Experimental studies on the fire resistance of circular hollow steel columns filled with steel-fibre-reinforced concrete

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EXPERIMENTAL STUDIES ON THE FIRE RESISTANCE OF CIRCULAR HOLLOW STEEL COLUMNS FILLED WITH STEEL-FIBRE-REINFORCED CONCRETE

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ABSTRACT

Tests were carried out to determine the fire resistance of circular hollow steel columns filled with steel-fibre reinforced concrete. The results of six full-scale fire resistance tests are described in this report. The main study variables were the column dimensions and load intensity. These studies were conducted as part of a research program aimed at developing simple design equations capable of predicting the fire resistance of concrete-filled hollow steel columns.

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1. INTRODUCTION

Circular hollow steel sections are very efficient structural sections in resisting compression loads. By filling these hollow steel columns with concrete, the load-carrying capacity of these columns can be increased substantially. In addition, a high fire resistance can be obtained without using surface fire protection for the steel. The elimination of such surface protection, in turn, increases space in the building and improves the architectural aesthetics. Also, the fact that formwork is not required provides a significant saving in construction cost and time.

These benefits have stimulated research into the structural and fire resistance performance of concrete-filled hollow steel sections in several laboratories around the world. For a number of years, the National Fire Laboratory of the Institute for Research in Construction, National Research Council of Canada (NRCC), has been engaged in studies aimed at developing methods for predicting the fire resistance of concrete-filled steel columns. Both experimental and numerical studies on the fire resistance of hollow steel columns filled with concrete were carried out with the support of the Canadian Steel Construction Council (CSCC) and the American Iron and Steel Institute (AISI).

Three types of concrete filling, namely plain, bar-reinforced and fibre-reinforced concrete, were considered in the study. Studies on hollow steel columns filled with plain concrete and bar-reinforced concrete were completed [1, 2, 3, 4] and the work on HSS columns filled with steel-fibre-reinforced concrete is at an advanced stage.

This report deals with circular hollow steel columns filled with fibre-reinforced concrete. The results of six fire resistance tests on full-size circular columns are described in detail, including the column temperatures, axial deformations and fire resistances.

2. TEST SPECIMENS

2.1 Dimensions

All six columns were 3810 mm long from end plate to end plate and were of circular cross section. The outside diameter, D, of the columns ranged from 323.9 mm to 406.4 mm. The wall thickness, t, of all six sections was 6.35 mm. The dimensions of each column are listed in Table 1.

2.2 Materials

2.2.1 <u>Steel</u>

Steel hollow structural sections (HSS) meeting the requirements of CSA Standard G40.20-M81 [5], Class H, were used. The sections were made with Grade 300W steel which had a minimum yield strength of 300 MPa. The sections were supplied by Stelco Inc. The end plates were constructed using mild steel.

2.2.2 Concrete

Two batches of concrete mix were supplied by Dufferin Concrete from Ottawa. Columns C-52, C-54 and C-58 were cast from the first batch while the other three columns, C-65, C-66 and C-67, were cast from the second batch of concrete. The mixes were made with general purpose Type 10 Portland cement, carbonate stone and silica based sand. RIBTEC[1] steel fibres of XOREX type, supplied by Ribbon Technology Corporation [6], were used as reinforcement. The fibres, which were 50 mm long and 0.9 mm equivalent diameter, had an aspect ratio of 57. The percentage of steel fibres in the concrete mix was 1.76% by mass. Superplasticizer, Mighty 150[1], and retarding admixtures, Master Builder 100 XR[1], were added to the mix to improve workability. Batch quantities of the concrete are given in Table 2. The 28-day cylinder compressive strengths were 43.2 and 41.2 MPa, respectively.

2.3 Fabrication

2.3.1 Steel Column

The hollow steel sections were fabricated by cutting the supplied sections to 3797 mm in length. Steel end plates were then welded to both section extremities, with special attention being given to the centering and perpendicularity of the end plates. The total column length was 3810 mm including end plates.

The hollow steel sections and end plates were first joined by a groove weld. Secondly, a fillet weld was added around the outside diameter of the hollow steel section. AWS 5.18 Type E705-6 welding rods were used for both welds. Figure 1 shows elevation and cross-sectional details of a typical column.

Before assembly, a hole was cut in each plate to provide an opening through which the concrete was poured. The hole was approximately 25 mm smaller in diameter than the inside diameter of the section. This construction provided a 13 mm lip to transfer the load from the steel plate to the concrete filling. The end plate connection detail is shown in Figure 2.

Five small holes were drilled in the wall of the steel sections (see Figure 1). Two pairs, 13 mm in diameter, located 457 mm from each end of the columns, were provided as vent holes for the water vapour produced during the experiment. The fifth hole, 25 mm in diameter, located near the top end plate, was used for entry of thermocouple wires.

2.3.2 Concrete Placement

The concrete was mixed in a truck mixer. The steel fibres were added to the fresh concrete and mixed for approximately 5 minutes to provide uniform dispersion. The columns were put in an upright position and filled with the concrete. A concrete placement bucket and a funnel were used to deposit the concrete in the steel column. An internal vibrator was used to consolidate the concrete inside the column. The top surface of the column was finished with a small trowel. The section was sealed at both ends with plastic sheet and tape to avoid possible moisture leaks. The columns were left upright for 28 days, then stored horizontally at room temperature, with no particular curing measures

[1]Certain commercial products are identified in this paper in order to adequately specify the experimental details. In no case does such identification imply recommendation or endorsement by the National Research Council of Canada, nor does it imply that the product or material identified is the best available for the purpose.

being taken, until the test date. In general, six months or more elapsed between the time a column was poured and the time it was tested. However, for Column C-66, the curing period was limited to four months.

Before each test, the moisture condition in the centre of a column section was measured by inserting a Vaisala[1] moisture sensor in a hole drilled in the concrete through one of the vent holes. In general, a moisture content, corresponding to approximately 85 to 95% relative humidity, was measured.

2.3.3 Instrumentation

Type K chromel-alumel thermocouples, with a thickness of 0.91 mm, were used for measuring concrete temperatures at several locations across the mid-height section of the columns. The thermocouples were tied to a steel rod that was secured to a bar running along the longitudinal axis of the column. The bar was fixed at both ends of the column as shown in Figure 3. In addition, a thermocouple was attached to the steel wall of each column at mid-height. The thermocouple locations are shown in Figure 4.

3. TEST APPARATUS

The tests were carried out by exposing the columns to heat in a furnace specially built for testing loaded columns and walls. The test furnace was designed to produce conditions to which a member might be exposed during a fire, i.e., temperatures, structural loads and heat transfer. It consisted of a steel framework supported by four steel columns, with the furnace chamber inside the framework (Figure 5). The characteristics and instrumentation of the furnace are described in detail in Reference [7]. Only a brief description of the furnace and the main components is given here.

3.1 Loading Device

A hydraulic jack with a capacity of 9778 kN produces a load along the axis of the test column. The jack is located at the bottom of the furnace chamber. Eccentric loads can be applied by means of hydraulic jacks, one at the top and one at the bottom of the column, located at a distance of 508 mm from the axis of the column. The capacity of the top jack is 587 kN and that of the bottom jack is 489 kN.

3.2 Furnace Chamber

The furnace chamber has a floor area of 2642 x 2642 mm and is 3048 mm high. The interior of the chamber is lined with insulating materials that efficiently transfer heat to the specimen. The ceiling and floor insulation protects the column end plates from fire. It should be noted that only 3200 mm of the column is exposed to fire.

There are 32 propane gas burners in the furnace chamber, arranged in eight columns containing four burners each. The total capacity of the burners is 4700 kW. Each burner can be adjusted individually, which allows for a high degree of temperature uniformity in the furnace chamber. The pressure in the furnace chamber is also adjustable and was set somewhat lower than atmospheric pressure.

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[1] ibid

3.3 Instrumentation

The furnace temperatures were measured with the aid of eight chromel-alumel thermocouples. The thermocouple junctions were located 305 mm from the test specimen, at various heights. Two thermocouples were placed opposite each other at intervals of 610 mm along the height of the furnace chamber. The locations of their junctions and their numbering are shown in Figure 6. Thermocouples 4 and 6 were located at a height of 610 mm from the floor, Thermocouples 2 and 8 at 1220 mm, Thermocouples 3 and 5 at 1830 mm and Thermocouples 1 and 7 at 2440 mm. The temperatures measured by the thermocouples were averaged automatically and the average temperature was used to control the furnace temperature.

The loads were controlled by servocontrollers and measured with pressure transducers. The accuracy of controlling and measuring loads is about 4 kN at lower load levels and relatively better at higher loads.

The axial deformation of the test columns was determined by measuring the displacement of the jack that supports the column. The rotation of the end plates of the columns was determined by measuring the displacement of the plates at a distance of 500 mm from the centre of the hinge at the top and bottom respectively. The displacements were measured using transducers with an accuracy of 0.002 mm.

4. TEST CONDITIONS AND PROCEDURES

4.1 End Conditions

Five columns were tested with both ends of the column fixed, i.e. restrained against rotation and horizontal translation. For this purpose, eight 19 mm diameter bolts spaced regularly around the column, were used at each end to bolt the end plate to the loading head at the top and the hydraulic jack at the bottom. Column C-52 was tested under hinged end conditions, i.e., with restraint against horizontal translation only. The hinged condition was obtained by bolting the end plates to the receiving plate with a roller bearing at each end.

4.2 Loading

All columns were tested under a concentric load, except Column C-52 where the load was eccentric by 25 mm. The applied load on the columns ranged from 32 to 67% of the factored compressive resistance of the columns (C_{rc}) or 70 to 120% of the factored compressive resistance of the concrete core (C'_r), determined according to CSA Standard CSA/CAN-S16.1-M89 [8]. The factored compressive resistances of each column, as well as the applied loads, are given in Table 1. The factored compressive resistances of the columns were calculated using the effective length factors, K, recommended in CSA/CAN-S16.1-M89 for the given end conditions, i.e., 0.65 for fixed ends and 1 for pinned ends.

All loads were applied approximately 45 minutes before the start of the test and were maintained until a condition was reached at which no further increase of the axial and rotational deformations could be measured. This condition was selected as the initial condition of the column deformations. The load was maintained constant throughout the test.

4.3 Fire Exposure

The ambient temperature at the start of each test was approximately 20°C. During the test, the column was exposed to heating controlled in such a way that the average temperature in the furnace followed, as closely as possible, the CAN/ULC-S101 [9] or ASTM-E119 [10] standard temperature-time curve. This curve can be calculated using the following equation:

$$T_f = 20 + 750\,[1 - \exp(-3.79533\sqrt{t})] + 170.41\sqrt{t}$$

where: t = time in hours
T_f = temperature of furnace in °C

4.4 Recording of Results

The furnace, concrete and steel temperatures, as well as axial deformations of the columns, were recorded at two-minute intervals. In the case of the eccentrically loaded column test, the lateral deflection of the column at mid-height and the rotation of the end plates of the column were measured with varying frequencies, depending on the rate of change of the measured quantities.

4.5 Failure Criterion

The columns were considered to have failed, and the tests were terminated, when the axial hydraulic jack, which has a maximum speed of 76 mm/min, could no longer maintain the load. Generally, the failure of the columns, which was determined by visual observation, was in compression. However, bending was observed for Column C-52 which had an eccentric loading. This column failed by buckling.

