11 TEMPERATURES RECORDED AT THE CONCRETE CORE POSITION
TEST NO. LPC 81443
(355.6 mm O/D x 9.5 mm WALL CHS)

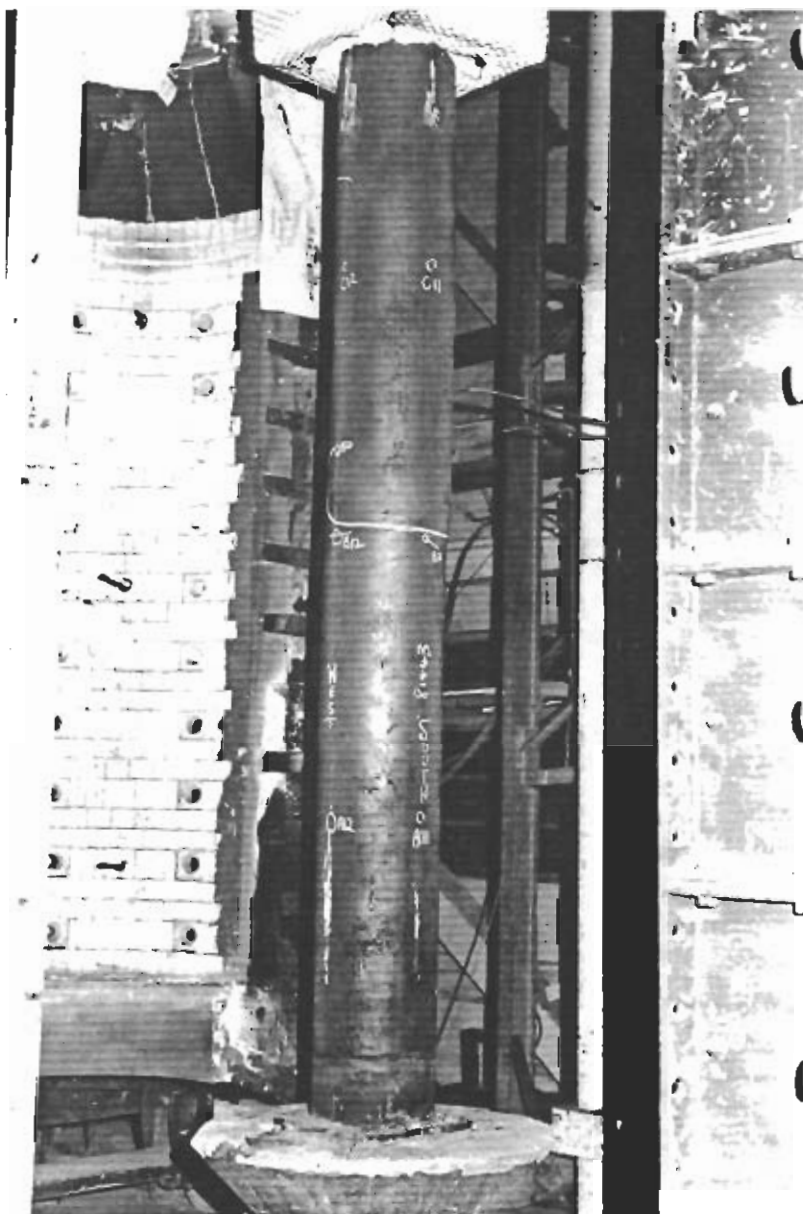


**FIG. A4.12 VERTICAL EXTENSION OF THE COLUMN RECORDED
DURING TEST NO. LPC 81443
(355.6 mm O/D × 9.5 mm WALL CHS)**



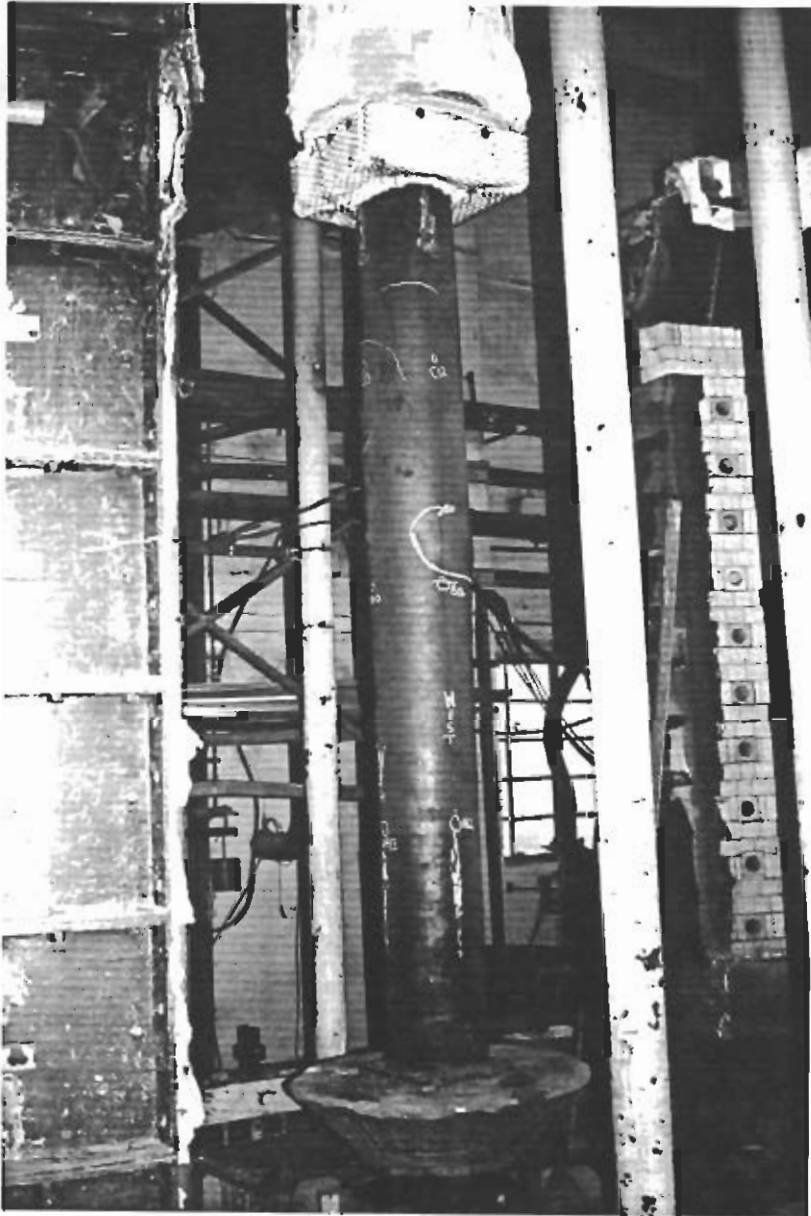
Test No. LPC 81443

FIG. A4.13 355.6 mm O/D CHS COLUMN
VIEW TAKEN AT CONCLUSION OF TEST



Test No. LPC 81443

FIG. A4.14 355.6 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE SOUTH WEST POSITION



