D. Latham.

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The Evaluation of Two Fire Tested Concrete Filled Hollow Circular Sections

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SUMMARY

THE EVALUATION OF TWO FIRE TESTED CONCRETE FILLED HOLLOW CIRCULAR SECTIONS

I.M. Gaunt, D.J. Latham and J.A. Chapman

A series of three concrete filled hollow sections of varying diameters and wall thicknesses have been manufactured and fire tested in a standard fire test until failure occurred to validate the computer models currently available for this type of work. After fire testing, two of the three columns were sectioned to evaluate the remaining strength of the concrete core and steel casing, to record the fracture modes of the assemblies, to correlate the thermocouple data with any visual evidence of thermal effects on the concrete and to evaluate the potential for reinstatement of this type of structure after exposure to a fire.

The sectioning of the two smaller columns revealed discolouration of the concrete core due to thermal effects which were broadly compatible with the thermal data.

The smaller of the two columns had little compressive strength remaining in the concrete core such that it proved impossible to extract test pieces to make a meaningful measurement. The concrete core in the intermediate sized column had more residual compressive strength and full section core tests from the column indicated a reduction in strength to approximately 50% of the original value. Correlation with the results of core tests from the original concrete used to fabricate the columns, and which were heat treated to simulate the temperatures observed during the fire test, suggested that the degradation in properties was due, primarily, to temperature effects.

Tensile tests carried out on the as-received tubes (post fire) showed that only the medium diameter tube would meet the BS4360 Grade 43C specification (to which the tubes were ordered). The smaller of the two tubes would fail on the tensile strength requirement. Tensile tests on the steel casing after fire testing showed a substantial reduction in both yield and tensile strength such that neither tube would pass the above specification for tensile strength and several individual results would also fail on yield/0.2% proof stress.

As these tubes were tested to failure, reinstatement was unlikely. However the performance of such tubes in a less severe fire is unknown and therefore further work is required to determine the temperature regimes where reinstatement is possible.

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THE EVALUATION OF TWO FIRE TESTED CONCRETE FILLED HOLLOW CIRCULAR SECTIONS

1. INTRODUCTION

A project has been initiated to evaluate the fire resistance of concrete filled hollow sections. The first part of the project comprised the manufacture and fire testing of three, 3.4 m long, concrete filled, hollow, circular sections of varying wall thickness and diameter, was aimed at validating the computer models currently available for this work and has already been carried out and reported by Wainman(1).

After the initial fire test, the columns were to be sectioned and evaluated to provide the following information;

(a) to correlate the temperatures measured by thermocouples during the test with the visual appearance of the concrete

(b) to evaluate the remaining strength of the concrete core after the fire test

(c) to evaluate the remaining strength of the steel casing after the fire test

(d) to evaluate the potential for reinstating assemblies of this type following exposure to a fire.

The two smaller diameter columns of the three produced were evaluated initially and the work on these two columns is the subject of this report.

2. PROCEDURE

Three columns were manufactured and fire tested. The details of the columns are as follows:

QA Code	Fire Test No.	OD (mm)	Wall Thickness (mm)	ID (mm)
1M49D	81441	244.5	6.3	231.9
1M50D	81442	323.9	6.3	311.3
1M51D	81443	355.6	9.5	336.6

All three columns were 3.4 m long.

Details of the steel tubes used for the columns are presented in Appendix 1.

The two smaller diameter tubes, QA code number 1M49D and 1M50D were sectioned in this part of the programme. A portable, abrasive wheel, cut-off saw was first used to removed the steel casing and then to section the concrete core into manageable lengths, a method which should result in minimum damage to the various parts of the column and allow the extent of any degradation in properties to be evaluated precisely. The sectioning plan is shown in Fig. 1 for Column No. 1M49D and in Fig. 2 for Column No. 1M50D.

Longitudinal modified API tensile test pieces were taken from 4 positions at 90° intervals around the circumference of each of the tubes, and at 3 locations along the length of the tubes corresponding to the thermocouple positions, to evaluate the properties of the steel casing after the fire test. Two test pieces could not be removed from the centre of 1M49D because of the deformation of steel tube in this area during the fire test.

Metallography samples were also removed from each of the tubes to evaluate the microstructure in the as-received and as-tested conditions using limited, quantitative, metallographic techniques.

Full diameter concrete sections, approximately 250 mm long, were also taken from both columns where possible. Because of the degradation of the concrete, it was not possible to maintain the sections from Column No. 1M49D intact and therefore three full diameter sections were removed only from Column No. 1M50D as shown in Fig. 2. These sections were capped by placing a flat topped mould around the section and filling the mould with a concrete mix similar to that recommended in BS1881(2). The final dimensions of the test pieces, which were restricted by the testing machine clearances, are listed in Table 2. After allowing four weeks for the capping mix to harden sufficiently, the three sections were then compression tested, as recommended in BS1881(2), and the failure loads and failure modes noted.

It was apparent, during the sectioning, that the columns had suffered some degradation in strength. This could have been caused either by the temperatures attained, by the movement restriction/loads applied during the fire test or by a combination of both of these factors. To evaluate the effect of temperature alone on the concrete strength, the surplus concrete, which was retained in two compacted samples at the time of manufacture of the columns, was used to produced nine, 75 mm diameter core samples. These were heated to various temperatures, based on the temperatures measured by the thermocouples in the columns during the fire test, before preparation and compression testing to BS1881(2). The temperatures attained during the fire test by the columns are included in Appendix 2, for Column No. 1M49D, and in Appendix 3, for Column No. 1M50D, and the temperatures used for the treatment of the core samples are based on these values. In addition, two samples were heated for a prolonged period at 220°C to evaluate the effect of an extended exposure to elevated temperatures.

3. RESULTS

3.1 Original Concrete

The results of the cube tests on the original concrete, presented in Table 1 for the various storage times listed, show a substantial increase in the compressive strength up to the ninety day value. Both the twenty eight and ninety day strengths exceed the requested strength of 50 N/mm^2.

3.2 Core Samples from 1M50D

The results of the full section compression tests are presented in Table 2. Also included in Table 2 are the compressive strengths of the sections converted to cube strength values using the relationship given in BS1881 Part 120(2). Although this formula cannot give an accurate comparison between the two types of test, it does indicate a significant drop in strength of the fire tested core to approximately 25% of the original value.

3.3 Core Tests

The temperatures used for heat treatment of the small core samples, together with the compression test results, are presented in Table 3. The results of the compression tests show an increase in strength from the untreated samples to the short (30 min) treatment at 230°C and then a reduction in strength after treatment at 400°C. Although no test was carried out on the sample treated at 550°C, the appearance suggested that the test piece would have negligible strength. The sample given an extended treatment (16 h) at 220°C showed a reduction in strength from the untreated sample in contrast to the sample given the short treatment at a similar temperature. Also presented in Table 3, are the density measurements on the cores taken after heat treatment but before testing. A small, progressive reduction in density is apparent as the treatment temperature is raised from 220°C to 400°C followed by a larger reduction in density after treatment at 550°C. In contrast to the compression test results, the heat treatment duration has had no effect on the density of the core samples.

3.4 Tensile Tests

The tensile test results for the fire tested columns are presented in Table 4 for Column No. 1M49D and in Table 5 for Column No. 1M50D. The results from the in-house tests carried out before fire testing are also presented in Tables 4 and 5 for comparison and show that, although both tubes would meet the yield/0.2% proof stress requirement, only the larger tube (No. 1M50D) would pass the tensile strength requirement on the in-house tests and then only by a small margin. However, the values quoted for the tensile properties on the tube certificates, presented in Appendix 1, show that both tubes would meet the specification. Both tubes show a reduction in yield and tensile strength after the fire test such that neither tube would achieve the minimum levels specified in BS4360 Grade 43C specification for tensile strength and, although the average yield stress results would exceed the requirements, several individual results would fall below the specification.

3.5 Metallography

The results of the metallographic evaluation are presented in Table 6. The microstructure of both tubes, shown in Fig. 3 in the as-received condition, is predominantly ferrite grains with a small quantity of pearlite. Tube No. 1M49 D had the largest grain size and there was negligible difference in the percentage pearlite present in the microstructure.

The microstructure of the smaller of the two tubes, No. 1M49D, has not changed significantly as a result of the fire test, as shown in Fig. 4. The grain size of the as-received tube is identical to that of the fire tested tube and the difference in percentage pearlite, shown in Table 6, is very small and can probably be explained by the diffusion of carbon away from the pearlite colonies during the period that the steel was in the austenitic region and the scatter inherent in this type of work. However, the microstructure of the larger of the two tubes, No. 1M50D, has transformed to a ferrite/bainite structure with negligible quantities of pearlite present, as shown in Fig. 4. Quantitative metallography is difficult on this type of structure and therefore the grain size and second phase proportion have not been measured.

4. OBSERVATIONS DURING SECTIONING

4.1 General

The deformations noted during the fire test have been recorded in detail previously(1) and the areas where major deformation took place during the tests are noted in Figs. 1 and 2. Other observations on the condition of the steel casing and concrete core are noted below.

4.2 Column No. 1M49D

With the exception of the sections close to the fracture, most of the concrete core appeared to be intact when the steel casing was removed. The surface of the concrete was buff coloured and contained a large number of cracks, as shown in Fig. 5. When the concrete was sectioned, two areas of cracking were evident. The concentration of surface cracks extended approximately 20 mm below the surface, whilst a lower concentration of cracks extended to approximately 50 mm below the surface - the same depth as the discolouration. The discoloured layer, which is probably caused by the temperature of the concrete exceeding the 300°C value above which the silica hydrates begin to decompose, was readily identified, particularly when the surface of the concrete was wet. A remnant central zone of the concrete, approximately 130 mm diameter, appeared to be intact and unaffected by discolouration or cracking but, on handling, a large number of cracks began to open and it was apparent that, along much of the column, the centre of the concrete core had little strength. The concrete near the ends of the column appeared to have been less affected because there was no discolouration, negligible surface cracking was evident and the centre of the concrete core had a higher strength. The precise point at which the concrete began to shown signs of degradation was difficult to isolate but appeared to lay within section one at the top of the column and within section seven at the bottom of the column.

The appearance of the concrete in cross-section is shown in Fig. 6 and the discolouration and surface cracking is shown schematically in Fig. 7. An example of the cracking through the centre of the concrete core is shown in Fig. 8.

Close to the fracture, the concrete was extensively cracked and had very little strength when the steel casing was removed. Some of the concrete was little more than aggregate and cement and there was no remaining indication of the primary fracture mode or of the main shear plane in the area of the main failure.

4.3 Column No. 1M50D

In contrast to the smaller diameter column, the surface of the concrete in this column was grey in colour and smooth with no surface cracking, as shown in Fig. 9. When the concrete was sectioned, a similar cracking pattern to that observed in 1M49D was evident with extensive cracking up to 15 mm below the surface and a lower concentration of cracks extending approximately 40 mm below the surface, as shown in Fig. 10. A discoloured layer was present which also extended approximately 40 mm below the surface. The central core of the concrete, similar to that found in column 1M49D but approximately 230 mm in diameter, was present, was not discoloured and appeared to be free of cracking in the sections remote from the main fracture. A schematic illustration of the areas of cracking and discolouration in this column is presented in Fig. 11. However, when several lengths of the concrete core, which were taken from various parts of the column, were handled, a number of cracks appeared which reduced the strength of the sections to a very low level. As noted previously, three, 250 mm long sections for full section size compression tests were removed from the positions shown in Fig. 2 and retained intact until they were processed for further testing. It should be noted that the location from which the sections were taken was towards the upper end of the column, remote from the mid-point, and may not have been subjected to the thermal cycles presented in Appendix 2.

5. DISCUSSION

5.1 General

Comparison of the tensile test results, quoted on the release certificates for the two tubes in question, with the values measured in-house shows the latter to be substantially lower than the values quoted by the various producers. This is often found during material evaluation exercises and has been attributed to factors such as the material producers performing the tensile tests at strain rates which are near the upper limit of the allowed range and strain introduced into the test piece during manufacture. Because the tubes in this work were compared in the as-received condition and after the fire test, the comparisons will be drawn simply from the in-house tests.

5.2 Column No. 1M49D

Examination of the cross-section of the concrete core of this column shows a depth of discolouration of approximately 50 mm. If this is related to the position of the thermocouples, shown in Fig. 13, and to the thermocouple traces shown in Appendix 2, the measured temperatures appear to correlate well with the 300°C temperature contour marking the limit of the discolouration observed on the cross-section of the core.

It is apparent, from the comments made above in Sections 4.4 and 5.2, that both the concrete core and steel casing in this column had seen a marked reduction in properties. The compressive strength of the concrete, in particular, appeared to have been reduced to a very low level along most of the length of this column. The only regions which retained some strength were those near the extreme ends which were remote from the main thermal treatment cycle. Similar comments can also be applied to the steel casing, based on the in-house tests. Although only the yield/0.2% proof stress achieved the BS4360 Grade 43C specification (to which the tubes were ordered) before the fire tests, there were reductions of 34% in yield/0.2% proof stress and 13% in tensile stress after testing such that neither tube would achieve the specified levels.

5.3 Column No. 1M50D

The pattern of cracking and depth of discolouration in the concrete core in this column were similar to those noted in Column No. 1M49D. The only major difference was the depth of the various cracking modes and discolourations which were 5 mm to 10 mm less in this column than noted above. It is assumed that, because of the larger diameter of this column, and the subsequent greater thermal mass to heat through in what is, effectively, a short heat treatment cycle, the thermal gradient would be steeper and, unless time were allowed for equilibrium to be attained, the depth of penetration of the heat from the furnace would be less. A similar trend is also noted for the temperatures measured by thermocouple. However, when the assumed 300°C temperature contour from the discolouration is superimposed on the temperatures measured by thermocouple, there is a discrepancy with the thermocouples appearing to record temperatures lower than would be expected from evaluation of the appearance of the concrete. Whilst some variations were noted in the depth of the discolouration along the length of the concrete core during sectioning, and the depth of the discolouration was at approximately the same distance below the surface as the outer ring of thermocouples, these are insufficient to explain the difference and it must be assumed that some other factors such as the liberation of steam noted during the test(1) or the presence of cracks or voids near to the thermocouples, must have had an effect.

In common with the smaller diameter column described above, this column had also seen a substantial reduction in both the tensile properties of the casing and the compressive strength of the concrete core. In this case, it was possible to measure the compressive strength of the core and, although comparison of the core strength with the original cube strength measured on the original concrete mix supplied is not precise, the results suggest a substantial reduction in compressive strength after the fire test to approximately 25% of the original value. However, comparison with the cube strength calculated from the core strength measured in the core tests suggests a smaller reduction to approximately 40% of the original value. This discrepancy can only be explained by the inaccuracy inherent in converting from core strength to cube strength and by the fact that the concrete samples used for the core test pieces were manufactured after the columns, were not stored and cured under ideal conditions and would thus be expected to exhibit a lower standard cube strength. If the comparison is made only between core strengths, the compressive strength of the full size fire tested core has reduced to approximately 50% of the original value. It should also be noted that, because the measurements were made on an area of the column which had probably been subjected to a thermal cycle which was less damaging than that applied to the central region where the failure occurred, this reduction in compressive strength should be taken as a minimum and the compressive strength of the concrete core in the central area of the column may have been reduced further.

The tensile properties of the steel casing had also been reduced as a result of the fire test by a larger margin than for Column No. 1M49D. A reduction of 37% in the yield/0.2% proof stress and 18% in the tensile strength values were recorded with the result that, although this casing would meet the BS4360 Grade 43C specification before the fire test, the properties measured after the fire test would fail to meet the original specification.

5.4 General Comments

The core sample heat treated at 550°C showed that substantial cracking occurred after treatment at this temperature in both the matrix (due to decomposition of the silica hydrates above 300°c and to the dehydration of the portlandite above 500°C) and the aggregates and the cracking mode was similar to that observed in the subsurface layers in both the columns. In view of the temperatures measured by the outer layer of thermocouples in the concrete and those in the steel casing (Appendices 2 and 3), it appears likely that this subsurface layer was exposed to elevated temperatures in excess of 500°C. The difference in depth of this layer between the columns can probably be explained through the variations in thermal gradient caused by the different thermal masses.

The cracking in the layer between 15/20 mm and 40/50 mm below the surface cannot be explained in terms of the effects of temperatures above 500°C. Although the colouration of the concrete suggests that this area of the column has been subjected to temperatures above 300°C, there is no evidence to suggest that the temperatures exceeded 500°C. The only explanations for the existence of the cracking are the thermal stresses set up by the differing temperatures attained by the various parts of the columns and the large amount of steam which was generated during the fire test⁽¹⁾. There is no evidence to suggest that the loads imposed on the column during the test played any part in generating the cracks with the exception of those in the main failure area.