5. RESULTS AND DISCUSSION

The results of the six column tests are summarized in Table 1, in which the column characteristics, test conditions, fire resistances and failure modes are given for each column. The furnace, concrete and steel temperatures recorded during the tests, as well as the axial deformations of the column specimens, are given in Tables A1 to A6 and plotted in Figures A1 to A6, in Appendix A. Positive axial deformation values indicate expansion of the column. Figures B1 to B6 in Appendix B show photographs of the column specimens after the fire tests.

Data from the tests indicate that fire resistances up to three hours can be obtained for circular HSS columns filled with fibre reinforced concrete. In contrast, the fire resistance of HSS columns filled with plain concrete is limited to one to two hours [3]. The results for Column C52 also indicate that a high fire resistance can be obtained under eccentric loads. The fire resistance of Column C58 was only 65 minutes. This could be due to the high load intensity used for this particular column. The five columns, subjected to axial loading, failed in compression mode, while Column C-52, which was subjected to eccentric loading, failed in buckling mode.

The increased fire resistance of fibre-reinforced concrete-filled columns, as compared to plain concrete-filled columns [1], can be attributed to superior mechanical properties of fibre-reinforced concrete. Results from the experimental studies carried out to determine mechanical properties at elevated temperatures [11] indicate that the compressive strength of fibre-reinforced concrete increases with temperature up to about

400°C. The steel fibres prevented early cracking and also contributed to the compressive strength of concrete at elevated temperatures.

These fire tests were carried out in order to validate mathematical models capable of predicting the fire resistance of HSS columns filled with fibre-reinforced concrete. The development of such methods is currently in progress. The mathematical models will be used to conduct detailed parametric studies in order to determine the influence of various parameters on the fire resistance of HSS columns filled with fibre reinforced concrete. In the interim, the test results given in this report can be used for assessing the fire resistance of HSS columns filled with fibre-reinforced concrete that lie within the range of the variables examined in this study.

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Table 1. *Summary of test parameters and results*

Col. No.	Test Date	HSS Dimensions D x t (mm)	Concrete Strength (MPa) 28 day	Test day	Factored Resistance (kN) C'r	Crc	Test Load (kN) C	Load Intensity C/C'r	C/Crc	Failure Mode	Fire Resistance (min)
C-52	89/09/12	323.9 x 6.35	43.2	48.2		2446	780		0.32	B	165
C-54	89/07/05	355.6 x 6.35	43.2	48.9	2010	4127	1695	0.84	0.41	C	183
C-58	94/10/04	406.4 x 6.35	43.2	43.3	2663	5175	3200	1.20	0.67	C	65
C-65	92/02/11	323.9 x 6.35	41.2	57.0	1571	3446	1600	1.02	0.46	C	199
C-66	87/09/24	323.9 x 6.35	41.2	49.1	1571	3446	1200	0.76	0.35	C	182
C-67	87/11/30	355.6 x 6.35	41.2	53.5	1918	4035	1500	0.78	0.37	C	227

Factored Resistance

C'r = Factored compressive resistance of concrete core of the column according to CAN3-S16.1-M89

Crc = Factored compressive resistance of concrete-filled HSS column according to CAN3-S16.1-M89

Failure Mode

B = Buckling

C = Compression

Table 2. Batch quantities for concrete mix

	Pour No. 1 88/10/18	Pour No. 2 87/05/21
Cement (kg/m^3) (normal type)	439	439
Coarse aggregate (kg/m^3)		
19 mm	788	788
9.5 mm	340	340
Total	1128	1128
Fine aggregate (kg/m^3)	621	621
Steel fibres (kg/m^3)	42	42
Water (kg/m^3)	161	161
Water/cement ratio	0.37	0.37
Superplasticizer	Mighty 150	Mighty 150
Retarding admixture	Master Builder 100 XR	Master Builder 100 XR
28-day compressive strength (MPa)	43.2	41.2