Test No. LPC 81443

**FIG. A4.15 355.6 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE NORTH WEST POSITION**



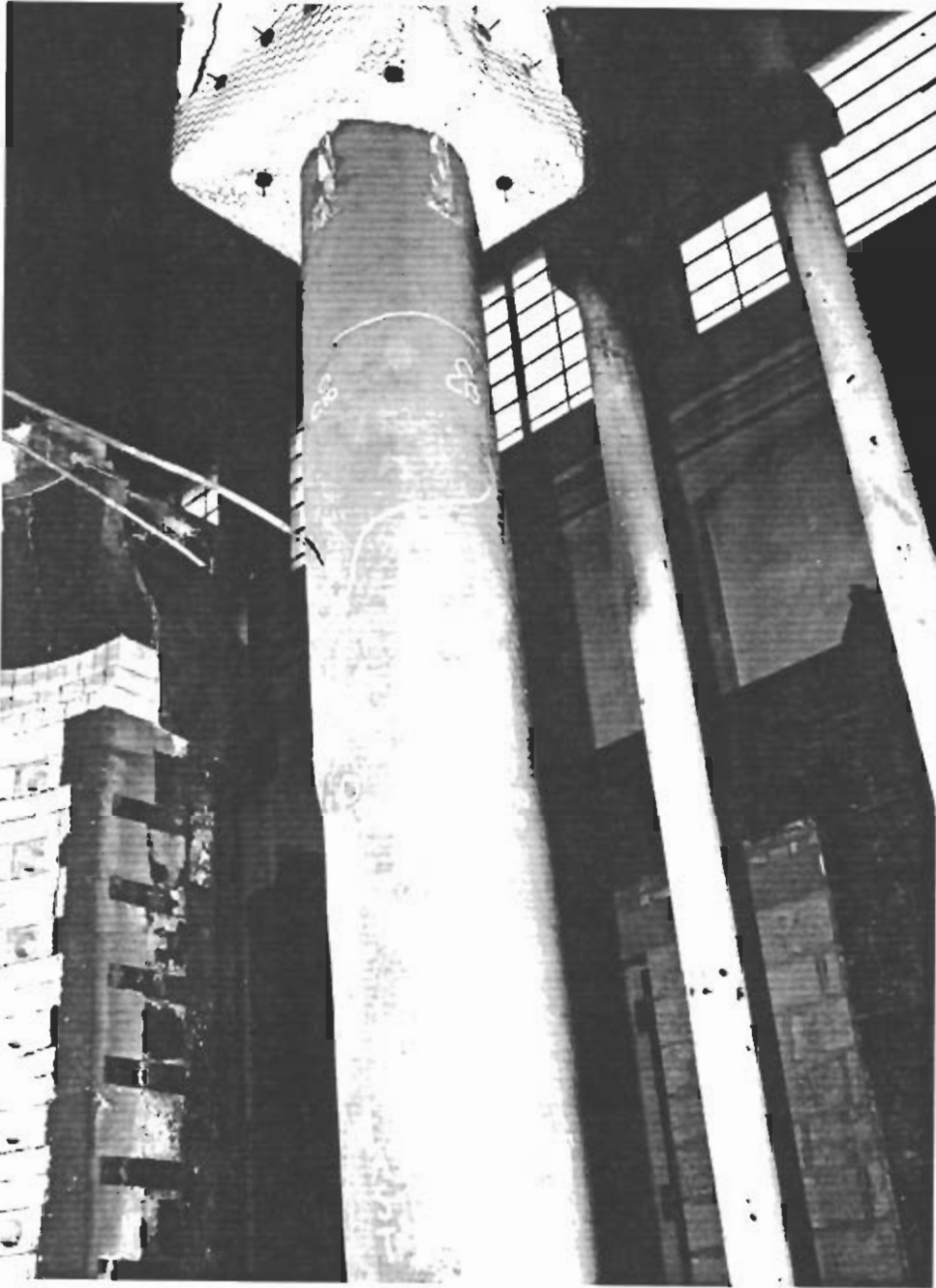
Test No. LPC 81443

**FIG. A4.16 355.6 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE SOUTH EAST POSITION**



Test No. LPC 81443

**FIG. A4.17 355.6 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE SOUTH WEST POSITION**



Test No. LPC 81443

**FIG. A4.18 355.6 mm O/D CHS COLUMN AFTER THE TEST
VIEWED FROM THE NORTH EAST POSITION**