The various areas of the cross-section of Column No. 1M50D showing the differing degrees of cracking have been calculated and the residual compressive strength of the whole section, based on the results of the core tests, has been estimated. The results, shown in Table 7, suggest that, if the centre of the core is assumed to have been unaffected by the fire test, the compressive strength of the cross-section as a whole will be reduced to approximately 75% of the original value after making allowances for the reduction in strength of the various cracked areas. Since the compression tests suggest that the core has a compressive strength of only 50% or less, of the original figures, a discrepancy of approximately 25% is outstanding. The results, presented in Table 7, suggest that the centre of the core only contributes approximately 30% of the total compressive strength of the whole cross-section. A simple calculation, based on the cross-sectional area ratios, shows that it should contribute 55% of the total strength and the disparity must be assumed to be due to the tight cracks noted elsewhere in the structural evaluations. A similar analysis would not be relevant for Column No. 1M49D due to the lack of any measurements of the strength of the core. However, it should be noted that the cracked areas account for a substantially higher proportion of *the cross-sectional area of the column and, even if the central core was still intact and had not been* degraded, the overall strength of the core after fire testing would be proportionally less than that of the larger diameter column.

The substantial reduction in yield stress is not unexpected in the case of the tube produced by Hartlepool Pipe Mill and used for Column No. 1M49D. In order to attain the API Grade 5L properties (to which the tube was produced), and in addition to the BS4360 Grade 43C specification properties (which the tube met), the tube was made from a low carbon steel which was coiled at a low temperature. The tube was then cold formed, welded and a local weld line anneal applied to the area of the weld only. Consequently, the majority of the tube had a substantial amount of cold work present in the structure which increased the yield strength to a higher value than would be found in either a hot formed product or a product which had been fully softened after welding. During the fire test, the tube had attained temperatures of approximately 800°C and this reduced the yield stress by a substantial amount, and the tensile stress by a smaller amount, such that neither would pass the BS4360 Grade 43C specification. However the similar sections, produced by British Steel and intended primarily for the BS4360 grades, have a higher carbon level and would thus show a much lower reduction in tensile properties after a fire test.

It may also be assumed, in view of the similarities in composition and properties, that the tube used for Column No. 1M50D was produced, by Fuchs Rohrenwerk, in a similar manner to the British Steel product and therefore the same comments also apply to this assembly.

6. CONCLUSIONS

Two, concrete filled, steel columns fire tested to failure have been sectioned and the effects of the fire test on the concrete core and on the steel casing have been evaluated as far as possible. The following conclusions are drawn:

The concrete core in the 244.5 mm OD column had degraded so badly as to make it impossible to measure the compressive strength remaining after the fire test. The concrete core in the 323.9 mm OD column was less fractured and the full section core tests carried out indicate a substantial reduction in the compressive strength of the core to less than 50% of the compressive strength of the original concrete. The majority of the reduction in compressive strength can be explained by degradation of the properties through thermal effects.

There was little remaining evidence in either of the two columns examined to indicate the primary fracture plane/failure mode which occurred in the concrete core during the fire tests.

The steel casing has suffered a 13% to 18% reduction in the tensile and a 34% to 38% reduction in the yield strength. Consequently, the tensile properties would not meet the BS4360 Grade 43C specification, to which the tubes were ordered, after fire testing.

In view of the marked reduction in properties of both the concrete core and steel casting during the fire test, the potential for reinstatement of those structures, after such a fire, where failure occurred, must be low.

7. FURTHER WORK

The 355.6 mm OD column has not been sectioned and evaluated to date. Because the properties of the two smaller diameter columns had degraded to such a large degree during the fire test, there is little to be gained by evaluating the third column. Further tests on concrete filled columns fire tested under less severe conditions are recommended in order to determine the temperature regime where reinstatement is possible.

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C.D.

TABLE 1
RESULTS OF CUBE TESTS ON AS-SUPPLIED CONCRETE

Subcode Number	Curing Time (Days)	Height (mm)	Width (mm)	Depth (mm)	Density (kg/m^3)	Maximum Load (kN)	Standard Cube Strength (N/mm^2)
(1)	7	151	150	150	2350	1035	46.0
(2)	7	152	150	150	2350	1029	45.5
(3)	28	150	150	150	2355	1247	55.5
(4)	28	150	150	150	2355	1294	57.5
(5)	90	150	150	150	2360	1375	61.0
(6)	90	150	151	150	2360	1392	62.0

TABLE 2
RESULTS OF COMPRESSION TESTS ON 323.6 mm COLUMN SECTIONS, QA CODE NO. 1M50D

Test QA Code	Diameter (mm)	Height (mm)	Maximum Load (kN)	Core Strength (N/mm^2)	X (1)	D (2)	In-Situ Cube Strength (3) (N/mm^2)
2J280X	311	255	1420	18.7	0.82	2.3	15.8
2J281X	311	270	1465	19.3	0.87	2.3	16.7
2J282X	311	290	1230	16.2	0.93	2.3	14.5

(1) 'X' is the LENGTH/DIAMETER ratio.
(2) 'D' is a constant dependant upon the orientation of the cores.
(3) Above results are calculated from BS1881, Part 120, 1983 using the formula:

$$\text{In}-\text{Situ Cube Strength} = \frac{D}{(1.5 + 1/X)} * \text{Core Strength (N/mm}^2)$$

TABLE 3
RESULTS OF COMPRESSION TESTS ON HEAT TREATED CORE SAMPLES

Test QA Code	Diameter (mm)	Length (mm)	Density (kg/m^3)	Heat Treatment Temperature (1)	Maximum Load, (kN)	X (2)	D (3)	Core Strength (4), (N/mm^2)	In-Situ Cube Strength (3) (N/mm^2)
2J246X1	76.16	150.99	2189	230	198	1.98	2.3	43.5	49.9
2J246X2	76.02	152.39	2176	230	174	2.00	2.3	38.3	44.1
2J246X3	76.29	146.25	2140	400	124	1.92	2.3	27.1	30.9
2J246X4	76.20	149.64	2165	400	112	1.96	2.3	24.6	28.1
2J246X5	76.00	150.00	2014	550	-	1.97	2.3	(5)	(5)
2J246X6	76.22	145.25	2274	NONE	151	1.91	2.3	33.1	37.6
2J247X1	75.33	150.79	2179	(1) 220	136	2.00	2.3	30.5	35.1
2J247X2	74.96	147.39	2177	(1) 220	147	1.97	2.3	33.3	38.1
2J247X3	74.83	140.07	2246	NONE	157	1.87	2.3	35.7	40.4

(1) All treatments carried out for 1 h at temperature except 2J247X1/2. These two test cores soaked for 16 h at 220°C.
(2) 'X' is the LENGTH/DIAMETER ratio.
(3) 'D' is a constant dependent upon the orientation of the cores.
(4) Above results are calculated from BS1881, Part 120, 1983, using the formula:

$$\text{In}-\text{Situ Cube Strength} = \frac{D}{(1.5 + 1/X)} * \text{Core Strength}$$

(5) No core test was carried out on this sample due to the obvious degradation of the test piece during the heat treatment.

TABLE 4
TENSILE TEST RESULTS FOR COLUMN NO. 1M49D

Position in Column	Subcode Number	0.2% Proof Stress (MPa)	Lower Yield Stress (MPa)	Upper Yield Stress (MPa)	Tensile Stress (MPa)	Elongation (%)
BS4360-43C Specification	Minimum	275	275	-	430	22
	maximum	-	-	-	580	-
As-Received Properties		-	355	-	430	41
Level C	1	-	274	283	382	45
	2	238	-	-	379	46
	3	-	290	294	390	45
	4	263	-	-	382	46
Average		252	282	289	383	46
Level B	1	-	261	-	380	45
	2	246	-	-	375	45
Average		246	261	-	378	45
Level A	1	-	268	-	377	45
	2	-	261	266	378	46
	3	-	284	289	382	45
	4	-	264	269	376	45
Average		-	269	275	378	45
O/A Average		249	272	280	380	45

TABLE 5
TENSILE TEST RESULTS FOR COLUMN NO. 1M50D

Position in Column	Subcode Number	0.2% Proof Stress (MPa)	Lower Yield Stress (MPa)	Upper Yield Stress (MPa)	Tensile Stress (MPa)	Elongation (%)
BS4360-43C Specification	Minimum	275	275	-	430	22
	Maximum	-	-	-	580	-
As-Received Properties		-	354	-	422	42
Level C	1	269	-	-	365	45
	2	236	-	-	359	47
	3	-	255	259	357	47
	4	-	253	259	357	47
Average		253	254	259	360	47
Level B	1	-	264	-	364	43
	2	-	259	-	357	47
	3	-	259	-	354	47
	4	244	-	-	363	47
Average		244	261	-	360	46
Level A	1	-	277	315	357	49
	2	-	260	-	354	49
	3	-	268	277	350	48
	4	263	-	-	353	49
Average		263	268	296	354	49
O/A Average		253	262	278	358	47

TABLE 6
QUANTITATIVE METALLOGRAPHY RESULTS

Column QA Code	Pearlite (%)	Grain Size (μm)
1M49D (As-received)	4.6 1.8 5.2	11.2 12.0 12.1
Average	3.8	11.8
1M50D (As-received)	3.3 3.8 2.3	7.4 8.5 8.4
Average	3.1	8.1
1M49D (Fire Tested)	1.6 2.6 1.6	11.6 12.0 11.5
Average	2.0	11.7

TABLE 7
PREDICTION OF CONCRETE CORE STRENGTH FROM CORE TEST RESULTS

Core Section	Proportion of Cross-Sectional Area (%)	Proportion of Strength from Core Test (%)	Strength Factored for Area and Core Strength (%) (*1)	Actual Strength Levels (%)
Central Core Area	55	100	55	30 (*2)
Cracked Area 15 mm - 40 mm Below Surface	25	78	20	20
Cracked Area up to 15 mm Below Surface	20	0	0	0
Totals	100	100	75	50

*1 Calculated from - Proportion of Cross-Sectional Area X Proportion of Strength from Core Test.

*2 Central Core Area Strength calculated from;
Actual Measured Strength (50%) - (Sum of Cracked Area Strengths (20%)).

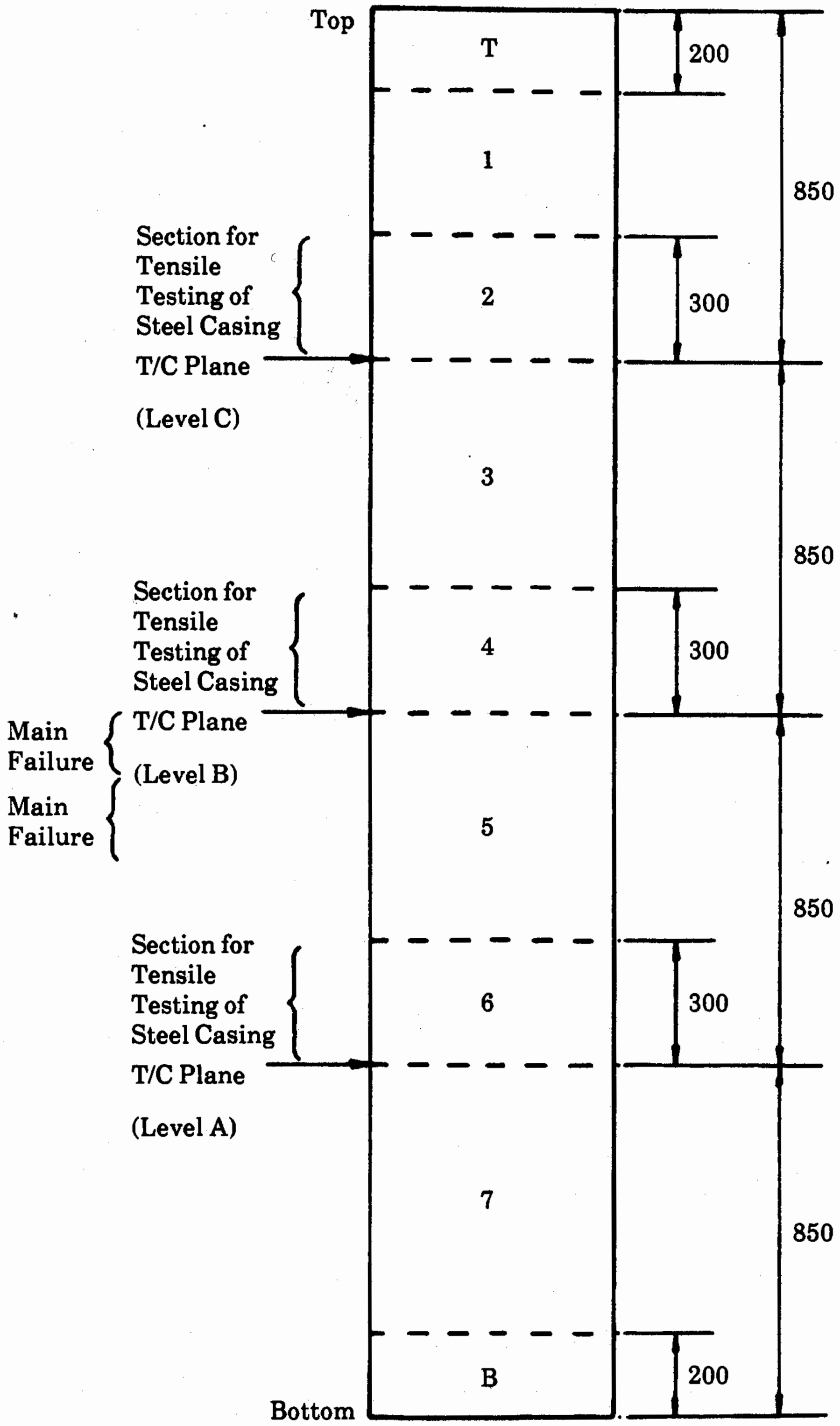


FIG. 1 COLUMN NO. 1M49D, SECTIONING PLAN (ALL DIMENSIONS IN mm) (R4/254)