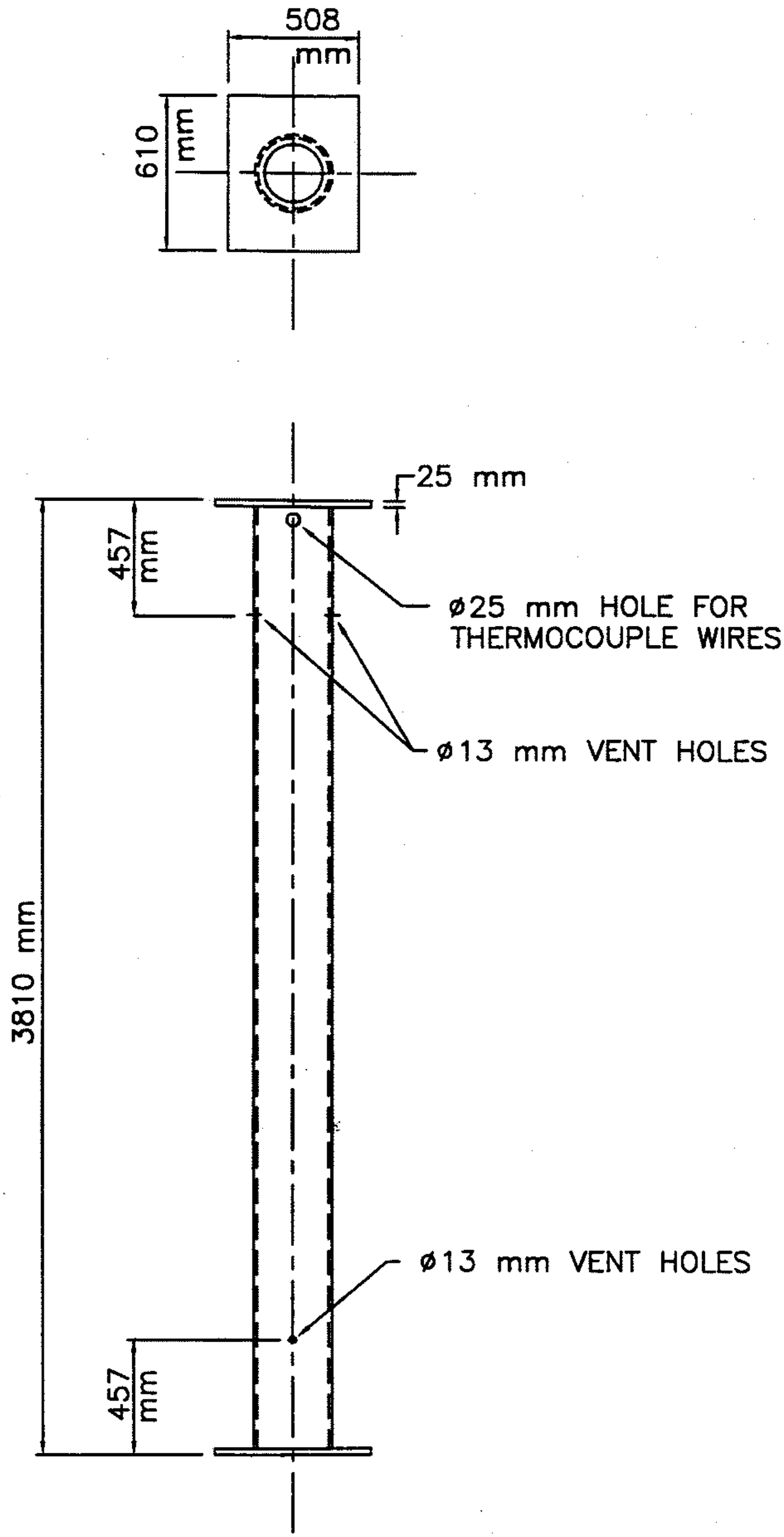


Figure 1. Elevation and cross-sectional details of a typical column

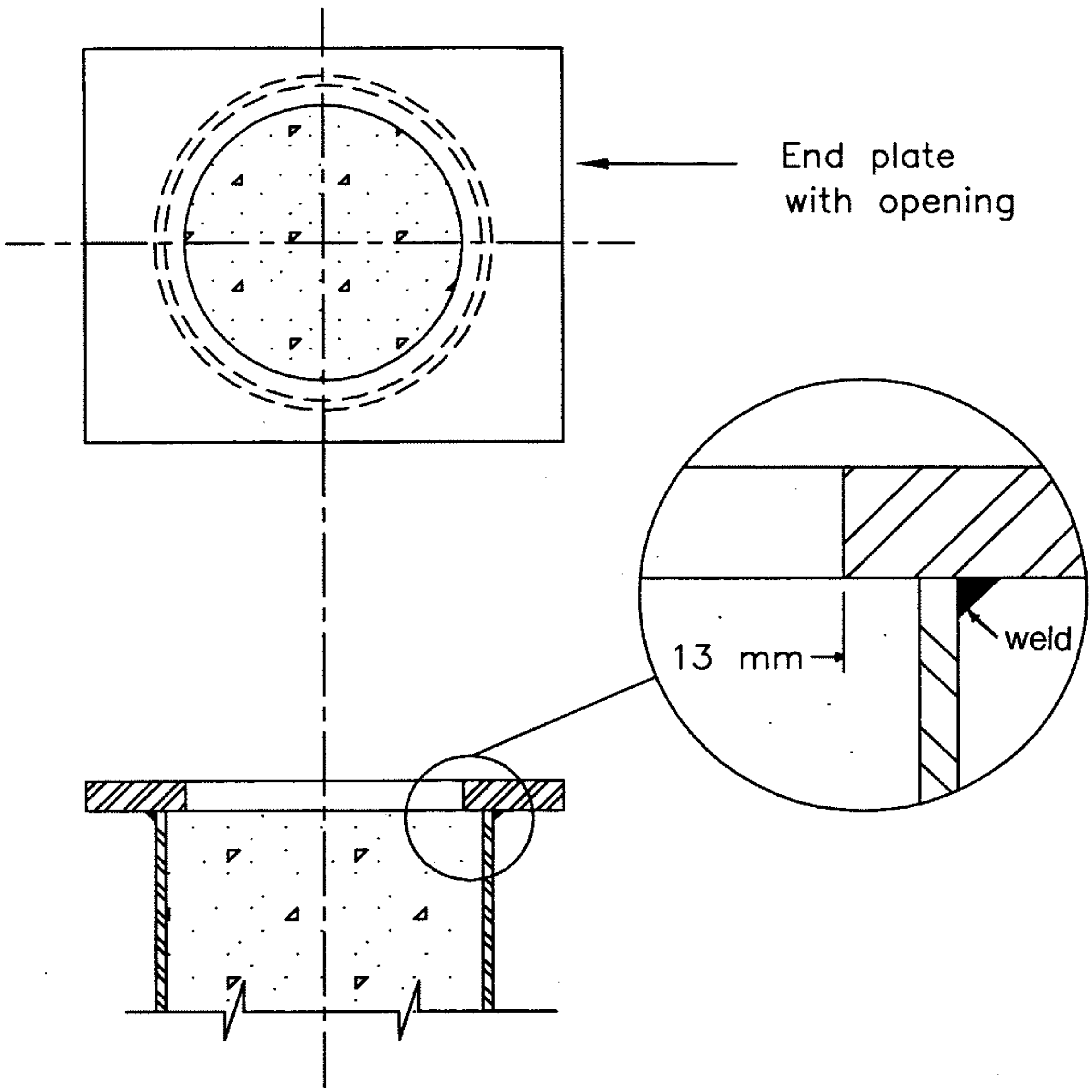


Figure 2. End plate connection details for columns

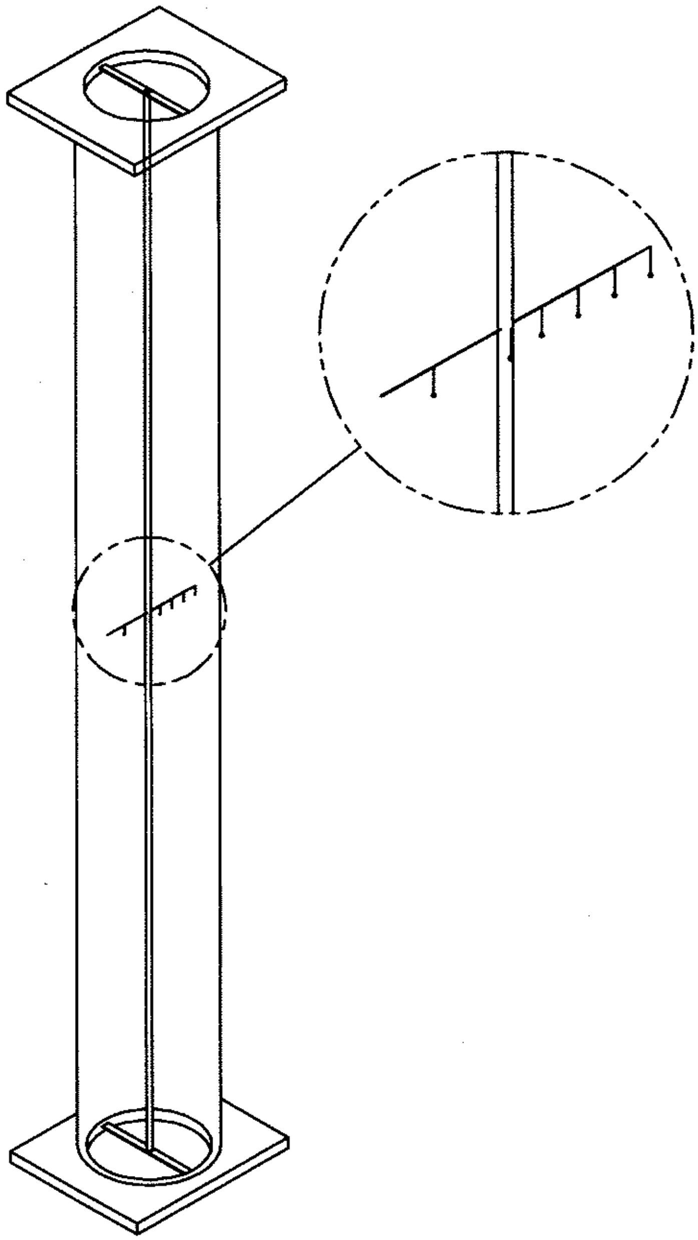


Figure 3. Layout of thermocouple frame in a column

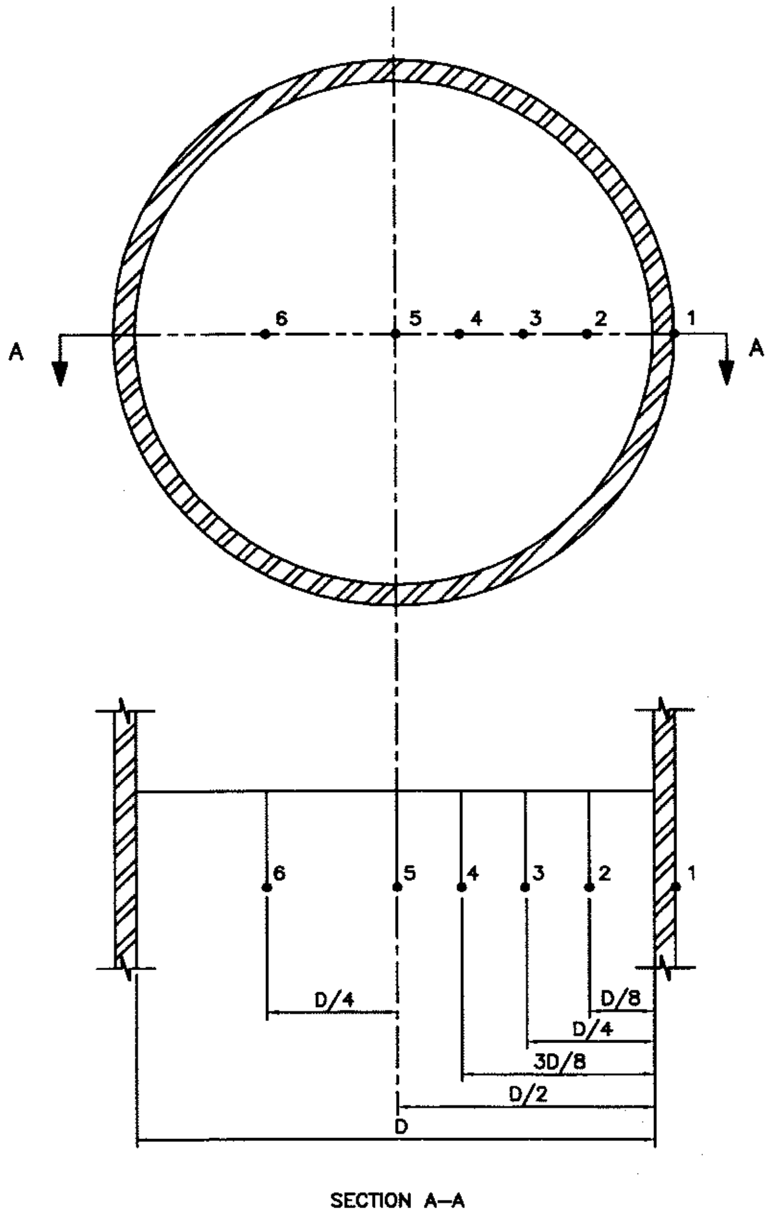


Figure 4. Location of thermocouples in a column

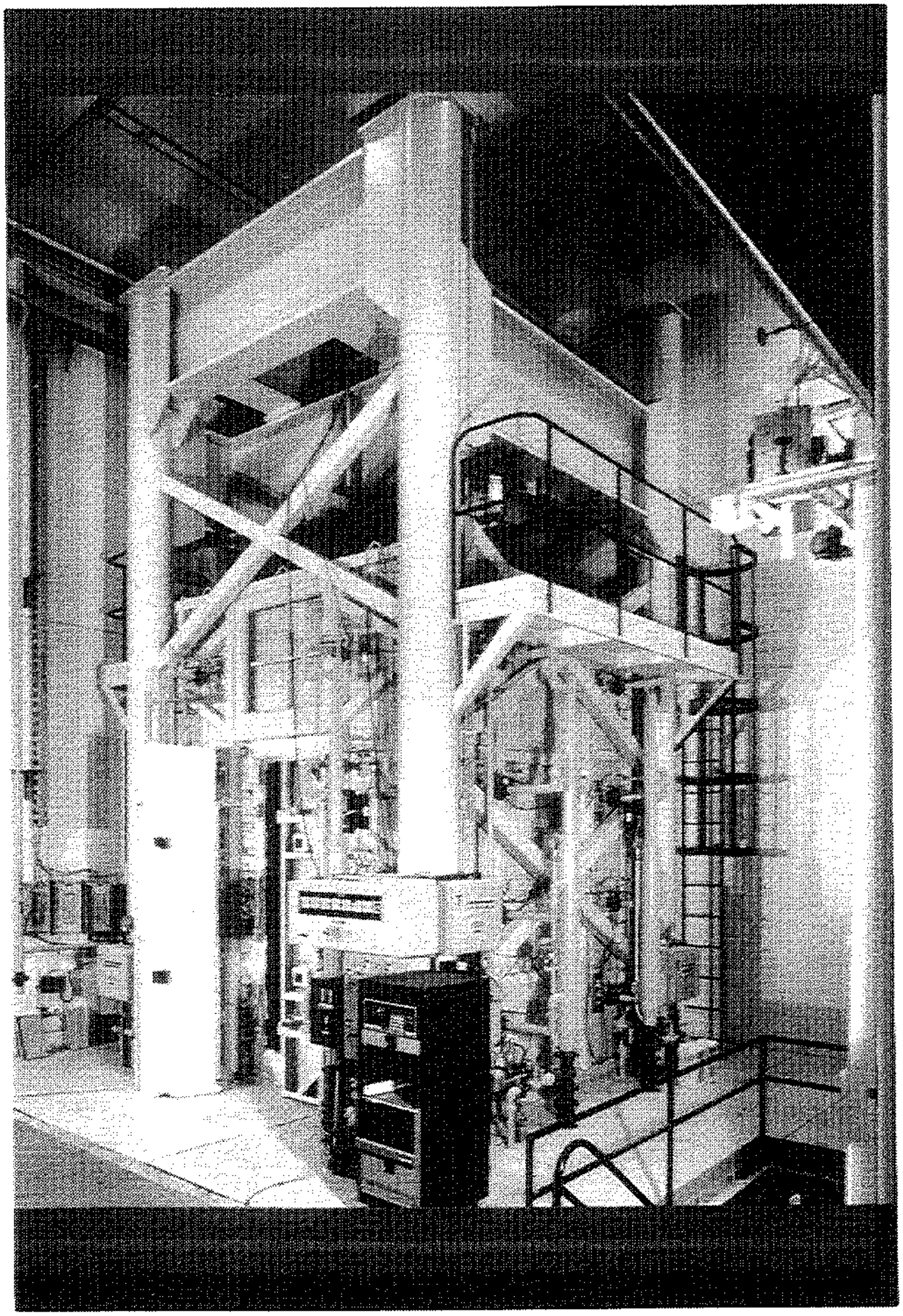


Figure 5. Column test furnace

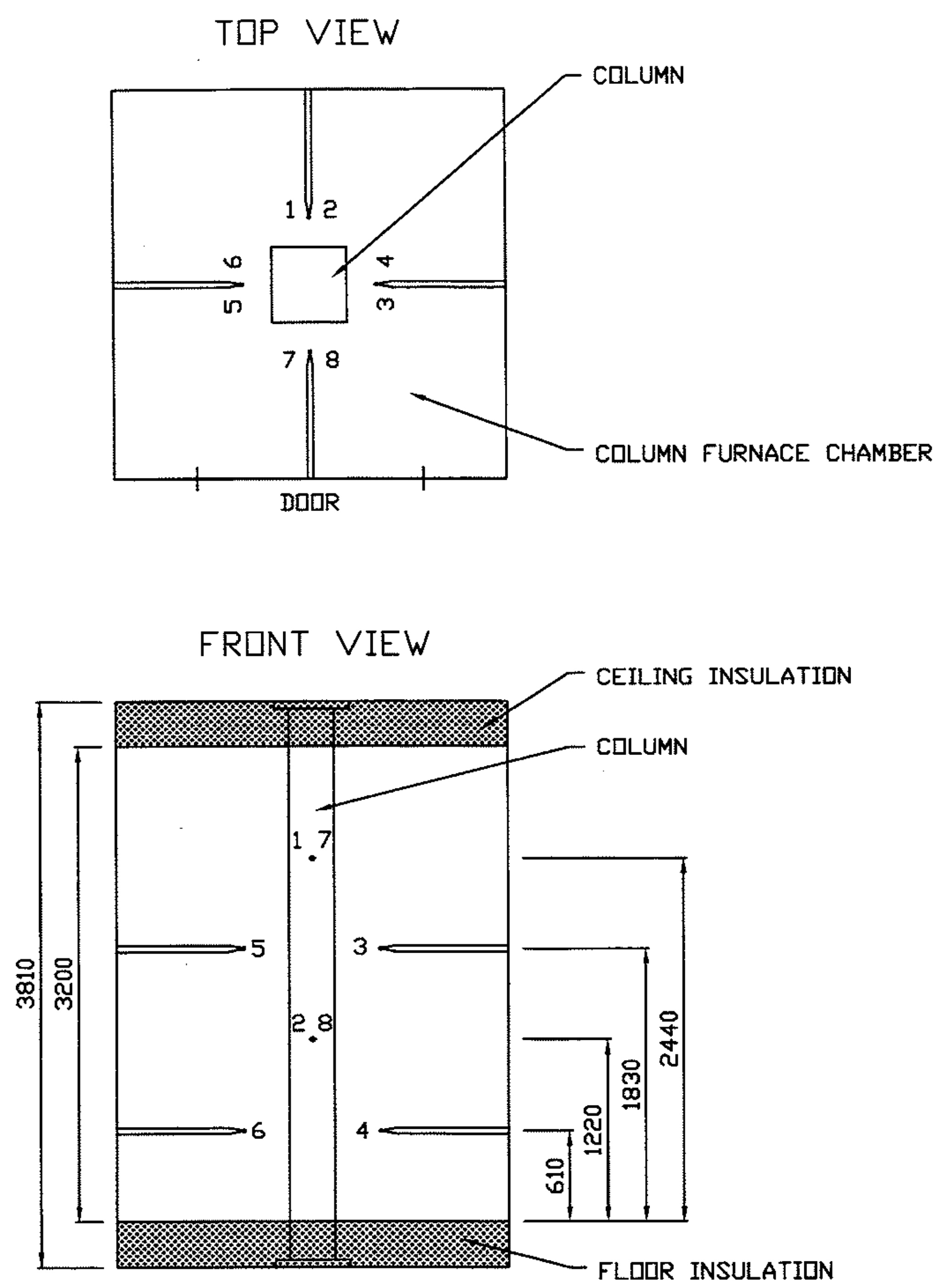


Figure 6. Location of thermocouples in furnace chamber

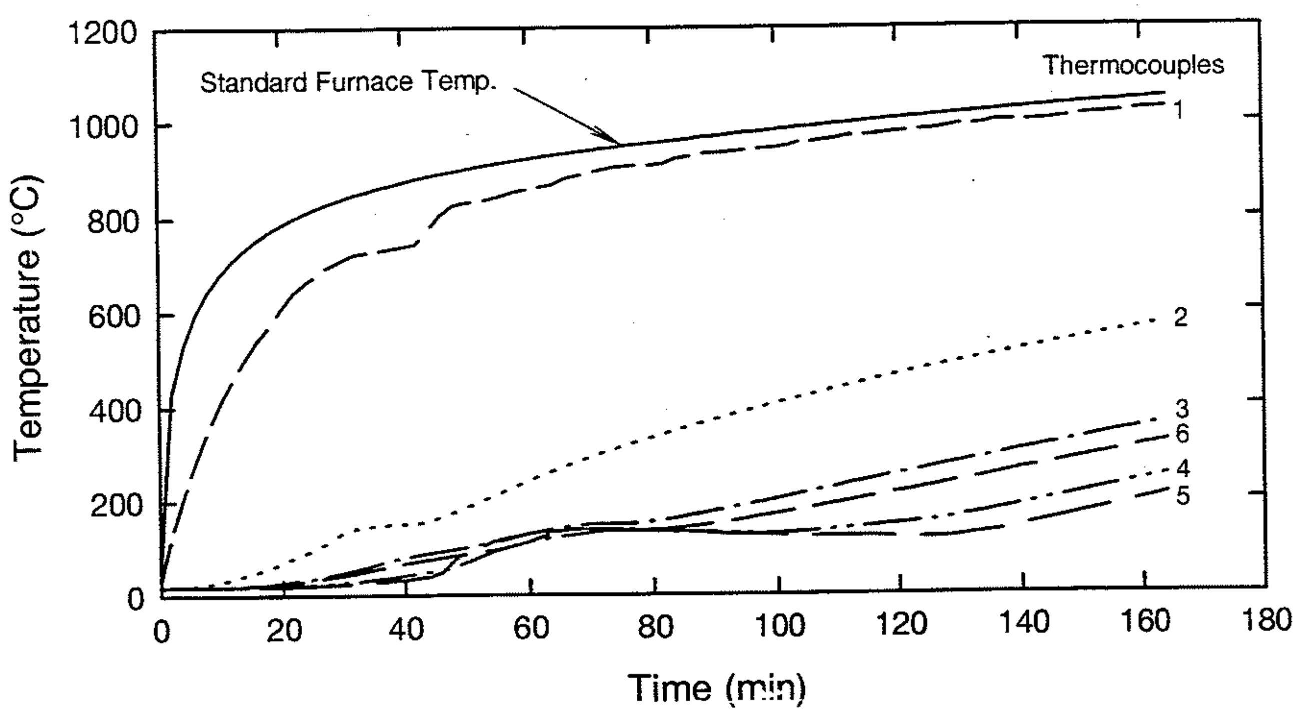
APPENDIX A

TEMPERATURES AND AXIAL DEFORMATIONS OF COLUMNS

Table A1 Temperatures and Axial Deformation of Column No. C-52

Time (min)	Std.Furn. Temp (°C)	Avg.Furn. Temp (°C)	Column Cross-section Temp. (°C) Measured at Thermocouple No. 1	2	3	4	5	6	Axial Def. (mm)
0	49	49	28	19	19	19	19	19	0.00
2	426	425	135	19	19	19	19	19	0.37
4	533	563	216	20	19	19	19	19	3.62
6	598	594	290	22	19	19	19	19	6.64
8	645	641	354	26	19	19	19	19	9.70
10	680	676	408	31	20	19	19	19	12.55
12	709	703	459	37	19	19	19	20	15.14
14	732	726	500	44	21	19	19	21	17.15
16	752	749	539	51	22	19	19	22	18.43
18	770	764	572	60	24	20	19	24	18.22
20	785	784	607	70	28	20	19	26	11.49
22	798	797	641	81	31	21	20	28	4.78
24	810	805	664	92	34	22	21	31	3.86
26	821	819	683	103	38	24	22	35	3.32
28	830	830	699	118	43	25	23	39	2.97
30	839	837	712	135	48	28	24	44	2.71
32	848	844	722	142	54	30	25	48	2.40
34	855	854	728	146	61	32	27	53	2.02
36	862	674	682	148	68	35	29	58	1.45
38	869	712	627	150	74	38	31	63	0.77
40	875	857	694	151	80	41	33	67	0.87
42	881	890	744	152	85	45	36	72	0.97
44	887	908	773	157	90	49	39	76	0.92
46	892	917	805	166	93	53	49	80	0.78
48	897	924	826	176	97	59	76	83	0.67
50	902	909	832	186	102	70	90	87	0.56
52	907	908	835	197	107	81	99	91	0.49
54	911	910	840	209	113	92	114	95	0.44
56	916	914	847	220	118	100	121	100	0.42
58	920	919	855	232	124	107	125	106	0.42
60	924	921	860	243	130	113	132	113	0.42
64	931	927	871	264	140	122	135	132	0.32
68	938	940	889	283	147	129	137	140	0.26
72	945	947	901	301	150	135	137	140	0.10
76	951	950	909	318	151	139	137	138	-0.09
80	957	946	910	335	156	137	135	137	-0.33
84	963	966	925	350	164	135	133	142	-0.47
88	969	973	934	365	173	133	131	147	-0.66
92	974	973	938	379	183	131	129	155	-0.88
96	979	976	942	393	193	129	127	163	-1.10
100	984	978	947	406	203	130	125	171	-1.32
104	989	991	958	419	213	132	124	180	-1.51
108	994	993	962	431	224	136	123	189	-1.75
112	999	1000	970	443	234	140	122	198	-1.98
116	1003	1002	974	455	245	145	123	207	-2.24
120	1008	1005	979	466	255	149	120	217	-2.50
128	1016	1014	988	488	275	160	120	235	-3.14
136	1024	1027	1002	508	295	178	133	254	-3.77
144	1032	1030	1003	527	314	198	154	274	-4.65
152	1039	1038	1015	546	334	219	176	293	-5.85
160	1047	1047	1025	564	353	240	199	313	-7.58
164	1050	1048	1028	574	363	251	210	323	-9.20

Note: The test was terminated at 2 hours and 45 minutes



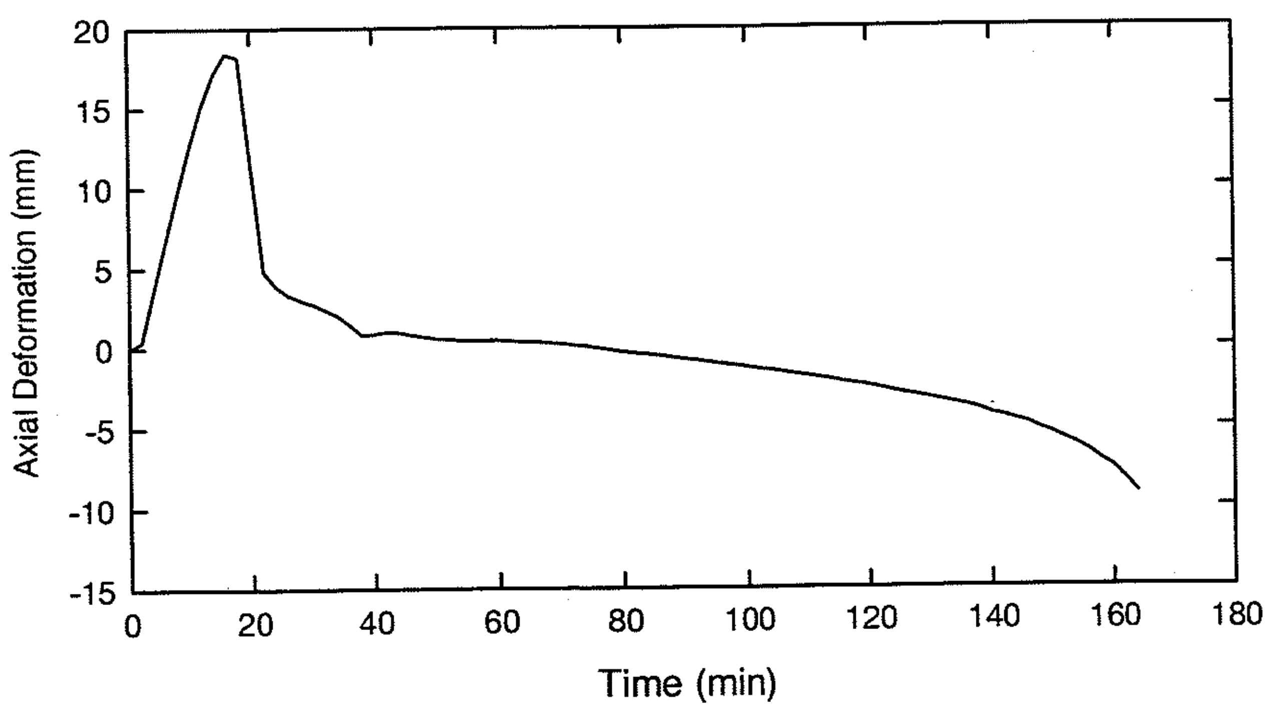
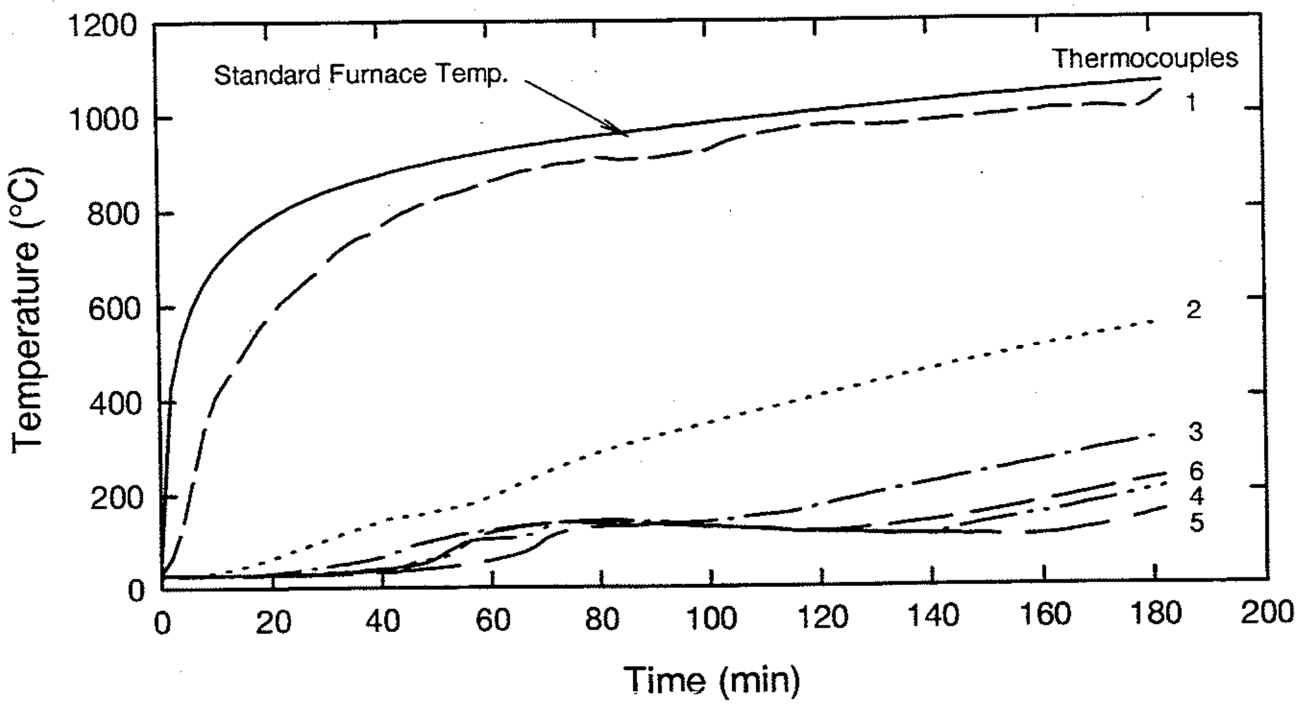