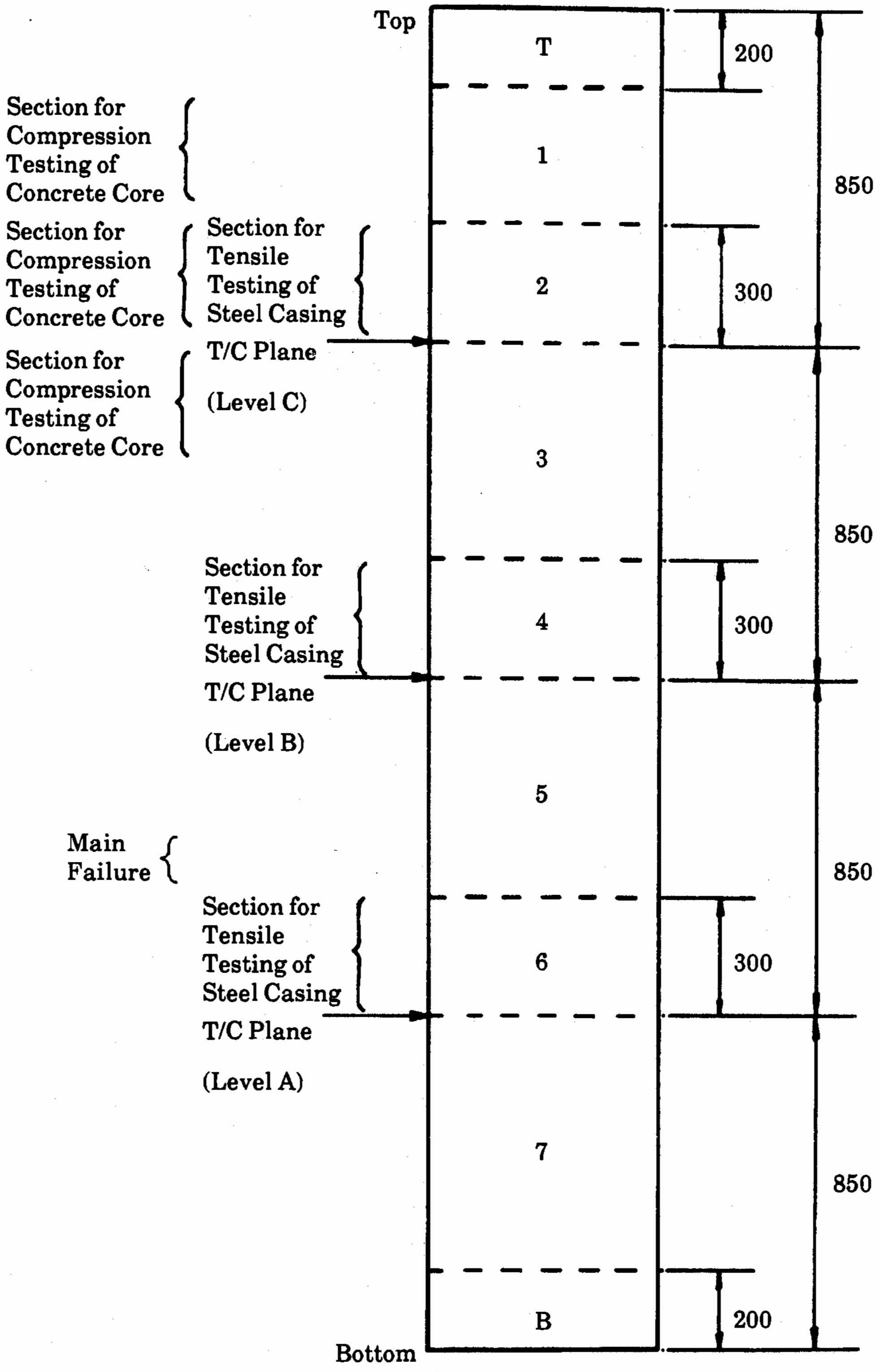
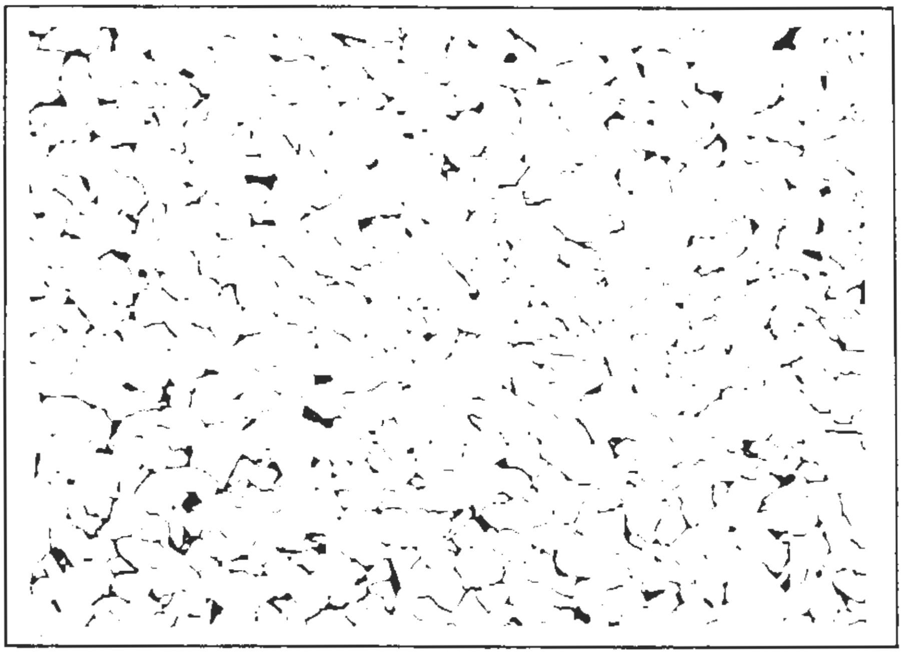
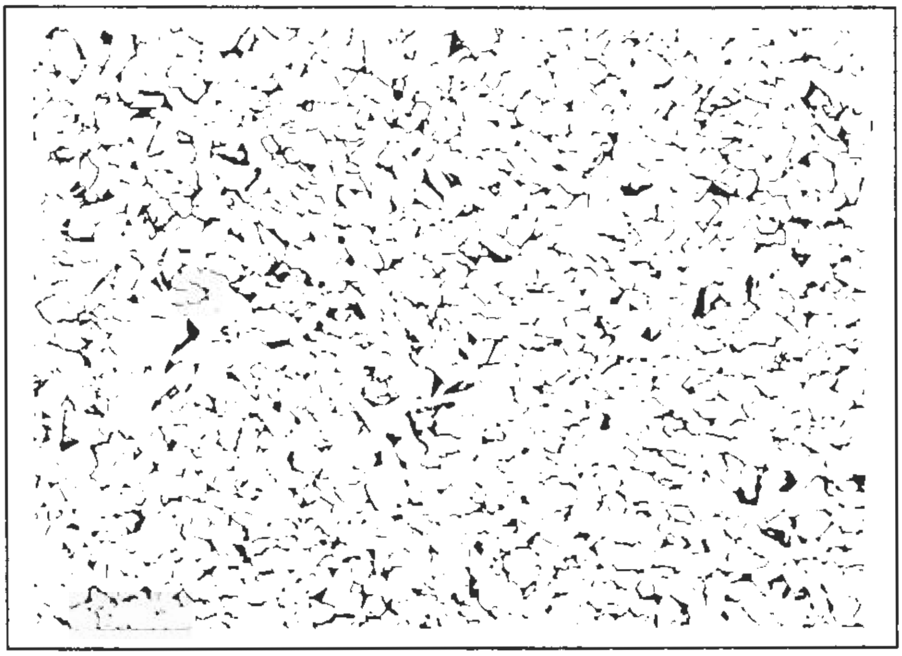


FIG. 2 COLUMN NO. 1M50D, SECTIONING PLAN (R4/225)
(ALL DIMENSIONS IN mm)

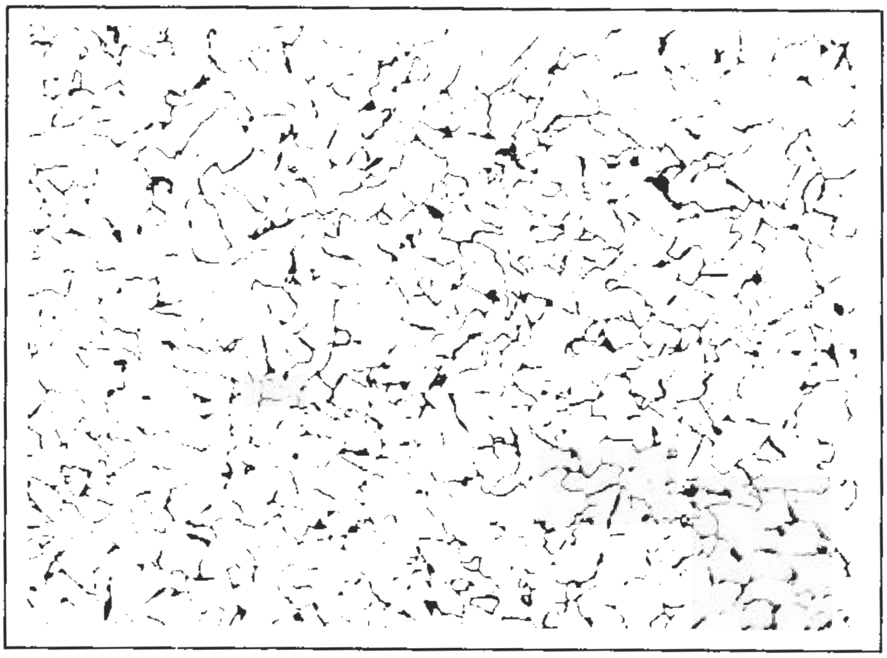


x 250 244.5 mm OD Column (a)

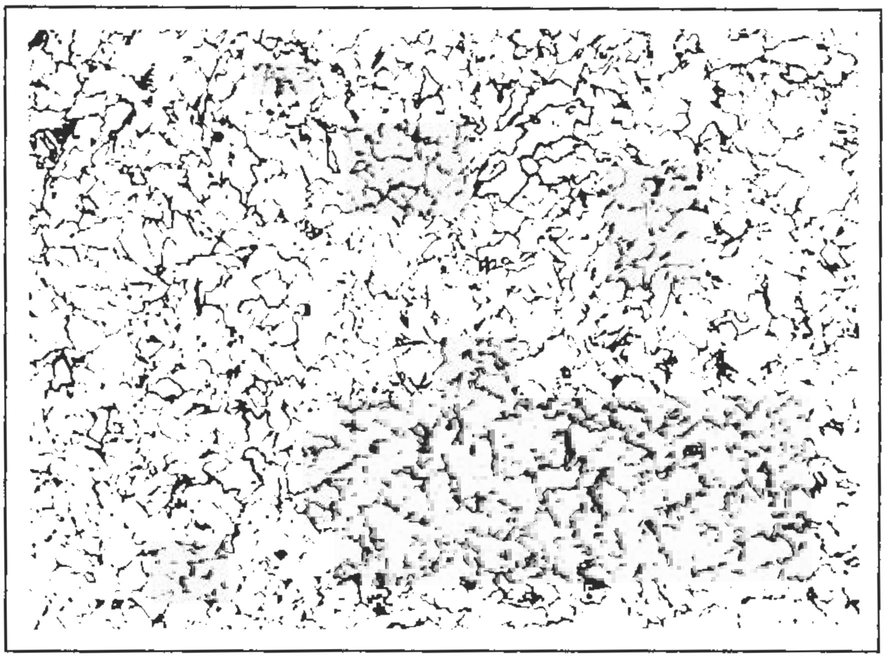


x 250 323.9 mm OD Column (b)

FIG. 3a and b MICROSTRUCTURES OF UNTESTED COLUMNS



x 250 244.5 mm OD Column (a)



x 250 323.9 mm OD Column (b)

FIG. 4a and b MICROSTRUCTURES OF FIRE TESTED COLUMNS

6606-15

FIG. 5 244.4 mm OD COLUMN, (CODE NO. 1M49D), SECTION 4

6606-9

FIG. 6 244.4 mm OD COLUMN, (CODE NO. 1M49D), SECTION 6

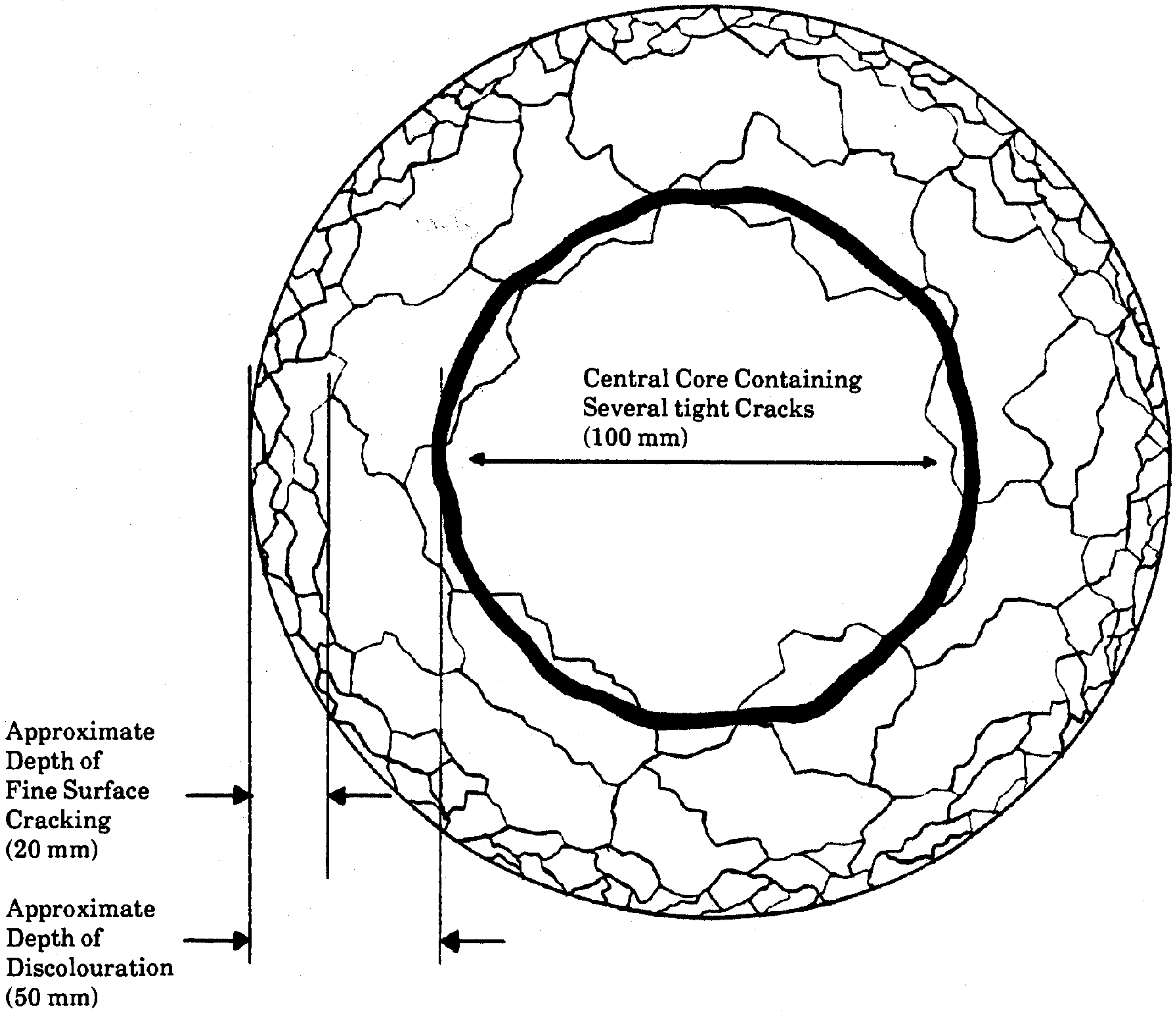
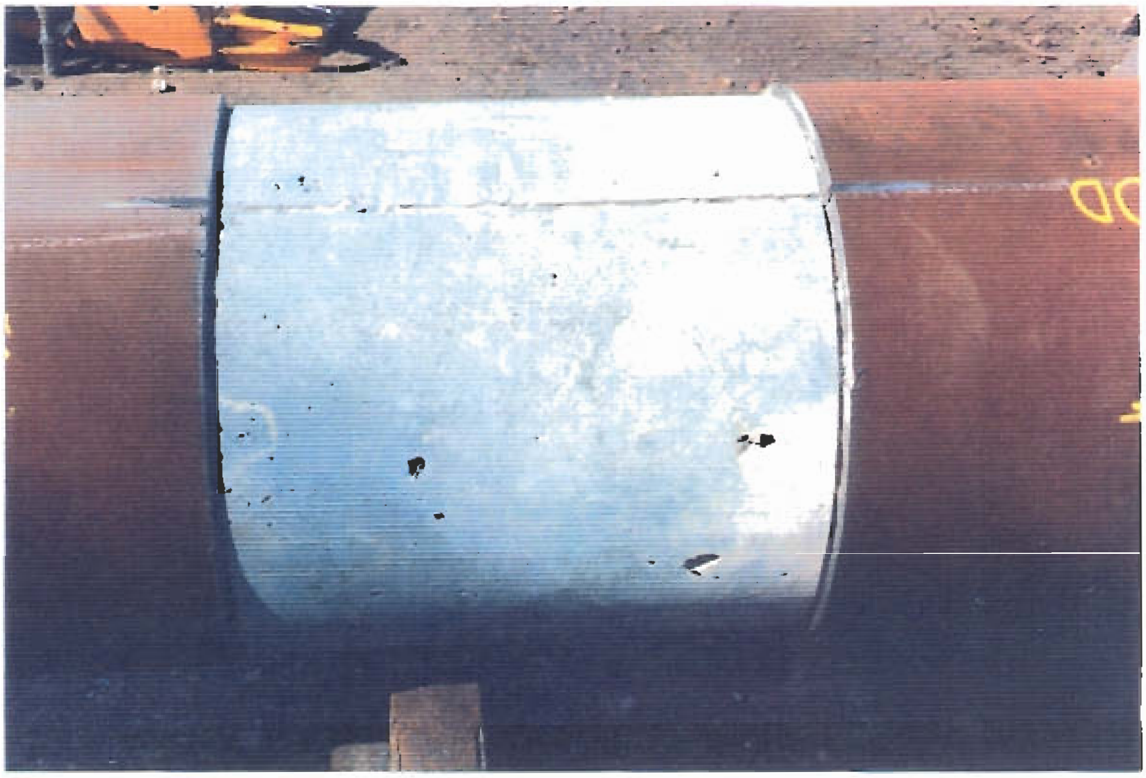