Figure A1. Temperatures and axial deformation of Column No. C-52

TABLE A2 Temperatures and Axial Deformation of Column No. C-54

Time (min)	Std.Furn. Temp (°C)	Avg.Furn. Temp (°C)	Column Cross-section Temp.(°C) Measured at Thermocouple No. 1	2	3	4	5	6	Axial Def. (mm)
0	49	49	30	27	28	28	28	28	0.00
2	426	243	67	27	28	28	28	28	0.00
4	533	472	136	28	28	28	28	28	0.54
6	598	657	243	29	28	28	28	28	3.64
8	645	671	343	31	27	28	28	27	7.33
10	680	677	404	34	28	28	28	27	9.55
12	709	699	444	39	28	28	28	27	10.64
14	732	727	480	44	28	28	28	27	10.74
16	752	749	515	50	29	28	28	27	4.42
18	770	768	552	57	30	28	28	28	3.08
20	785	781	581	64	32	28	28	28	2.40
22	798	798	608	72	34	29	28	28	1.89
24	810	807	626	80	36	29	28	29	1.50
26	821	821	647	88	39	31	28	29	1.19
28	830	829	665	96	42	32	28	30	0.77
30	839	836	688	104	46	33	29	31	0.33
32	848	848	710	112	50	34	29	32	-0.04
34	855	855	729	120	53	36	30	34	-0.41
36	862	861	743	128	57	38	31	35	-0.74
38	869	866	751	136	61	39	32	37	-1.04
40	875	875	766	143	66	40	33	39	-1.33
42	881	880	781	149	74	43	35	41	-1.60
44	887	887	794	153	83	46	36	43	-1.85
46	892	891	804	155	92	54	38	48	-2.08
48	897	896	814	159	97	58	40	53	-2.30
50	902	902	822	163	103	62	42	62	-2.52
52	907	907	831	169	109	68	45	77	-2.74
54	911	906	837	173	113	84	48	91	-2.96
56	916	914	845	179	117	101	51	102	-3.17
58	920	919	853	186	121	104	55	112	-3.37
60	924	924	861	195	124	104	59	119	-3.58
64	931	930	875	214	129	107	69	128	-3.98
68	938	937	887	235	135	117	88	134	-4.40
72	945	945	897	254	139	140	116	138	-4.88
76	951	951	901	272	142	138	125	140	-5.43
80	957	955	912	287	143	136	130	140	-5.94
84	963	951	906	302	143	138	131	139	-6.54
88	969	957	909	314	141	137	134	137	-7.10
92	974	959	914	326	138	134	134	135	-7.66
96	979	965	920	338	138	132	132	132	-8.24
100	984	969	926	349	141	128	129	129	-8.84
104	989	988	946	360	145	125	127	127	-9.40
108	994	995	958	372	151	123	124	124	-10.04
112	999	1005	966	383	156	120	123	121	-10.67
116	1003	1020	975	394	163	118	119	119	-11.33
120	1008	1021	977	405	173	116	117	119	-12.00
128	1016	1014	977	428	194	113	114	124	-13.37
136	1024	1025	981	449	212	111	111	134	-14.68
144	1032	1028	989	469	230	121	109	146	-16.06
152	1039	1035	998	489	247	139	107	161	-17.54
160	1047	1052	1007	508	265	154	108	178	-19.25
168	1054	1048	1011	525	284	173	120	197	-21.40
176	1061	1056	1010	542	302	192	139	215	-24.30
182	1066	1088	1043	554	316	208	159	215	-27.88

Note: The test was terminated at 3 hours and 2 minutes



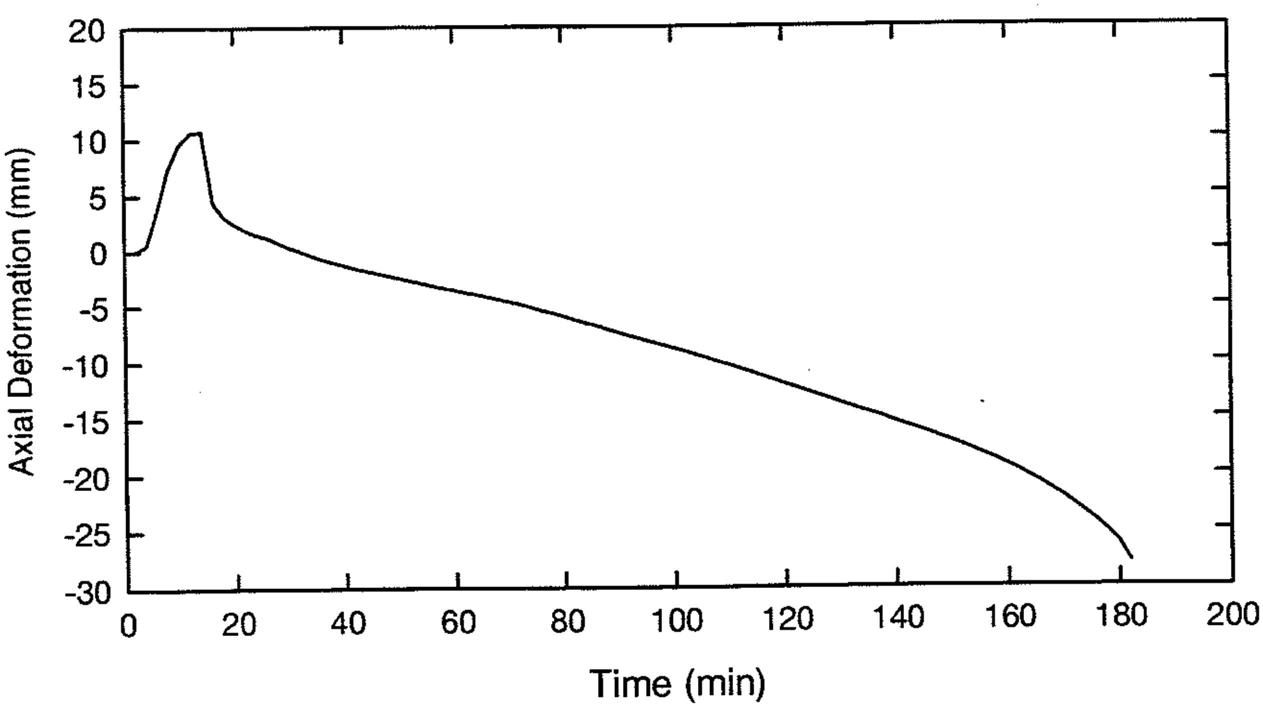
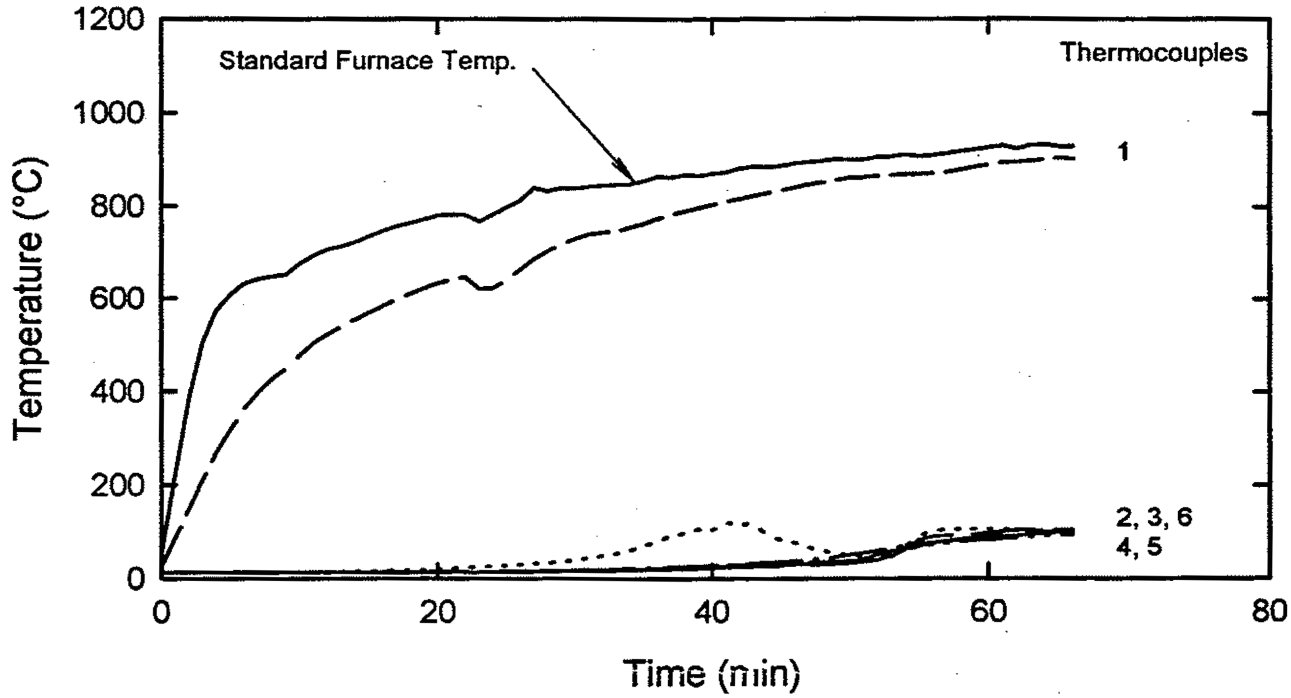