FIG. 7 SCHEMATIC ILLUSTRATION OF THE DEPTH OF DISCOLOURATION AND CRACK DISTRIBUTION IN COLUMN NO. 1M49D

6606-19

FIG. 8 244.5 mm OD COLUMN, (CODE NO. 1M49D), SECTION 2



6604-17

FIG. 9 323.9 mm OD COLUMN, (CODE NO. 1M50D), SECTION 2

6604-12

FIG. 10 323.9 mm OD COLUMN, (CODE NO. 1M50D), SECTION 4/3

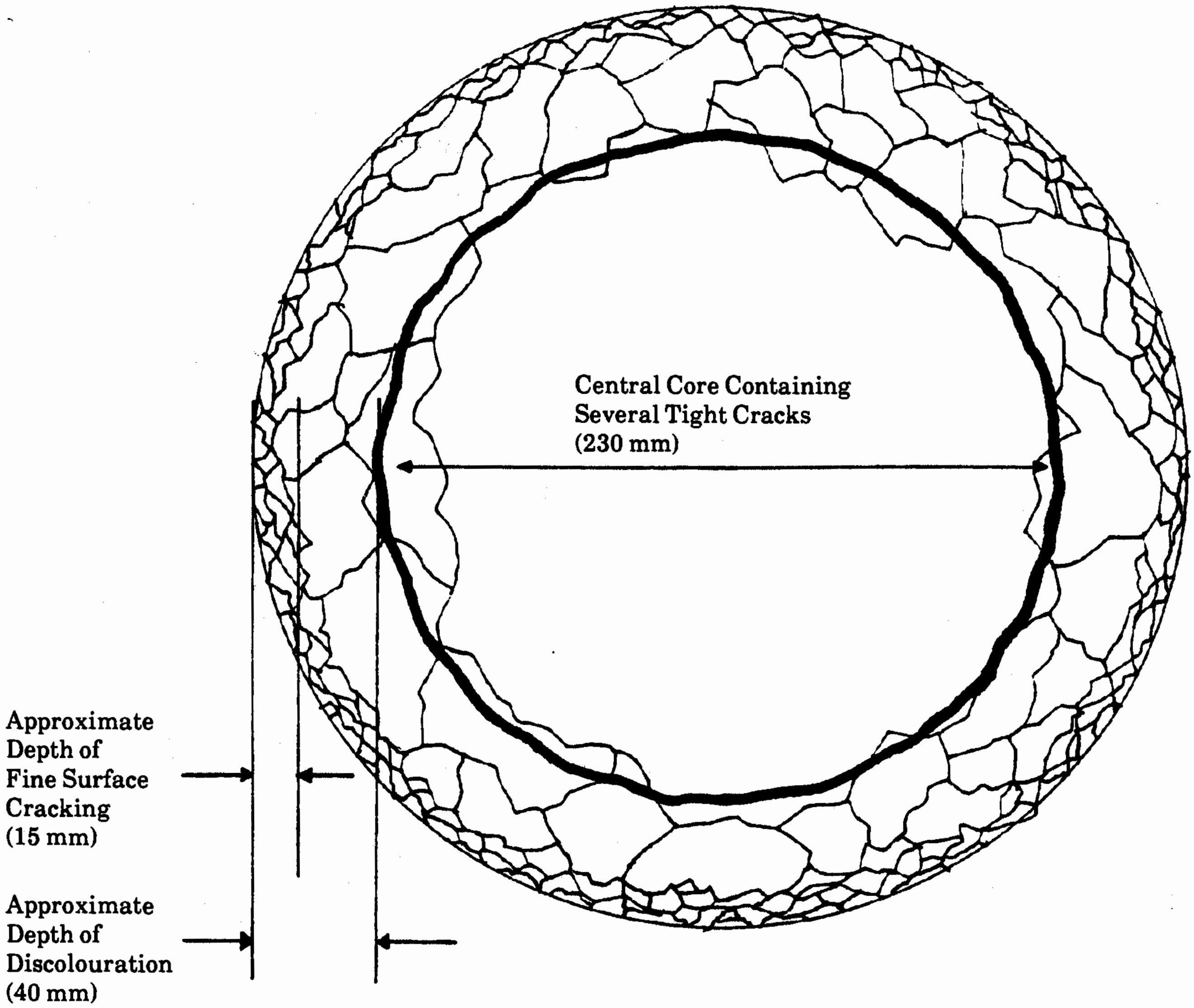


FIG. 11 SCHEMATIC ILLUSTRATION OF THE DEPTH OF DISCOLOURATION AND CRACK DISTRIBUTION IN COLUMN NO. 1M50D

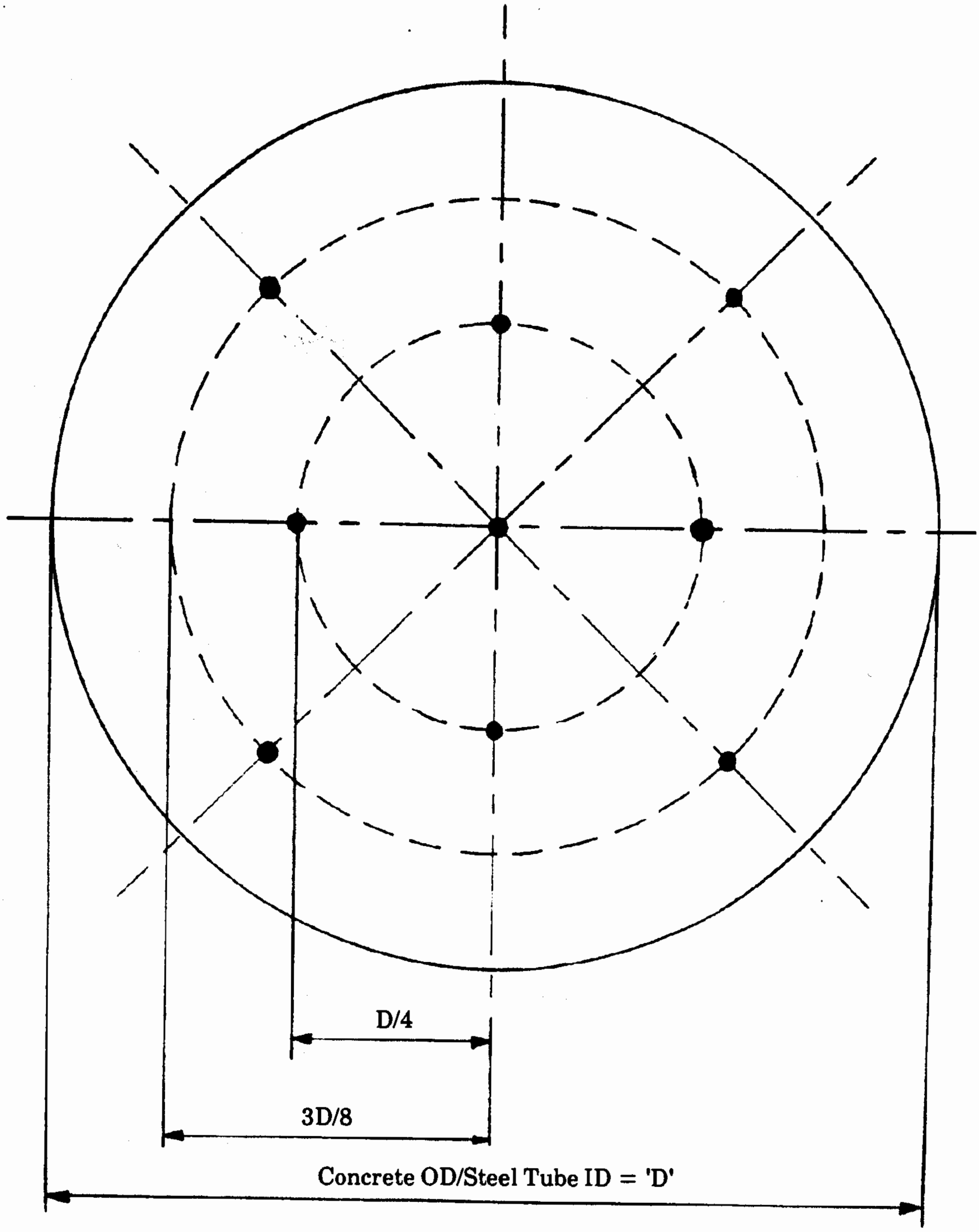


FIG. 12 POSITION OF THERMOCOUPLES IN THE CROSS-SECTION OF BOTH COLUMNS

APPENDIX 1

MATERIAL DETAILS

QA Code Number	1M49D
Dimensions:	244.5 mm OD x 12 m long x 6.3 mm wall thickness
Source:	British Steel, General Steels, Hartlepool Works
Date of Manufacture:	January 1991
Type of Tube:	Electrical Resistance Welded
Production Specification:	API Grade 5L, 1990 (Also to DIN 1626 St 37.0, 1984, except for tensile strength)
Certificate No.:	290/9120/0054
Cast No.:	5B46705
Reported Properties:	Yield: 342 MPa Tensile: 438 MPa Elongation: 36%

Ladle Analysis as Follows:

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb	Ti
0.07	0.23	0.57	0.021	0.002	0.023	0.003	0.01	0.023	0.015	0.003	0.004

QA Code Number	1M50D
Dimensions:	323.9 mm OD x 6 m long x 6.3 mm wall thickness
Source:	Stahlwerke Gebr. Fuchs Rohrenwerk, Germany
Date of Manufacture:	August 1989
Type of Tube:	Electrical Resistance Welded
Production Specification:	API Grade 5L, 1990
Certificate No.:	02/251/1500/90
Cast No.:	01-565510
Reported Properties:	Yield: 333 MPa Tensile: 449 MPa Elongation: 41%

Ladle Analysis as Follows:

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb	Ti
0.098	0.2	0.67	0.013	0.002	-	-	-	0.040	-	-	-

QA Code Number 1M51D

Dimensions: 355.6 mm OD x 12 m long x 9.5 mm wall thickness

Source: Vallourec Industries, France

Date of Manufacture: December 1989

Type of Tube: Hot Finished Seamless

Production Specification: API Grade 5L, 1990

Certificate No.: 13-90-07800

Cast No.: A1895

Reported Properties:
Yield: 377 MPa
Tensile: 513 MPa
Elongation: 33.5%

Ladle Analysis as Follows:

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb	V
0.135	0.15	0.97	0.017	0.002	0.10	0.06	0.03	-	0.18	-	0.021

APPENDIX 2

TEMPERATURE DETAILS FOR FIRE TEST OF TUBE NO. 1M49D

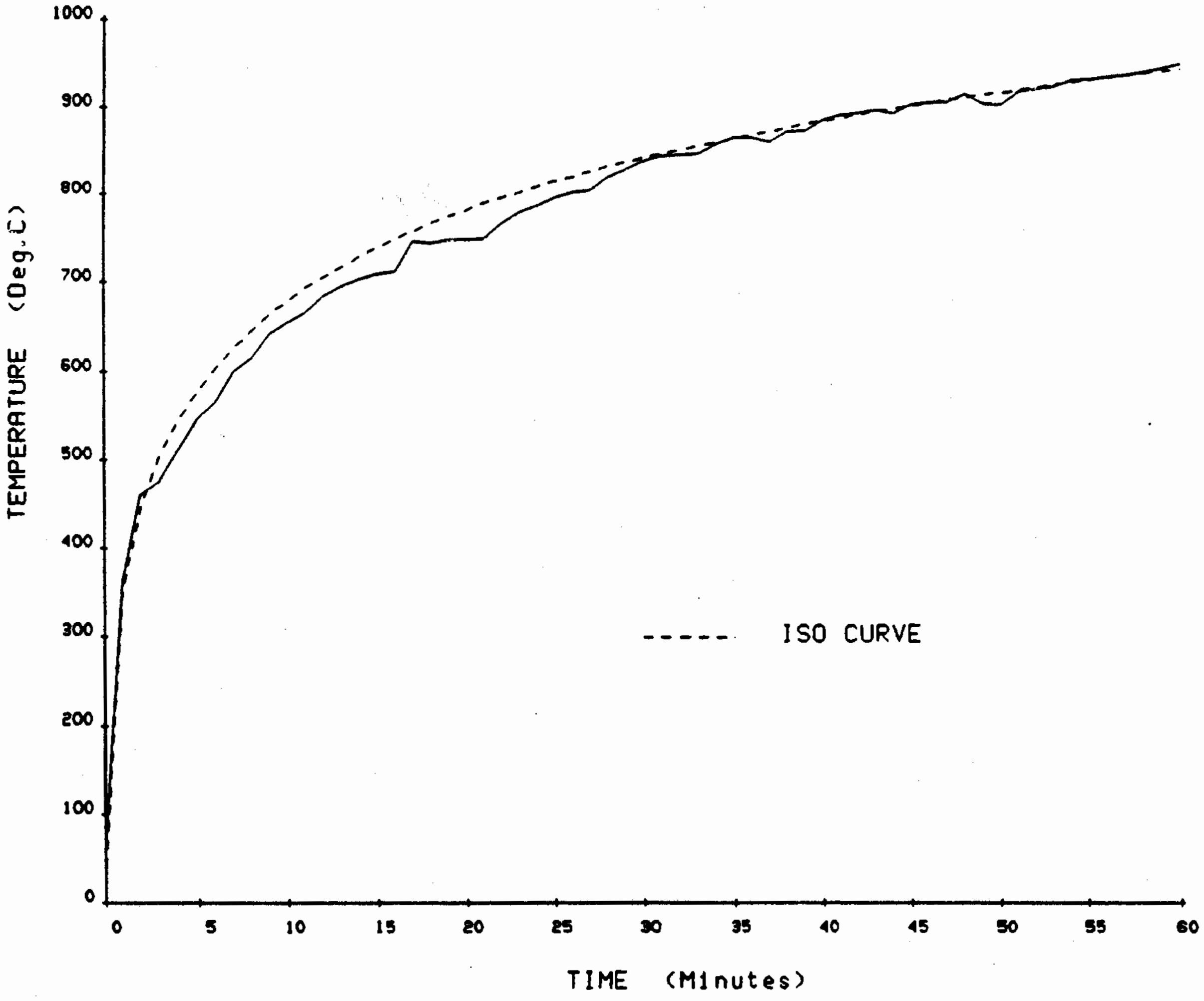


FIG. A2.1 COMPARISON OF AVERAGE FURNACE ATMOSPHERE TEMPERATURE AND THE STANDARD TEMPERATURE/TIME CURVE
COLUMN NO. 1M49D, TEST NO. LPC 81441
(244.5 mm OD × 6.3 mm WALL CHS)

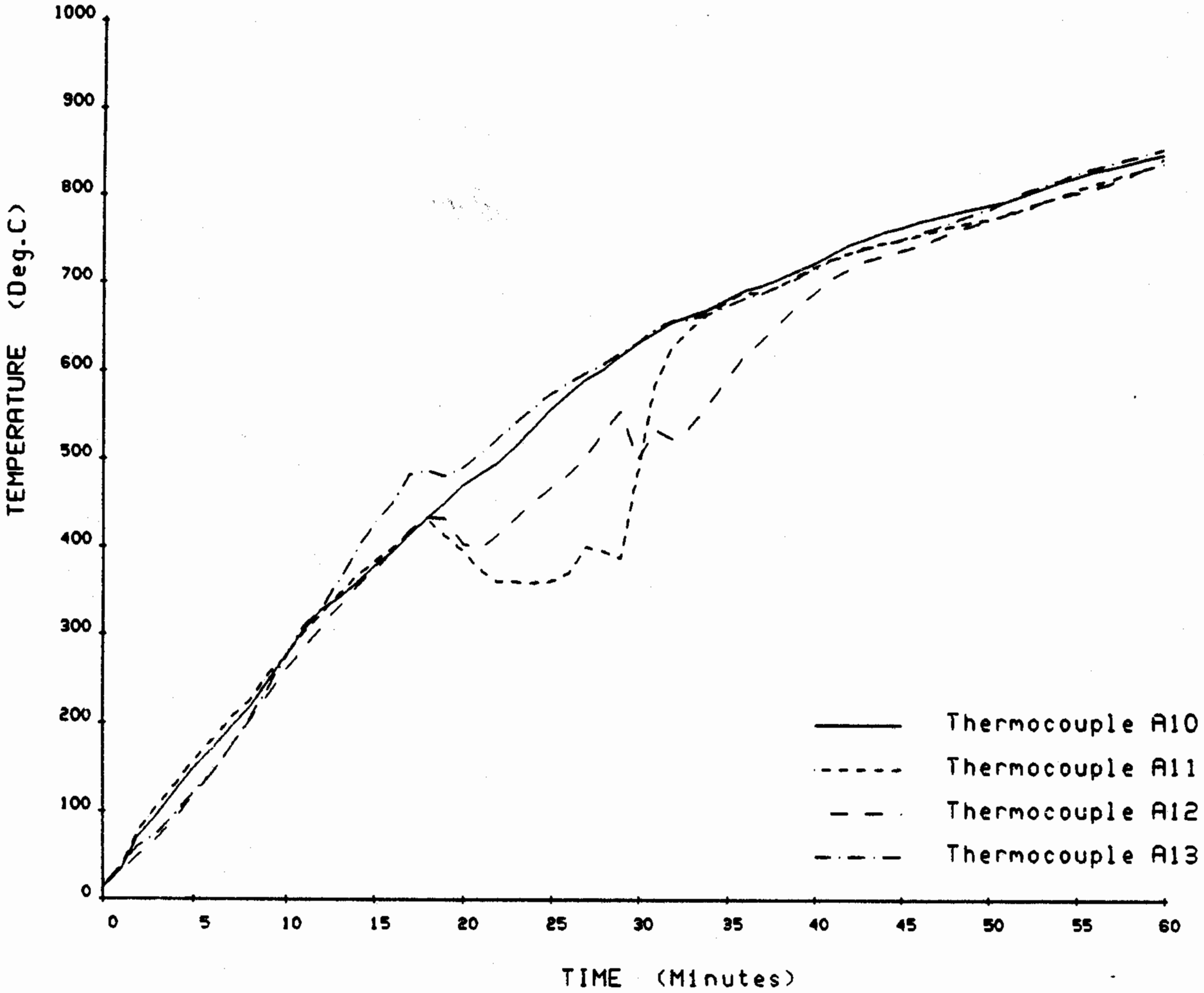


FIG. A2.2 TEMPERATURES RECORDED IN THE STEELWORK AT THE A POSITION
COLUMN NO. 1M49D, TEST NO. LPC 81441
(244.5 mm OD × 6.3 mm WALL CHS)