Figure A2. Temperatures and axial deformation of Column No. C-54

Table A3 Temperatures and Axial Deformation of Column No. C-58

Time (min)	Std.Furn. Temp (°C)	Avg.Furn. Temp (°C)	Column Cross-section Temp. (°C) Measured at Thermocouple No. 1	2	3	4	5	6	Axial Def. (mm)
0	51	49	25	14	14	14	15	15	0.00
2	387	384	149	14	14	14	14	14	0.59
4	572	570	269	14	14	14	14	14	0.78
6	632	633	362	14	14	14	14	14	0.79
8	647	647	425	14	14	14	14	14	0.79
10	676	675	477	15	14	14	14	15	0.79
12	707	706	522	15	14	14	14	15	0.73
14	724	723	554	16	14	14	14	15	0.51
16	748	747	583	18	14	14	15	15	0.24
18	763	763	611	19	15	15	15	15	-0.06
20	780	778	633	21	15	15	15	15	-0.36
22	781	781	647	24	15	15	15	16	-0.60
24	783	782	623	27	16	15	16	16	-0.77
26	812	811	664	31	17	16	16	17	-0.97
28	832	834	705	35	18	17	17	18	-1.24
30	838	839	732	41	19	18	17	19	-1.49
32	845	844	745	50	21	19	18	20	-1.75
34	848	847	755	61	22	20	19	22	-2.06
36	864	863	775	80	24	21	21	23	-2.35
38	868	867	792	98	26	22	22	26	-2.61
40	870	869	805	105	28	24	24	28	-2.85
42	881	880	817	116	32	26	26	30	-3.09
44	884	882	829	94	35	28	28	32	-3.34
46	892	891	841	78	38	31	30	34	-3.58
48	897	895	852	60	43	33	31	36	-3.83
50	901	900	861	51	50	38	34	38	-4.07
52	906	905	866	52	61	51	41	43	-4.31
54	911	910	869	70	71	64	60	63	-4.57
56	910	909	871	103	78	73	77	90	-4.87
58	918	917	879	106	84	79	85	95	-5.17
60	926	925	889	106	89	84	91	98	-5.53
62	923	923	895	105	93	88	97	105	-6.03
64	933	932	902	104	98	92	100	105	-6.76
66	928	927	902	105	102	95	101	105	-40.83



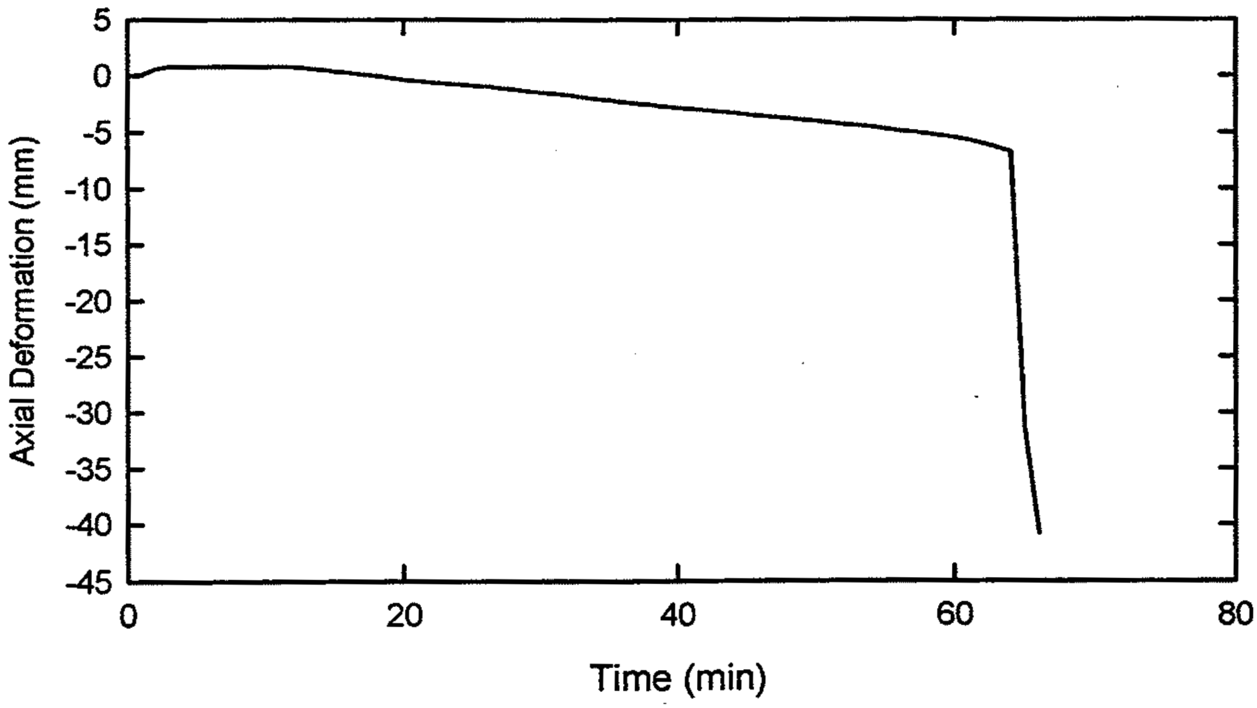


Figure A3. Temperatures and axial deformation of Column No. C-58

TABLE A4 Temperatures and Axial Deformation of Column No. C-65

Time (min)	Std.Furn. Temp (°C)	Avg.Furn. Temp (°C)	Column Cross-section Temp.(°C) Measured at Thermocouple No. 1	2	3	4	5	6	Axial Def. (mm)
0	49	49	27	19	19	19	19	19	0.0
2	426	462	137	19	19	19	19	19	1.0
4	533	526	200	19	19	19	19	19	3.3
6	598	615	298	19	19	19	19	19	4.6
8	645	652	373	20	19	19	20	19	5.2
10	680	687	429	21	19	19	20	20	5.3
12	709	706	455	22	20	19	20	20	4.4
14	732	728	492	24	20	19	20	20	3.2
16	752	743	533	26	20	19	20	21	2.2
18	770	760	559	29	21	20	20	22	1.5
20	785	782	584	33	22	20	20	24	1.0
22	798	793	616	37	23	20	20	26	0.7
24	810	802	642	42	25	21	21	29	0.4
26	821	810	664	47	27	22	22	33	0.2
28	830	833	684	52	29	23	23	38	0.0
30	839	842	700	57	32	24	25	42	-0.2
32	848	850	715	63	34	26	26	47	-0.4
34	855	845	726	69	37	28	28	50	-0.7
36	862	867	740	74	40	30	30	53	-1.0
38	869	872	745	80	44	33	33	56	-1.2
40	875	869	755	87	48	35	35	61	-1.4
42	881	879	766	94	52	38	38	65	-1.6
44	887	889	778	102	56	42	42	70	-1.8
46	892	897	788	110	61	45	45	75	-2.0
48	897	900	797	118	67	49	***	***	-2.3
50	902	905	806	125	72	53	***	***	-2.5
52	907	907	813	***	77	***	***	***	-2.7
54	911	909	820	***	83	***	***	***	-2.9
56	916	915	827	***	***	***	***	***	-3.0
58	920	915	832	***	***	***	***	***	-3.2
60	924	919	839	***	***	***	***	***	-3.4
64	931	934	855	***	***	***	***	***	-3.8
68	938	***	***	130	91	61	52	79	-4.2
72	945	***	***	137	101	74	70	85	-4.7
76	951	952	884	170	144	131	138	125	-5.2
80	957	954	893	177	143	141	140	140	-5.7
84	963	957	900	186	141	141	141	140	-6.3
88	969	967	908	197	139	139	141	139	-6.8
92	974	965	909	206	137	136	136	137	-7.4
96	979	974	912	218	139	134	134	137	-7.9
100	984	988	917	231	143	132	132	141	-8.5
104	989	983	919	242	148	130	130	146	-9.0
108	994	994	926	253	152	128	128	151	-9.6
112	999	994	929	263	158	126	126	159	-10.1
116	1003	995	934	273	166	124	126	167	-10.7
120	1008	1008	943	283	174	124	126	176	-11.2
128	1016	***	***	306	***	***	***	***	-12.4
136	1024	1025	964	323	204	134	133	217	-13.6
144	1032	1034	976	342	220	137	137	242	-15.0
152	1039	***	***	***	***	***	***	***	-16.4
160	1047	1047	995	***	256	158	171	***	-18.0
168	1054	1043	1001	***	278	189	200	***	-19.9
176	1061	***	***	***	302	204	214	***	-22.1
184	1067	1064	1018	***	321	245	251	***	-24.9
192	1074	1073	1029	***	341	266	273	***	-28.6
196	1077	1062	1030	461	351	276	284	***	-31.1