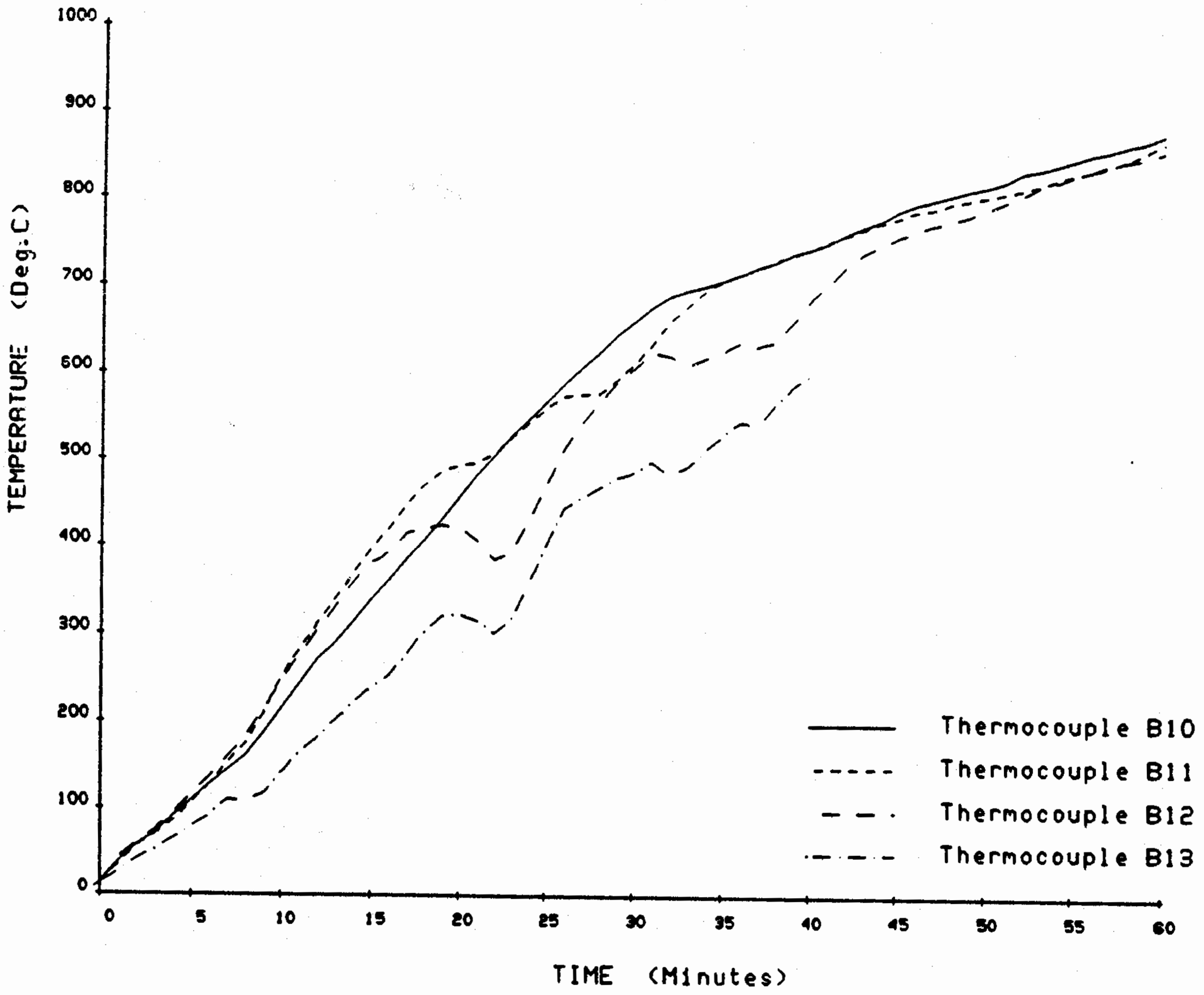


FIG. A2.3 TEMPERATURES RECORDED IN THE STEELWORK AT THE B POSITION COLUMN NO. 1M49D, TEST NO. LPC 81441 (244.5 mm OD × 6.3 mm WALL CHS)

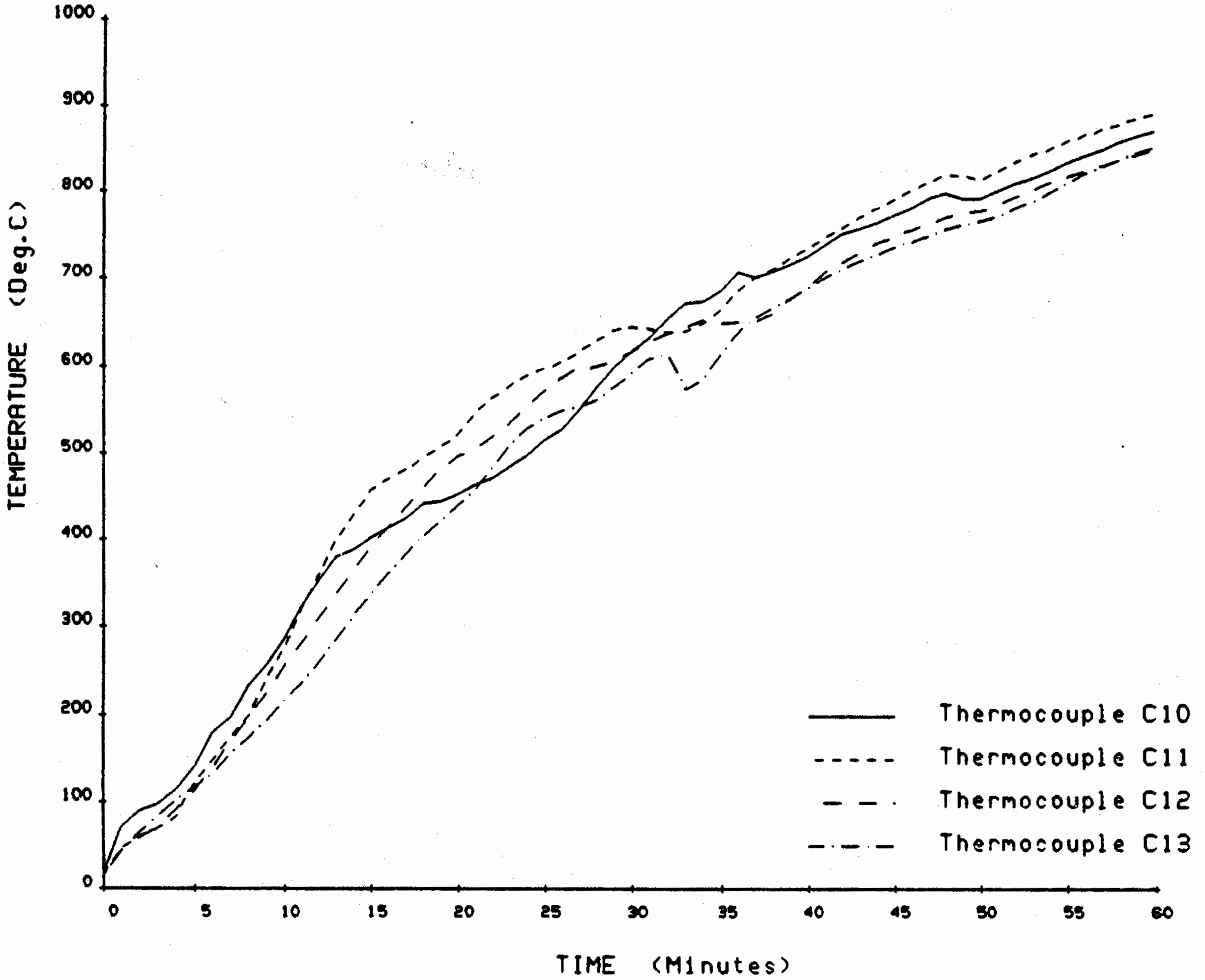


FIG. A2.4 TEMPERATURES RECORDED IN THE STEELWORK AT THE C POSITION
COLUMN NO. 1M49D, TEST NO. LPC 81441
(244.5 mm OD × 6.3 mm WALL CHS)

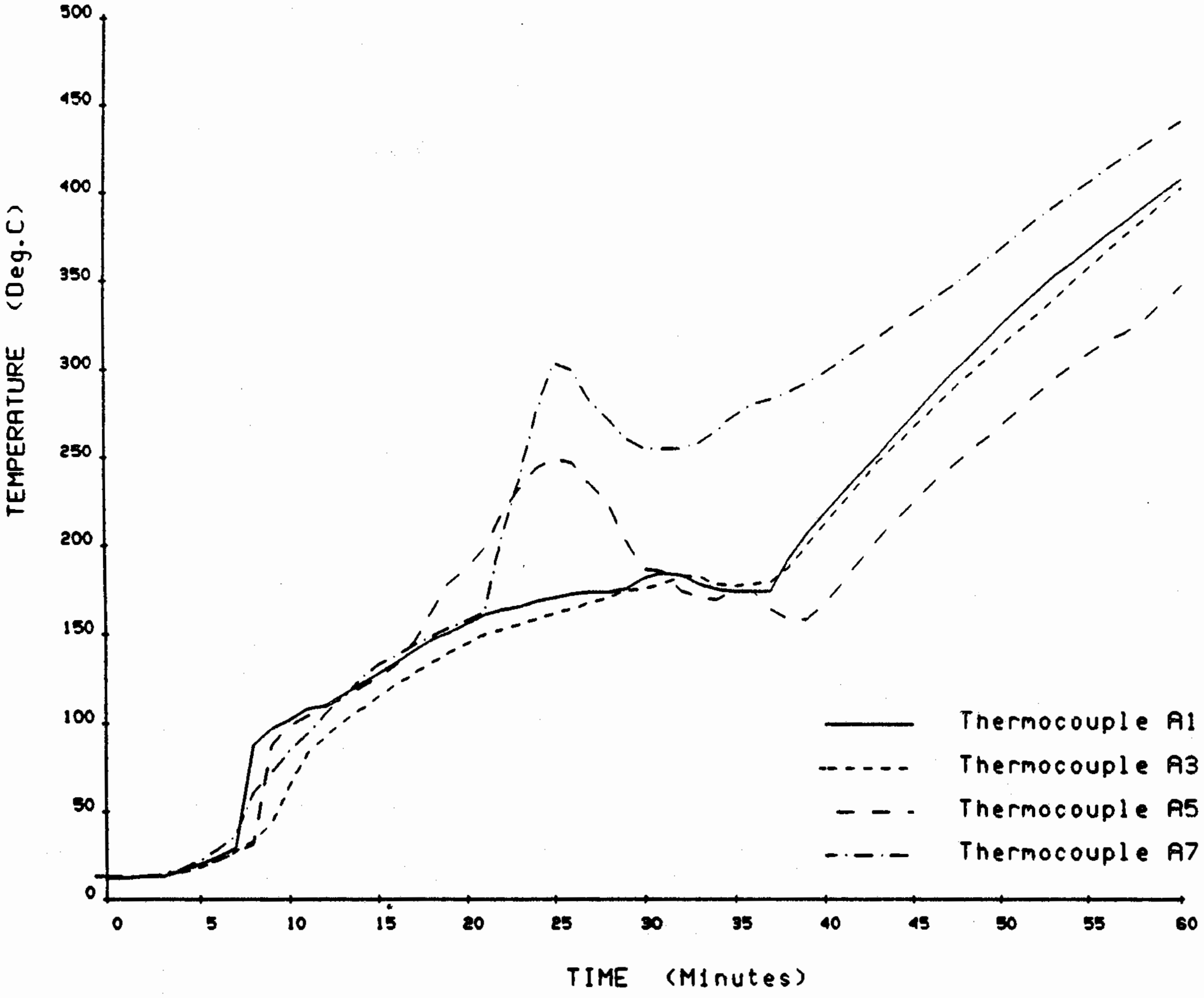


FIG. A2.5 TEMPERATURES RECORDED IN THE CONCRETE AT THE $^3/_8$ DIAMETER POSITION - LEVEL A COLUMN NO. 1M49D, TEST NO. LPC 81441 (244.5 mm OD × 6.3 mm WALL CHS)

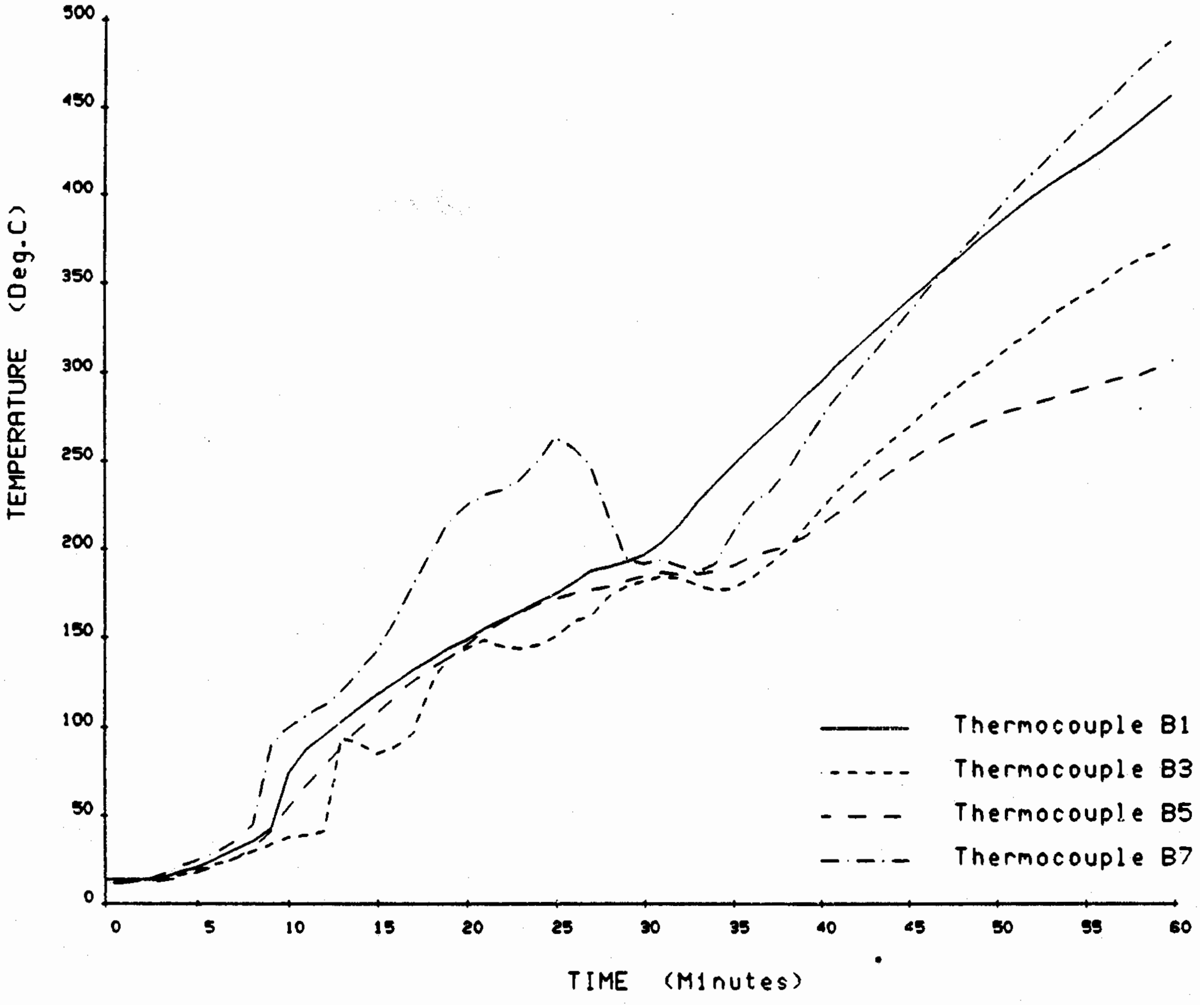


FIG. A2.6 TEMPERATURES RECORDED IN THE CONCRETE AT THE $^3/_8$ DIAMETER POSITION - LEVEL B COLUMN NO. 1M49D, TEST NO. LPC 81441 (244.5 mm OD × 6.3 mm WALL CHS)

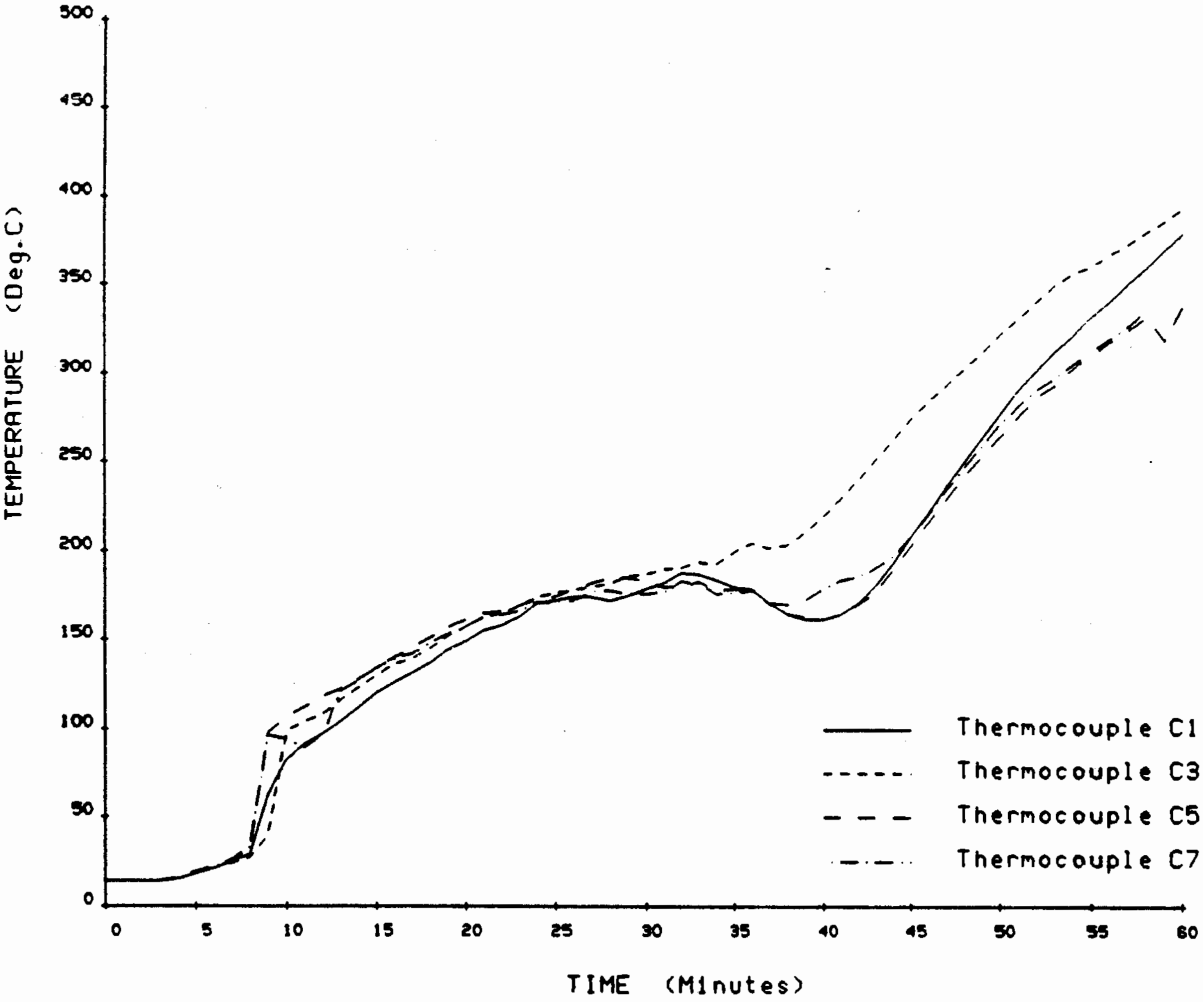


FIG. A2.7 TEMPERATURES RECORDED IN THE CONCRETE AT THE $^3/_8$ DIAMETER POSITION - LEVEL C COLUMN NO. 1M49D, TEST NO. LPC 81441 (244.5 mm OD × 6.3 mm WALL CHS)