*** Measurements not reliable

Note: The test was terminated at 3 hours and 19 minutes

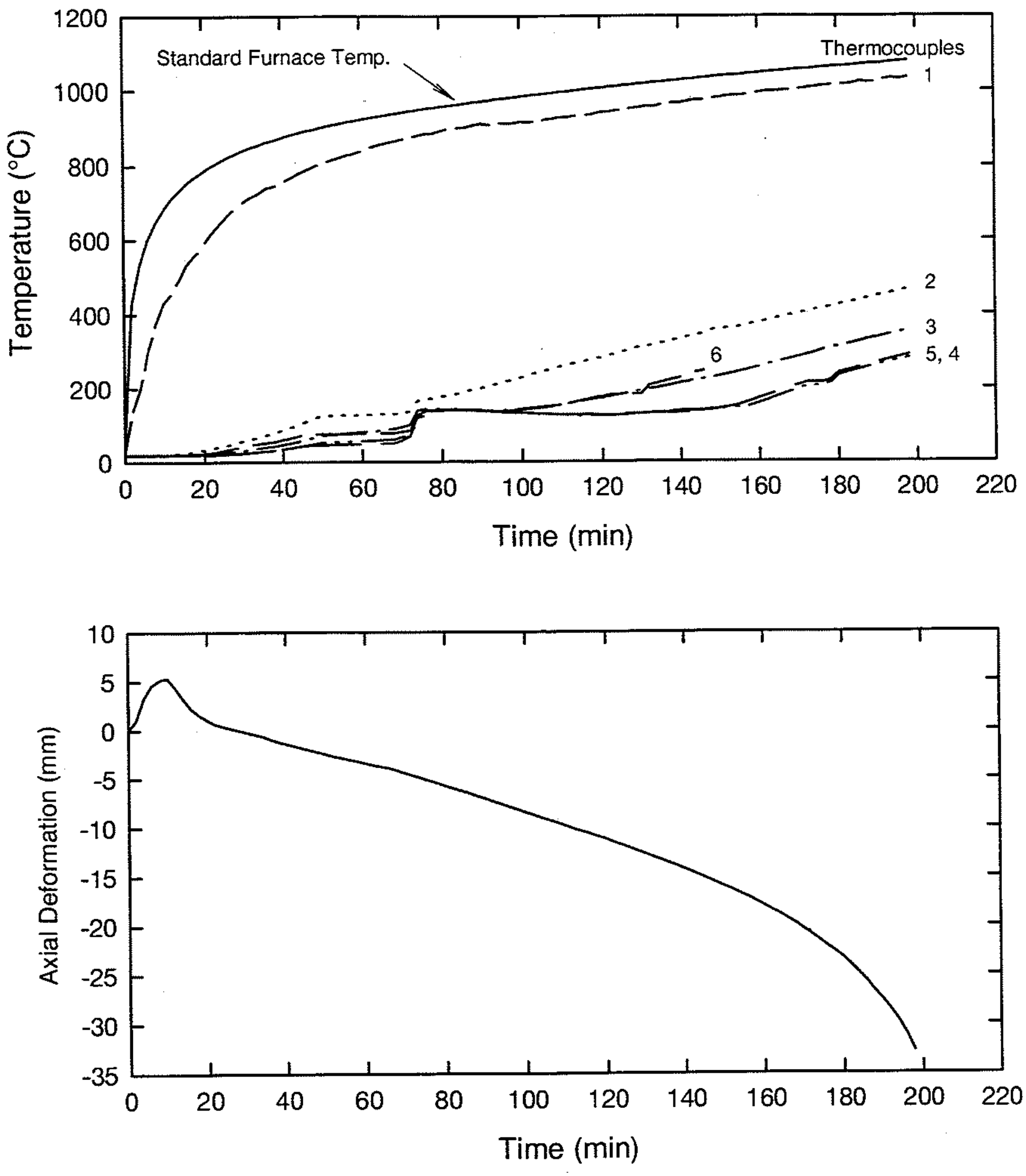


Figure A4. Temperatures and axial deformation of Column No. C-65

TABLE A5 Temperatures and Axial Deformation of Column No. C-66

Time (min)	Std.Furn. Temp (°C)	Avg.Furn. Temp. (°C)	Column Cross-section Temp.(°C) Measured at Thermocouple No. 1	2	3	4	5	6	Axial Def. (mm)
0	49	46	25	14	14	14	14	14	0.00
2	426	399	150	15	14	14	14	14	0.54
4	533	488	189	15	14	13	14	14	1.97
6	598	609	286	13	14	13	13	13	5.02
8	645	649	361	14	14	14	14	13	8.23
10	680	679	411	14	15	14	14	15	11.15
12	709	705	440	16	16	15	15	14	13.33
14	732	726	488	17	16	15	15	15	14.19
16	752	745	539	18	15	13	13	14	15.66
18	770	765	585	22	17	15	15	15	17.82
20	785	781	617	24	18	14	14	16	18.46
22	798	800	650	28	19	15	15	17	17.94
24	810	811	675	33	22	16	15	18	18.61
26	821	821	695	40	26	18	17	20	17.90
28	830	829	712	52	32	23	20	22	15.48
30	839	837	730	65	42	35	27	29	12.20
32	848	845	742	76	57	64	44	39	11.04
34	855	855	755	84	77	89	63	51	10.46
36	862	858	761	92	94	98	76	61	9.80
38	869	868	773	101	108	123	83	71	9.27
40	875	875	786	108	118	129	86	80	8.98
42	881	882	801	116	125	133	103	87	8.74
44	887	885	809	123	132	138	114	94	8.59
46	892	891	821	130	137	135	133	100	8.47
48	897	896	830	136	142	141	138	106	8.37
50	902	904	840	141	148	145	143	112	8.30
52	907	908	846	146	166	150	147	118	8.25
54	911	911	858	152	167	153	150	124	8.25
56	916	917	866	156	176	155	154	129	8.24
58	920	920	870	161	186	157	157	134	8.24
60	924	924	874	163	194	158	159	138	8.24
64	931	931	888	167	203	160	161	145	8.24
68	938	937	895	171	208	159	160	153	7.88
72	945	946	906	178	157	160	161	159	4.39
76	951	950	910	183	160	158	158	164	1.66
80	957	956	918	193	158	155	154	163	0.75
84	963	963	929	207	159	153	151	164	0.00
88	969	968	936	222	162	149	148	163	-0.66
92	974	972	941	233	166	147	145	163	-1.30
96	979	979	947	246	173	143	141	162	-1.91
100	984	982	954	258	182	141	139	163	-2.48
104	989	988	959	270	194	142	136	168	-3.06
108	994	994	965	282	205	145	134	175	-3.62
112	999	994	970	293	217	151	131	186	-4.20
116	1003	1001	976	304	227	159	130	195	-4.77
120	1008	1007	982	317	239	168	128	207	-5.35
128	1016	1013	993	338	260	176	125	228	-6.57
136	1024	1025	1005	359	279	194	159	249	-7.86
144	1032	1032	1013	379	299	222	197	271	-9.29
152	1039	1039	1020	400	319	249	229	294	-10.96
160	1047	1043	1025	420	340	274	255	316	-12.96
168	1054	1059	1046	441	360	298	279	337	-15.28
176	1061	1062	1045	458	379	318	300	357	-18.16
182	1066	1062	1028	472	393	333	315	371	-20.78

Note: Test was terminated at 3 hours and 2 minutes

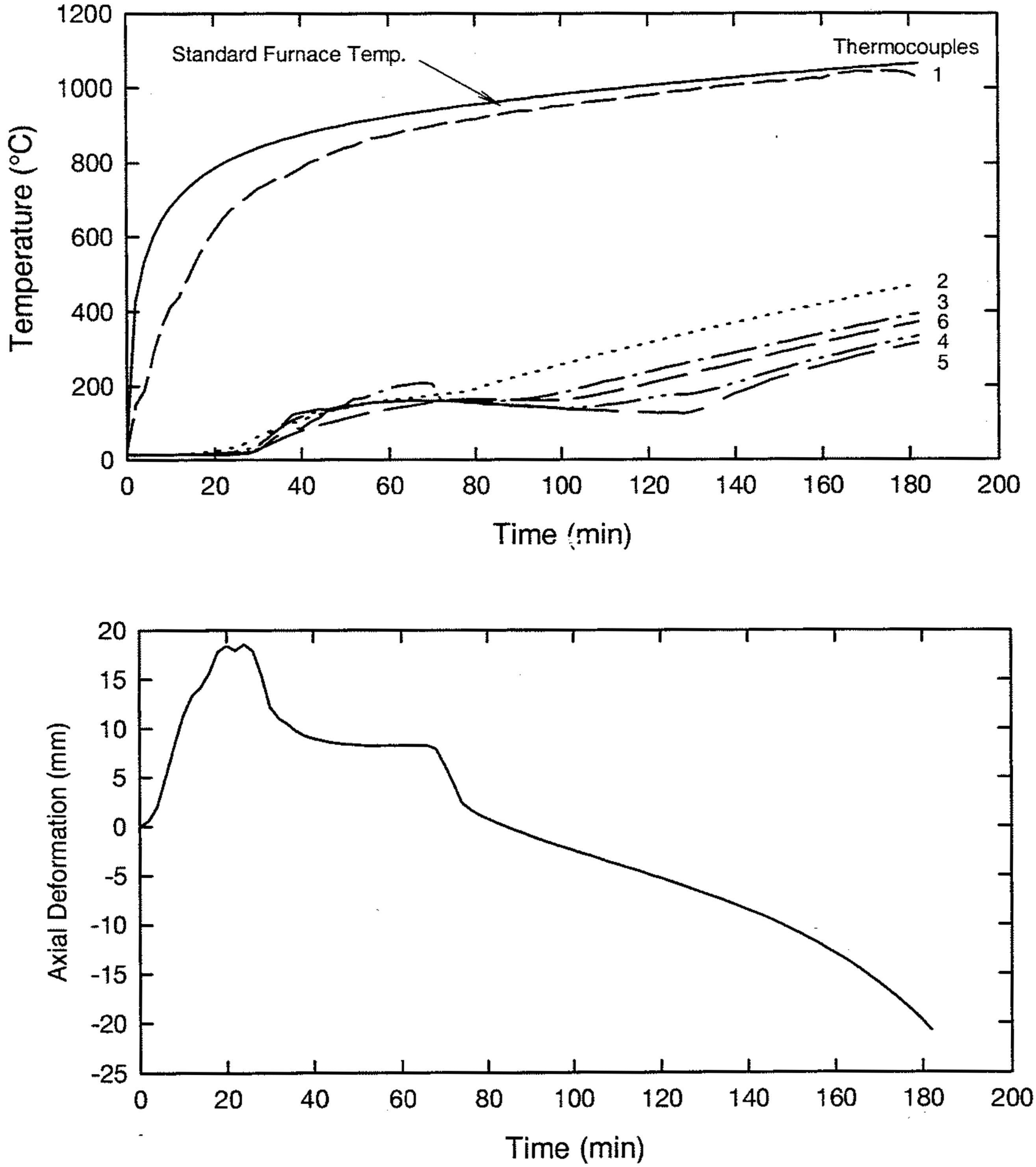


Figure A5. Temperatures and axial deformation of Column No. C-66

TABLE A6 Temperatures and Axial Deformation of Column No. C-67

Time (min)	Std.Furn. Temp (°C)	Avg.Furn. Temp (°C)	Column Cross-section Temperature Measured at Thermocouple No. 1	2	3	4	5	6	Axial Def. (mm)
0	49	52	28	22	22	22	24	23	0.00
2	426	384	104	23	23	21	23	23	0.42
4	533	556	181	23	24	21	21	24	1.96
6	598	635	265	22	23	22	21	23	5.57
8	645	645	332	23	23	21	21	23	8.53
10	680	672	388	23	22	23	21	22	10.88
12	709	701	440	27	24	21	21	24	12.82
14	732	718	481	27	22	23	21	24	13.88
16	752	741	515	31	24	21	23	24	13.91
18	770	771	545	35	24	23	23	26	6.26
20	785	797	581	39	26	21	24	28	3.55
22	798	815	613	43	26	23	21	31	2.39
24	810	820	637	50	28	26	22	35	1.76
26	821	827	649	56	30	24	23	37	1.43
28	830	833	675	64	31	22	21	39	1.17
30	839	840	702	84	37	25	25	43	0.94
32	848	854	722	104	42	30	29	50	0.70
34	855	858	735	117	43	27	25	52	0.43
36	862	865	744	124	50	31	28	61	0.17
38	869	871	755	135	61	34	31	70	-0.04
40	875	874	765	140	69	33	30	80	-0.20
42	881	883	780	143	77	38	34	89	-0.39
44	887	896	791	147	81	39	33	95	-0.53
46	892	895	801	155	91	44	37	103	-0.66
48	897	901	809	156	98	47	39	111	-0.79
50	902	906	817	157	105	49	41	121	-0.90
52	907	910	826	159	113	53	46	130	-0.98
54	911	913	832	160	127	57	49	134	-1.07
56	916	921	840	158	128	62	51	144	-1.20
58	920	924	845	155	119	66	54	148	-1.32
60	924	924	852	153	132	72	62	152	-1.45
64	931	929	864	152	139	94	121	148	-1.70
68	938	940	875	154	147	117	129	148	-1.95
72	945	948	886	155	151	131	130	152	-2.21
76	951	952	897	162	154	142	148	154	-2.56
80	957	957	905	174	154	149	154	156	-2.88
84	963	965	914	189	154	154	156	160	-3.23
88	969	970	922	206	152	152	152	166	-3.61
92	974	976	930	219	151	150	149	171	-3.99
96	979	981	935	235	150	149	149	180	-4.37
100	984	984	943	248	152	147	147	190	-4.75
104	989	989	947	259	154	143	143	197	-5.13
108	994	992	954	271	160	143	142	208	-5.49
112	999	998	961	281	166	143	140	216	-5.87
116	1003	1002	964	291	172	138	138	222	-6.25
120	1008	1007	972	303	181	139	135	231	-6.60
128	1016	1020	991	322	194	143	131	246	-7.37
136	1024	1023	993	341	213	146	129	267	-8.17
144	1032	1035	1009	362	229	156	126	287	-8.94
152	1039	1039	1015	381	248	166	124	305	-9.80
160	1047	1050	1025	403	264	183	122	324	-10.68
168	1054	1056	1034	421	280	203	137	344	-11.64
176	1061	1062	1038	439	299	223	179	362	-12.68
184	1067	1071	1050	458	322	245	215	383	-13.89
192	1074	1073	1057	475	338	266	238	401	-15.31
200	1080	1084	1061	492	354	284	258	422	-16.96
208	1087	1088	1066	510	370	305	278	440	-18.89
216	1093	1093	1079	526	386	323	297	456	-21.37
224	1099	1099	1090	542	401	337	315	471	-24.94