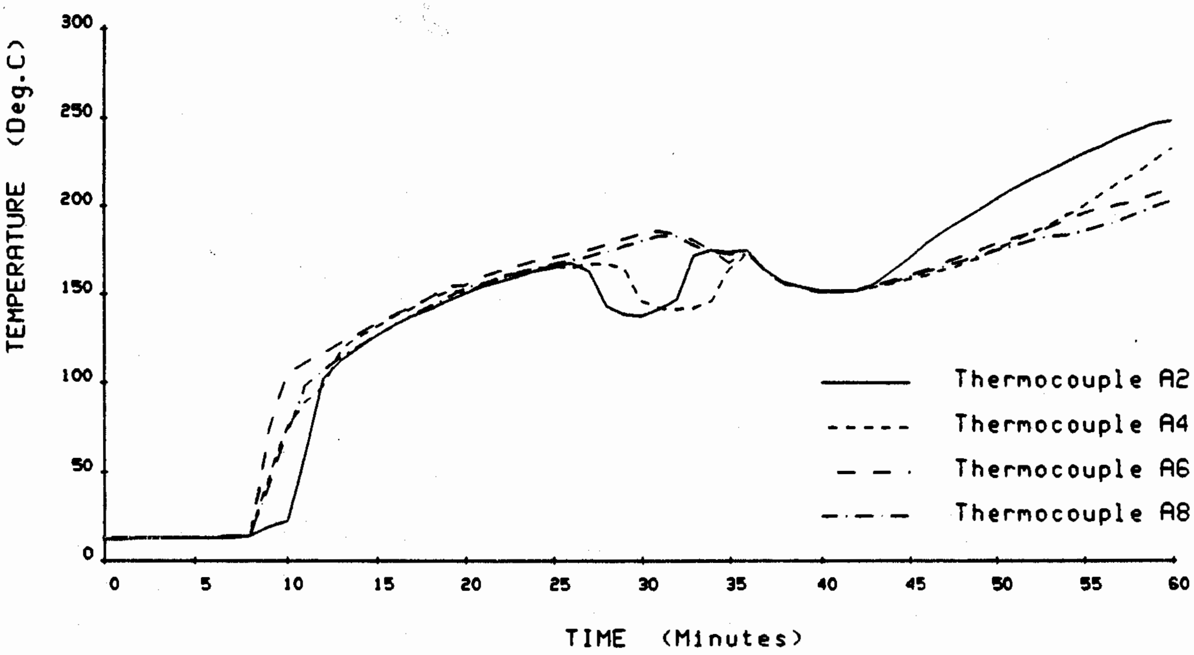


FIG. A2.8 TEMPERATURES RECORDED IN THE CONCRETE AT THE $1/4$ DIAMETER POSITION - LEVEL A COLUMN NO. 1M49D, TEST NO. LPC 81441 (244.5 mm OD × 6.3 mm WALL CHS)

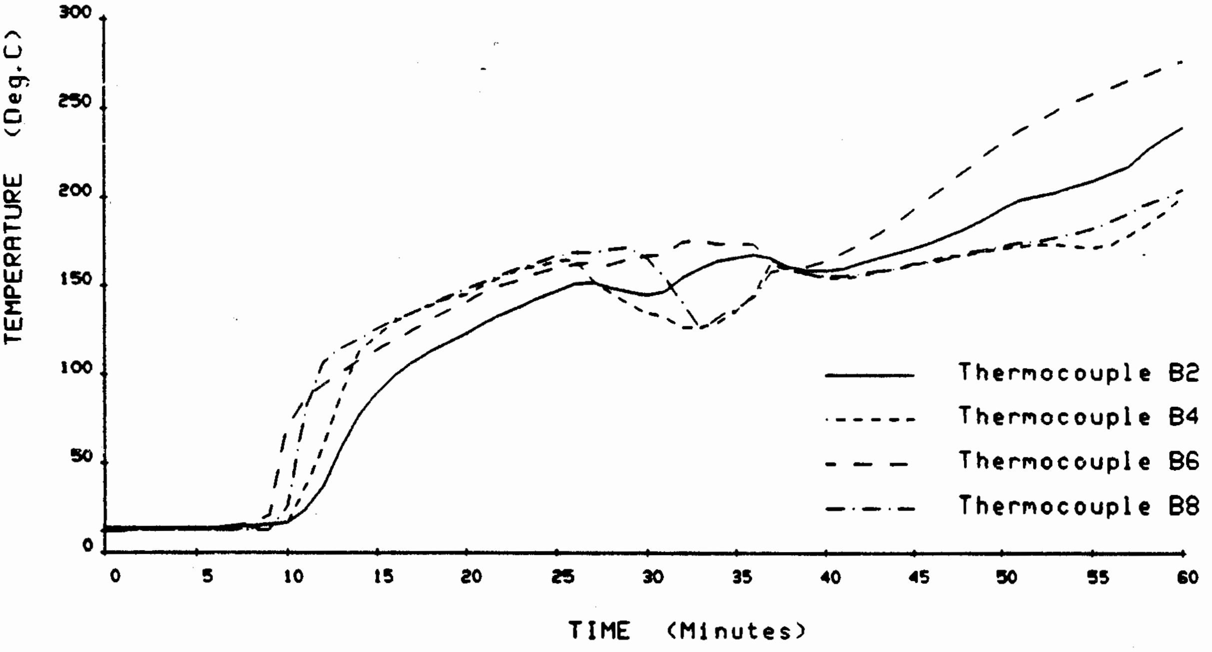


FIG. A2.9 TEMPERATURES RECORDED IN THE CONCRETE AT THE 1/4 DIAMETER POSITION - LEVEL B COLUMN NO. 1M49D, TEST NO. LPC 81441 (244.5 mm OD × 6.3 mm WALL CHS)

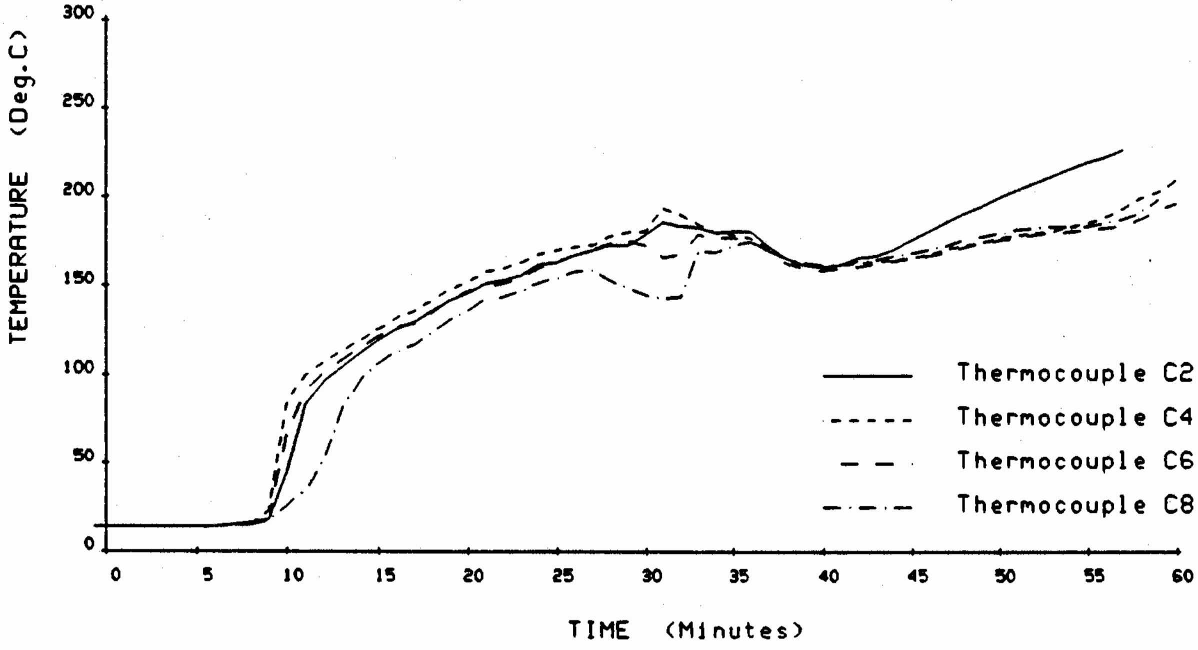


FIG. A2.10 TEMPERATURES RECORDED IN THE CONCRETE AT THE 1/4 DIAMETER POSITION - LEVEL C COLUMN NO. 1M49D, TEST NO. LPC 81441 (244.5 mm OD × 6.3 mm WALL CHS)

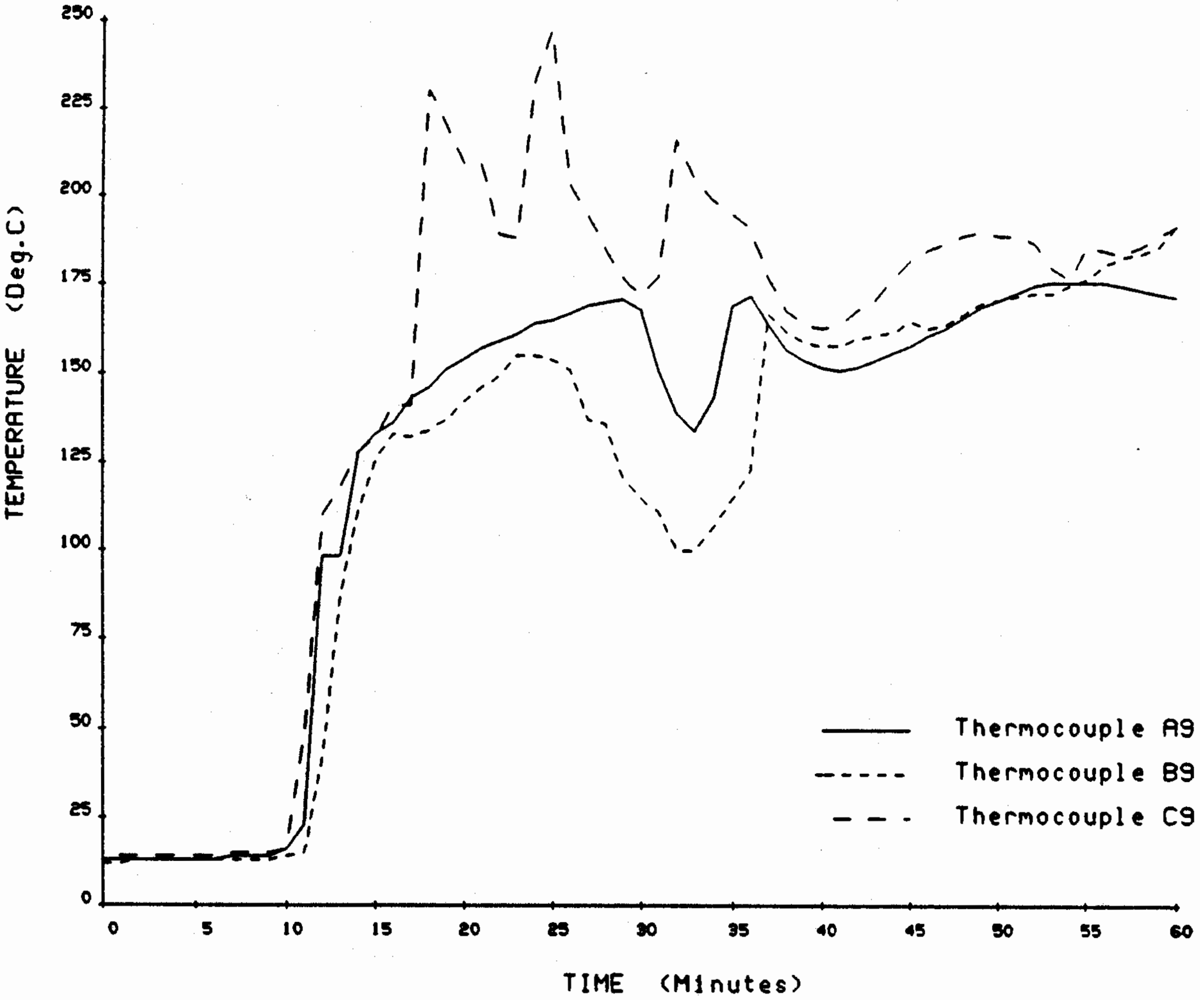


FIG. A2.11 TEMPERATURES RECORDED AT THE CONCRETE CORE POSITION
COLUMN NO. 1M49D, TEST NO. LPC 81441
(244.5 mm OD × 6.3 mm WALL CHS)

APPENDIX 3

TEMPERATURE DETAILS FOR FIRE TEST OF TUBE NO. 1M50D

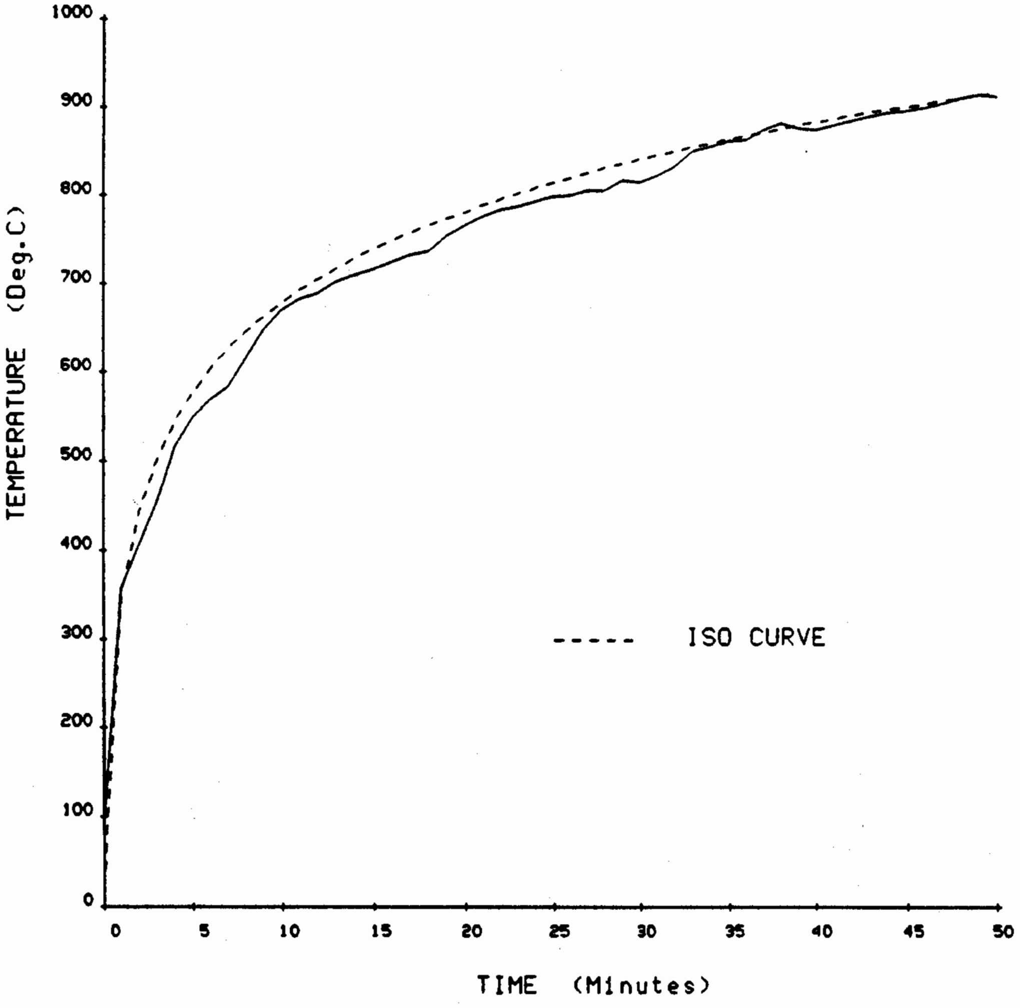


FIG. A3.1 COMPARISON OF AVERAGE FURNACE ATMOSPHERE TEMPERATURE AND THE STANDARD TEMPERATURE/TIME CURVE COLUMN NO. 1M50D, TEST NO. LPC 81442 (323.9 mm OD × 6.3 mm WALL CHS)

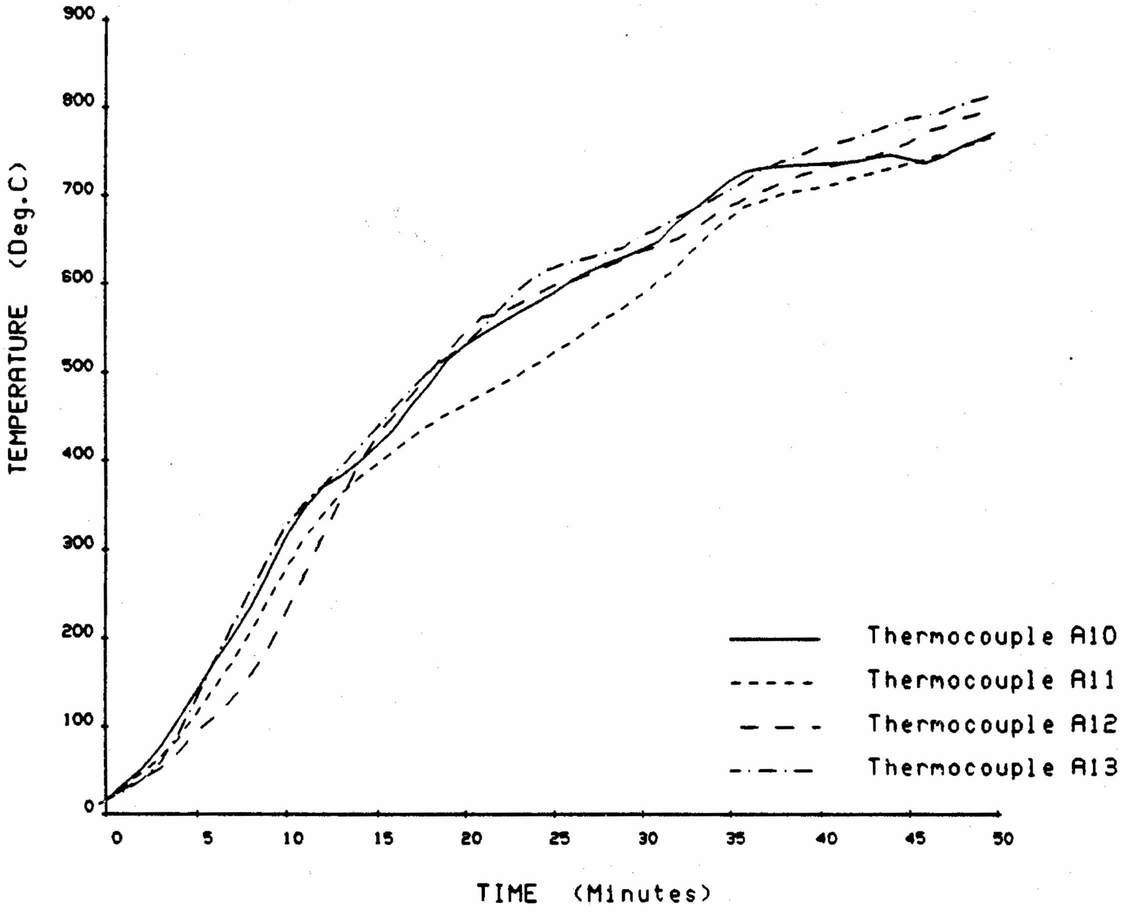


FIG. A3.2 TEMPERATURES RECORDED IN THE STEELWORK AT THE A POSITION
COLUMN NO. 1M50D, TEST NO. LPC 81442
(323.9 mm OD × 6.3 mm WALL CHS)

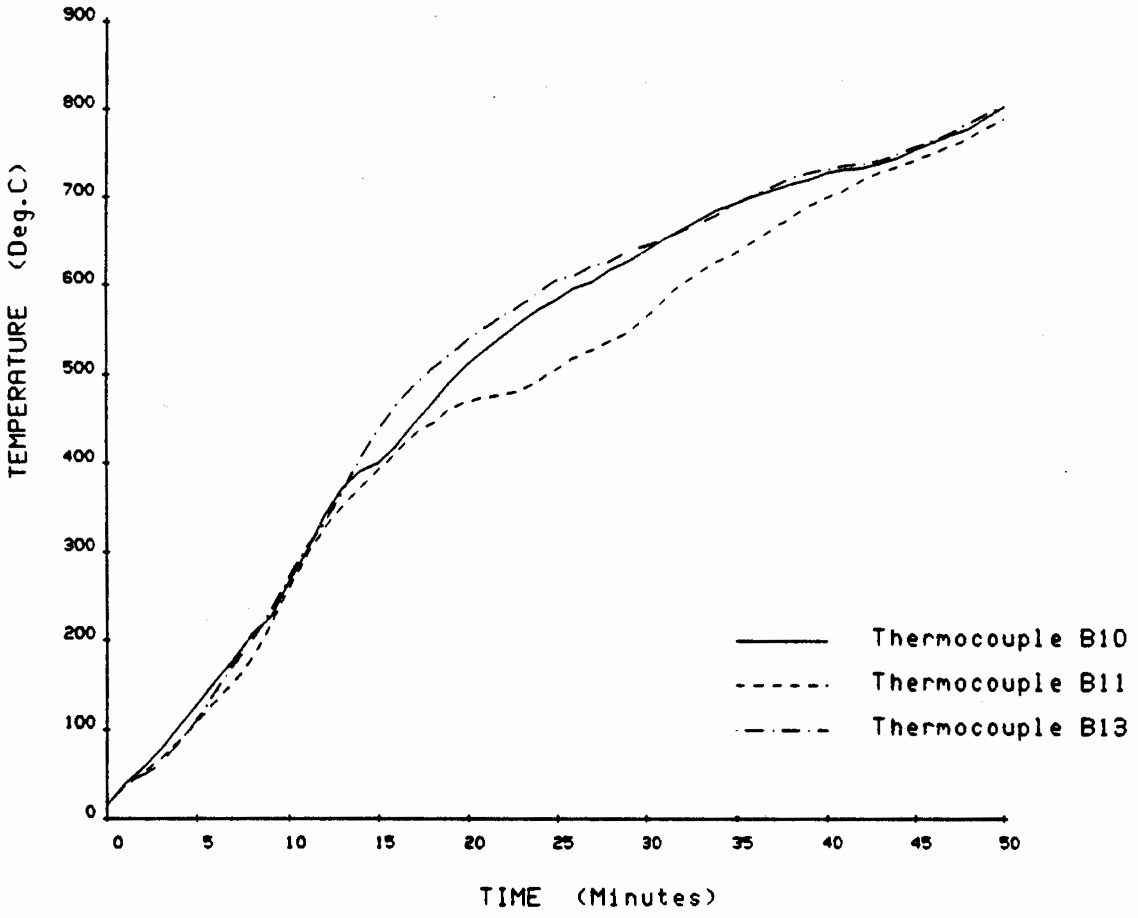


FIG. A3.3 TEMPERATURES RECORDED IN THE STEELWORK AT THE B POSITION
COLUMN NO. 1M50D, TEST NO. LPC 81442
(323.9 mm OD × 6.3 mm WALL CHS)

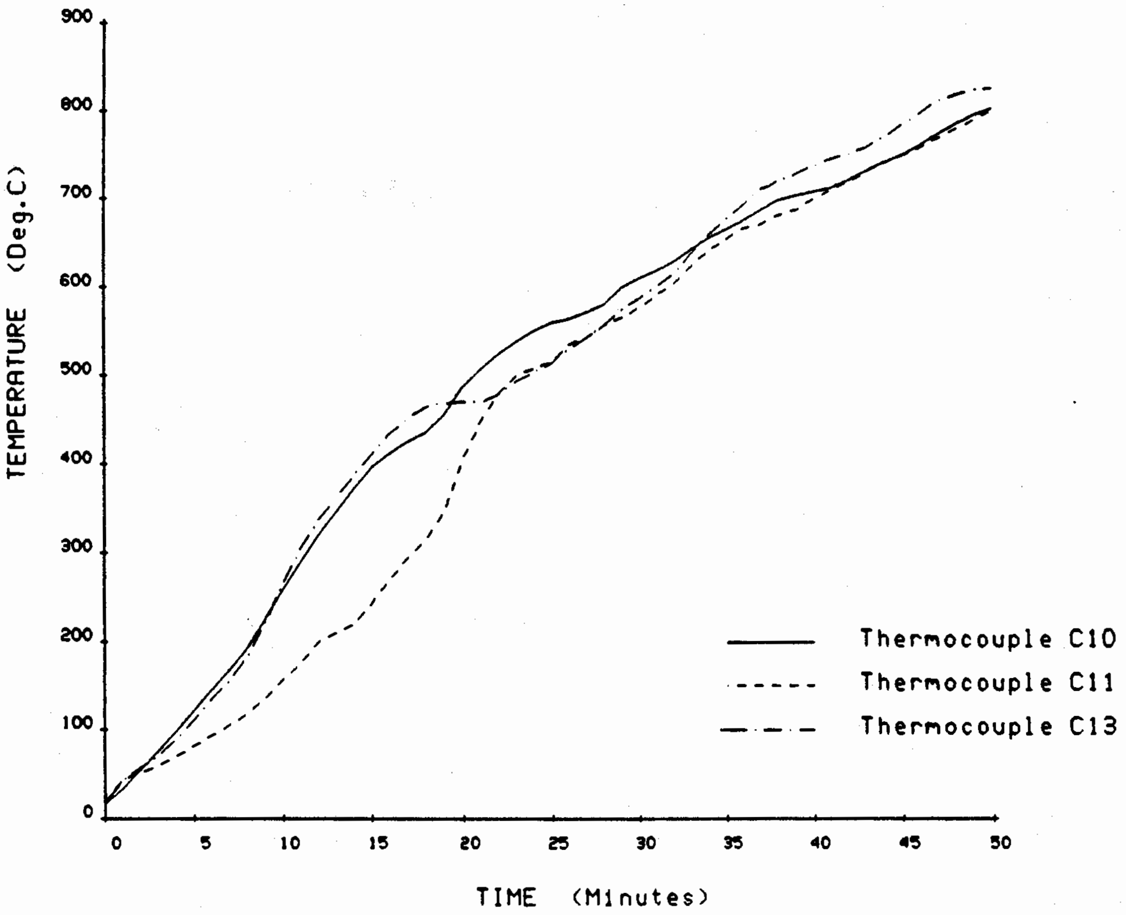


FIG. A3.4 TEMPERATURES RECORDED IN THE STEELWORK AT THE C POSITION COLUMN NO. 1M50D, TEST NO. LPC 81442 (323.9 mm OD × 6.3 mm WALL CHS)

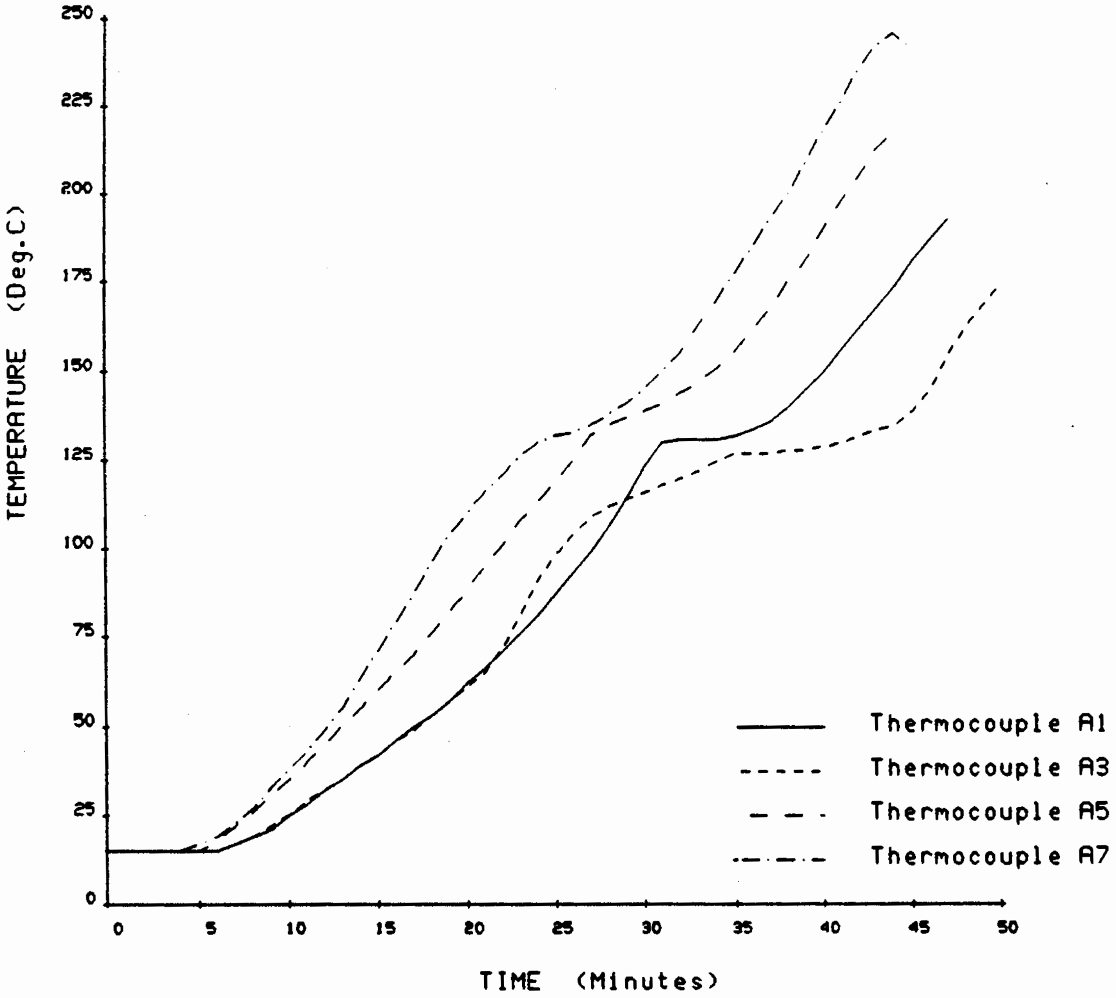


FIG. A3.5 TEMPERATURES RECORDED IN THE CONCRETE AT THE $^3/_8$ DIAMETER POSITION - LEVEL A COLUMN NO. 1M50D, TEST NO. LPC 81442 (323.9 mm OD × 6.3 mm WALL CHS)

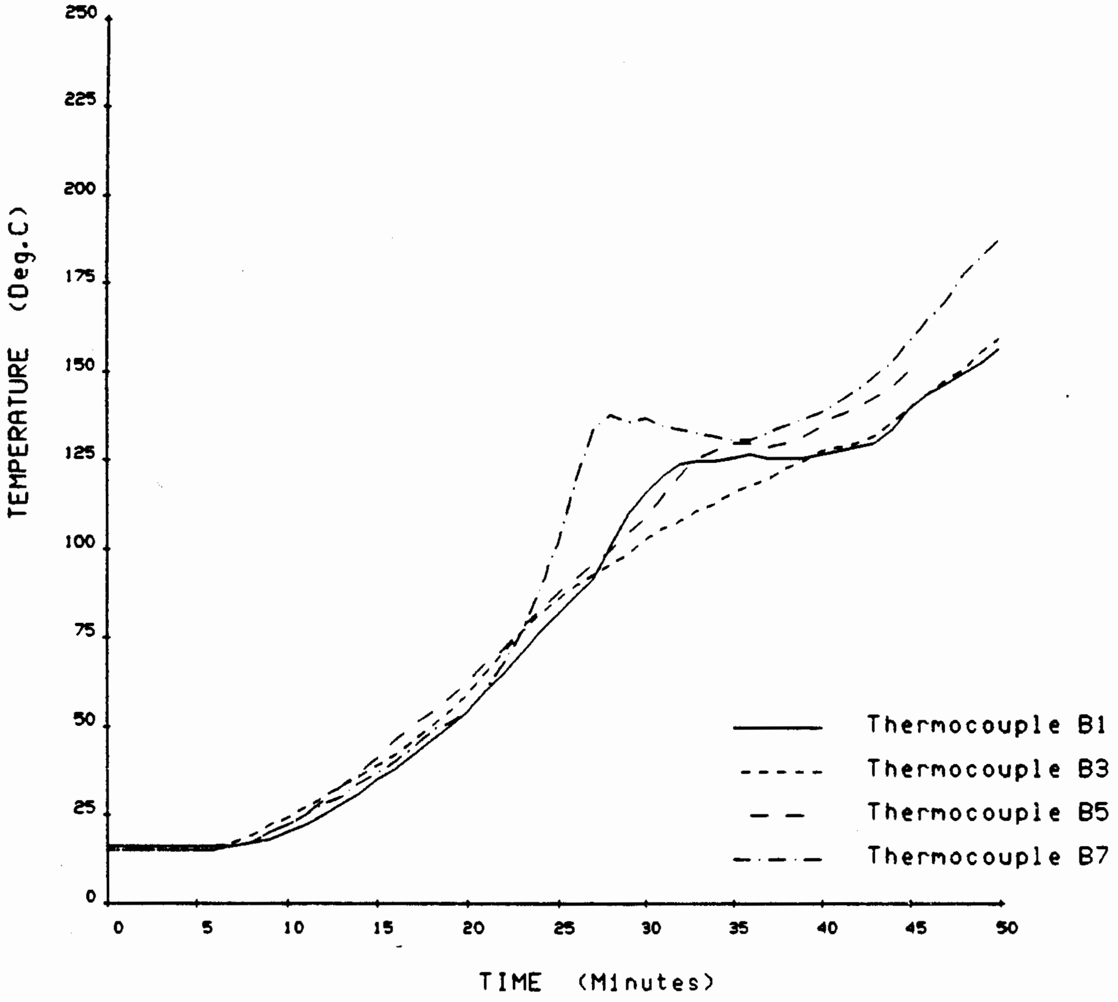


FIG. A3.6 TEMPERATURES RECORDED IN THE CONCRETE AT THE $^3/_8$ DIAMETER POSITION - LEVEL B COLUMN NO. 1M50D, TEST NO. LPC 81442 (323.9 mm OD × 6.3 mm WALL CHS)

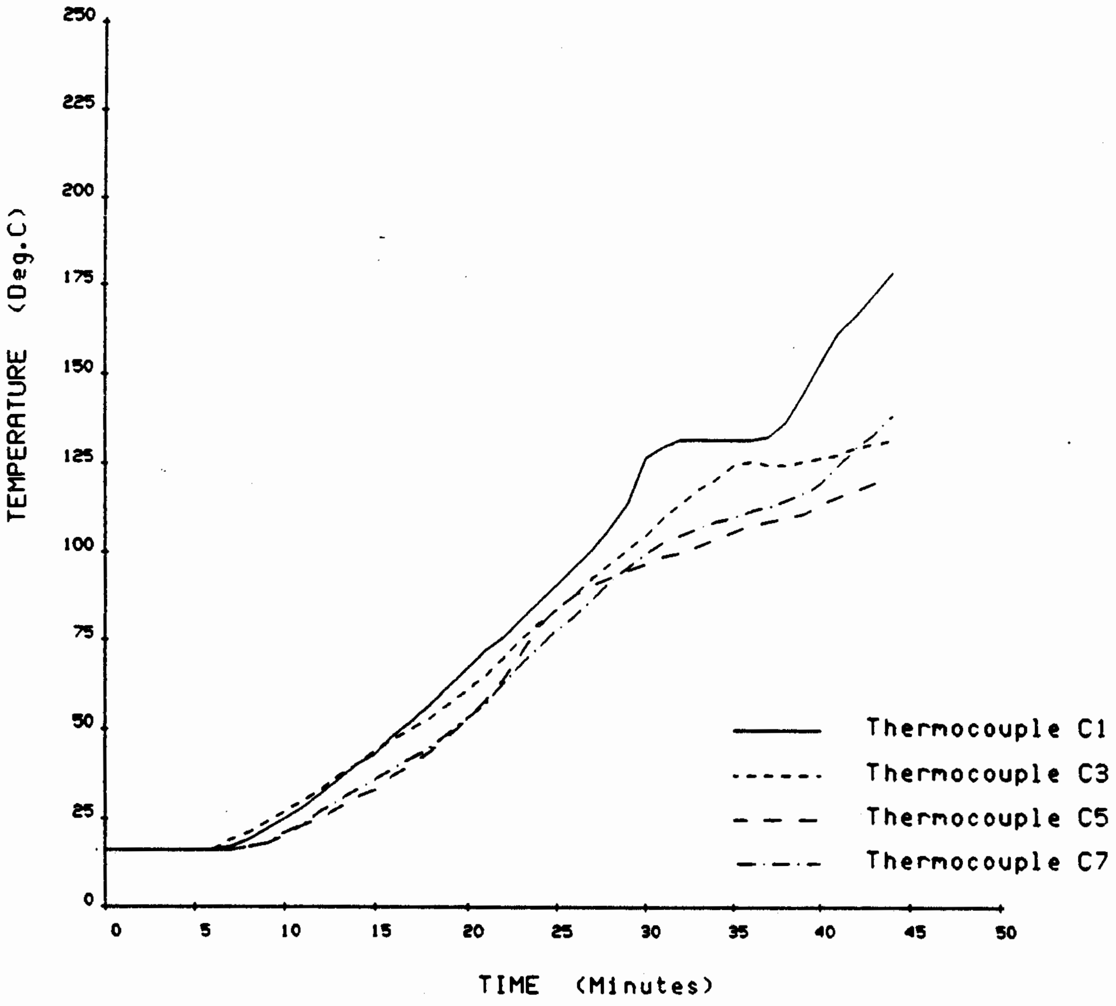


FIG. A3.7 TEMPERATURES RECORDED IN THE CONCRETE AT THE $^3/_8$ DIAMETER POSITION - LEVEL C COLUMN NO. 1M50D, TEST NO. LPC 81442 (323.9 mm OD × 6.3 mm WALL CHS)

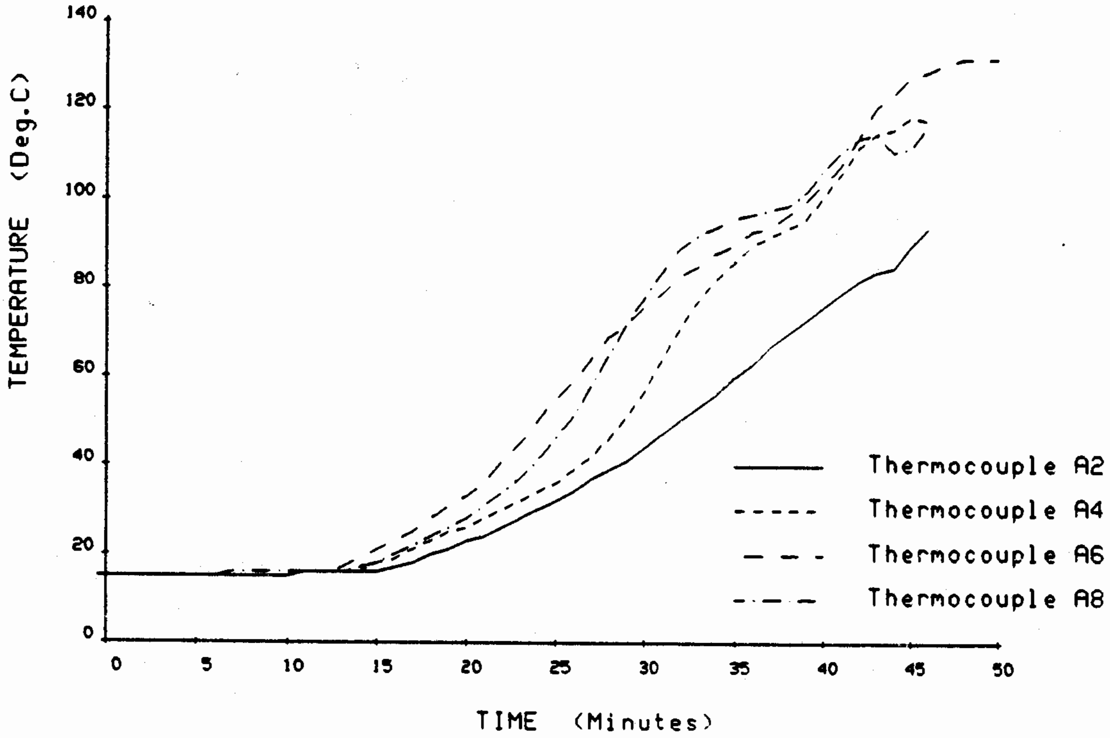


FIG. A3.8 TEMPERATURES RECORDED IN THE CONCRETE AT THE 1/4 DIAMETER POSITION - LEVEL A COLUMN NO. 1M50D, TEST NO. LPC 81442 (323.9 mm OD × 6.3 mm WALL CHS)

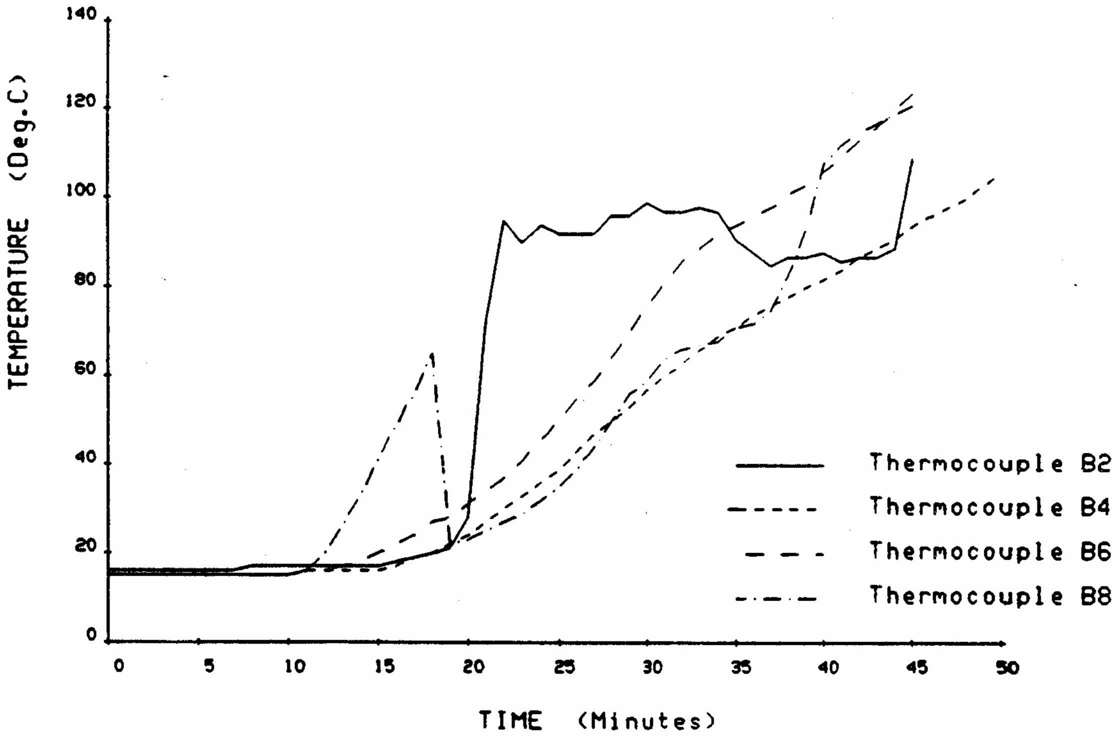


FIG. A3.9 TEMPERATURES RECORDED IN THE CONCRETE AT THE $^1/_4$ DIAMETER POSITION - LEVEL B COLUMN NO. 1M50D, TEST NO. LPC 81442 (323.9 mm OD × 6.3 mm WALL CHS)

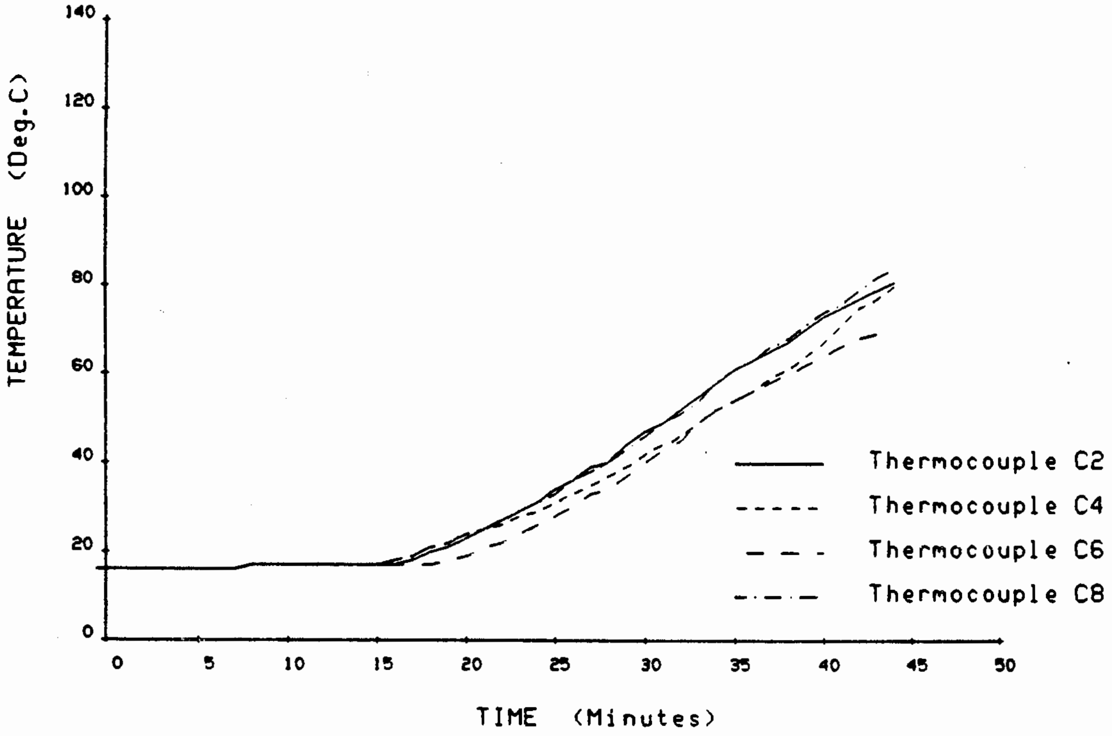


FIG. A3.10 TEMPERATURES RECORDED IN THE CONCRETE AT THE 1/4 DIAMETER POSITION - LEVEL C COLUMN NO. 1M50D, TEST NO. LPC 81442 (323.9 mm OD × 6.3 mm WALL CHS)

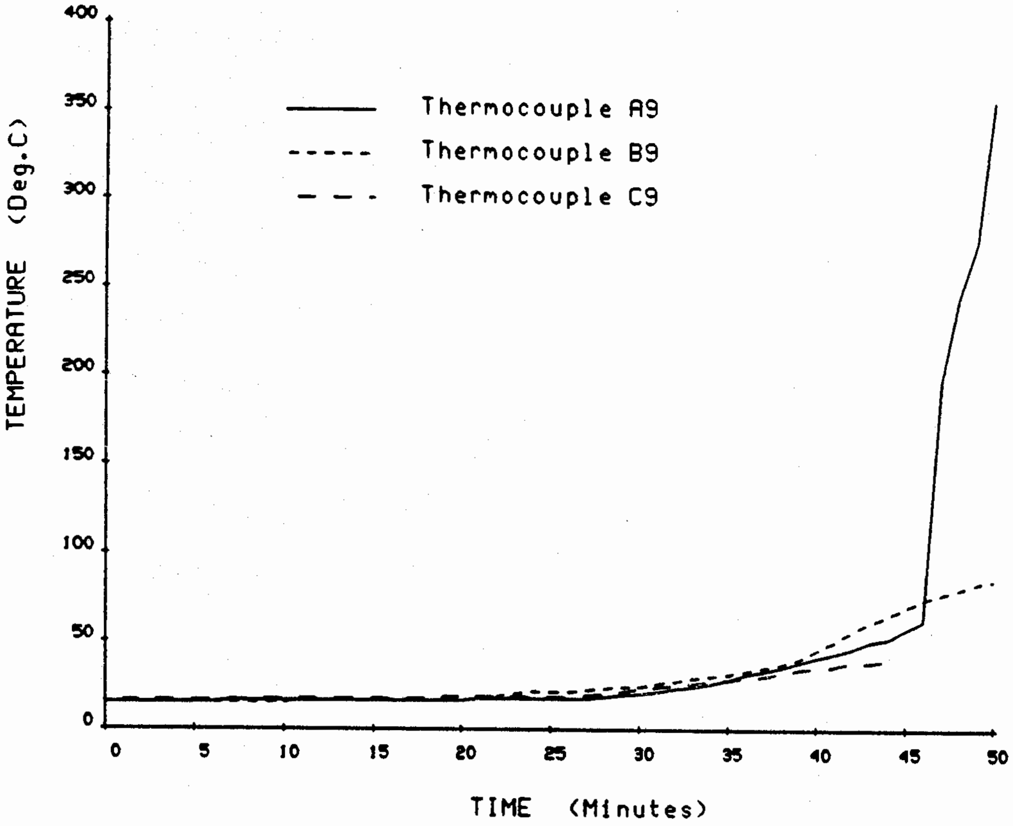


FIG. A3.11 TEMPERATURES RECORDED AT THE CONCRETE CORE POSITION
COLUMN NO. 1M50D, TEST NO. LPC 81442
(323.9 mm OD × 6.3 mm WALL CHS)