Note: Test was terminated at 3 hours and 47 minutes

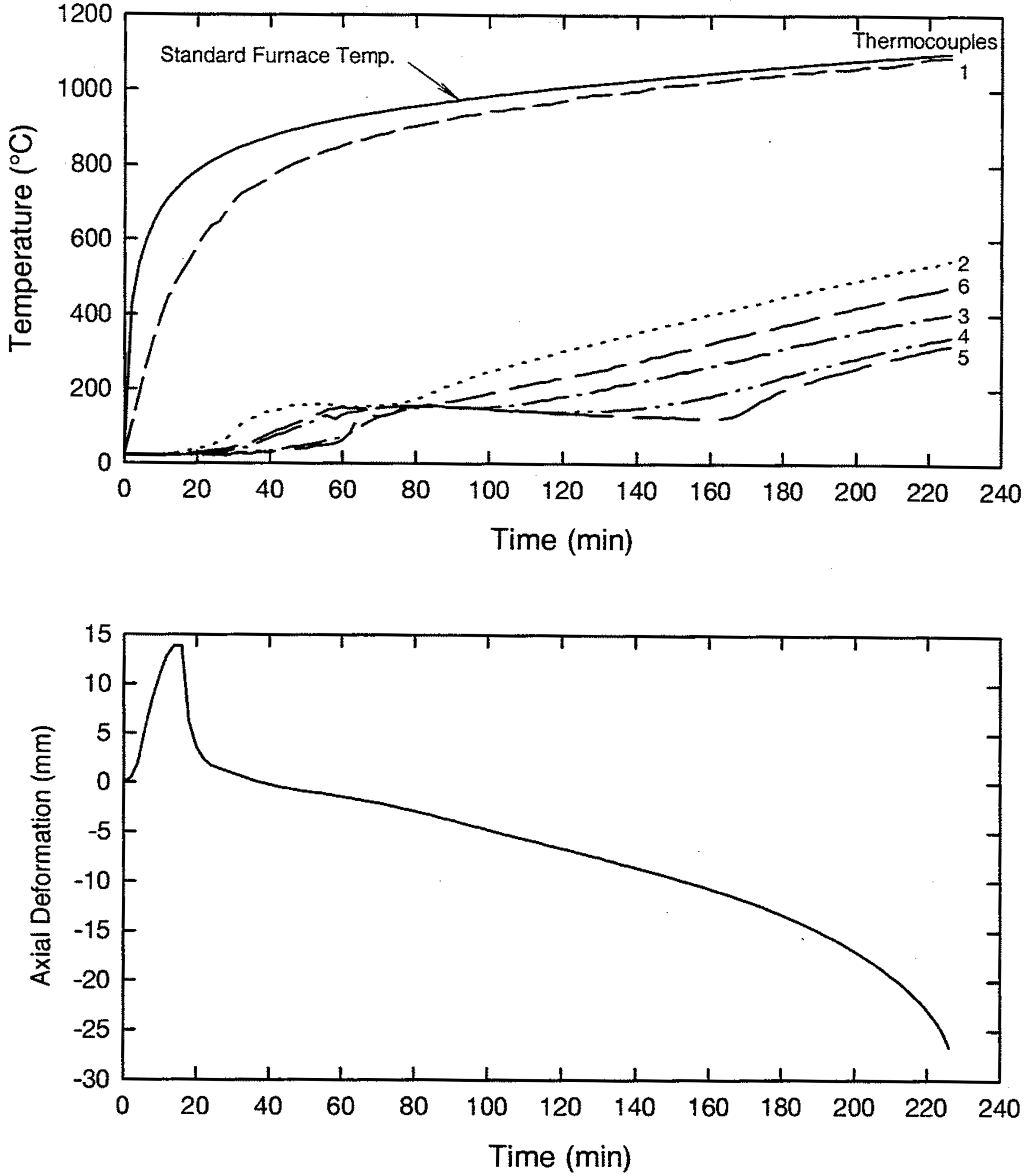


Figure A6. Temperatures and axial deformation of Column No. C-67

APPENDIX B

VIEW OF COLUMN SPECIMENS AFTER FIRE TEST

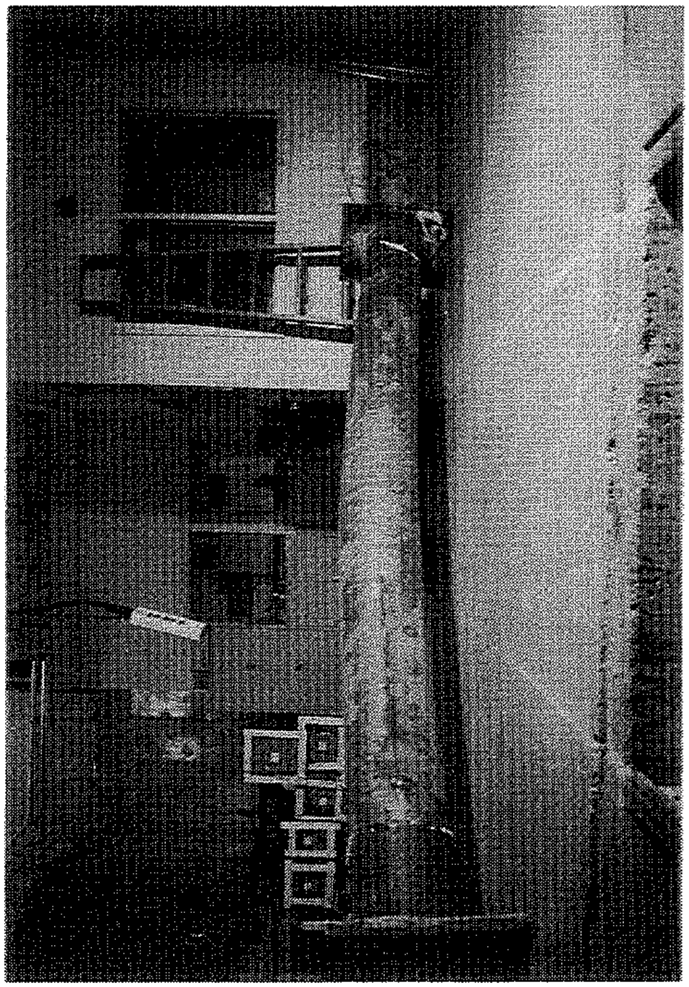


Figure B.1. Column No. C-52 after fire test

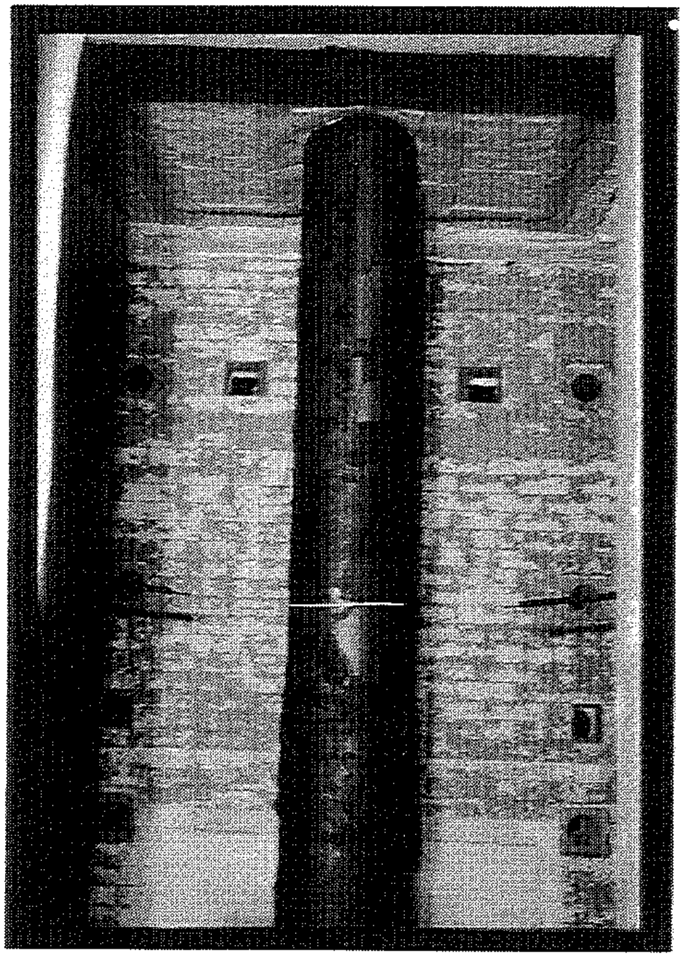


Figure B.2. Column No. C-54 after fire test

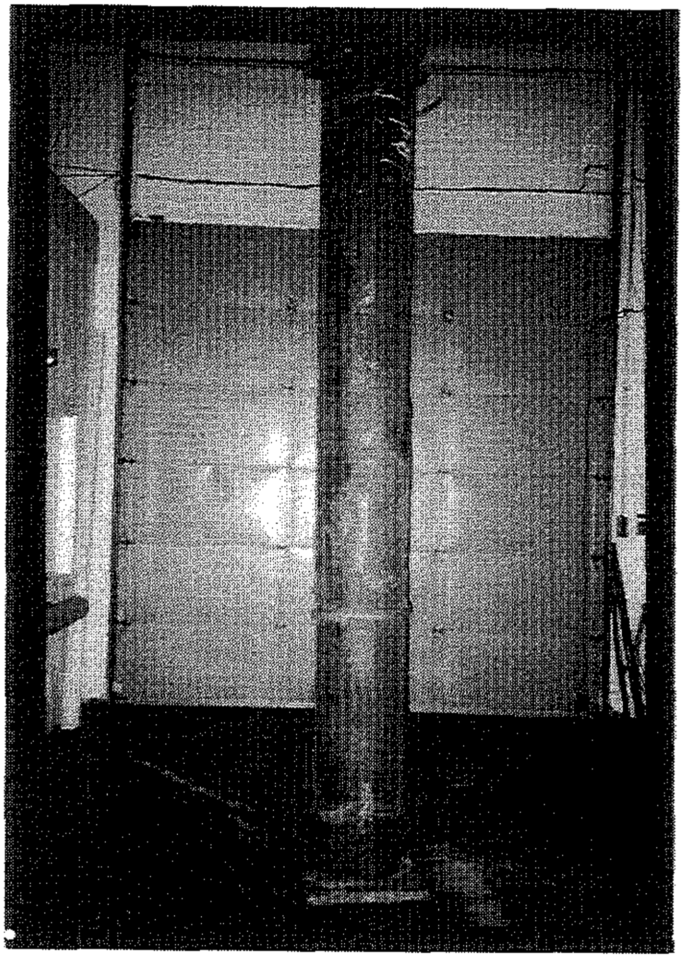


Figure B.3. Column No. C-58 after fire test

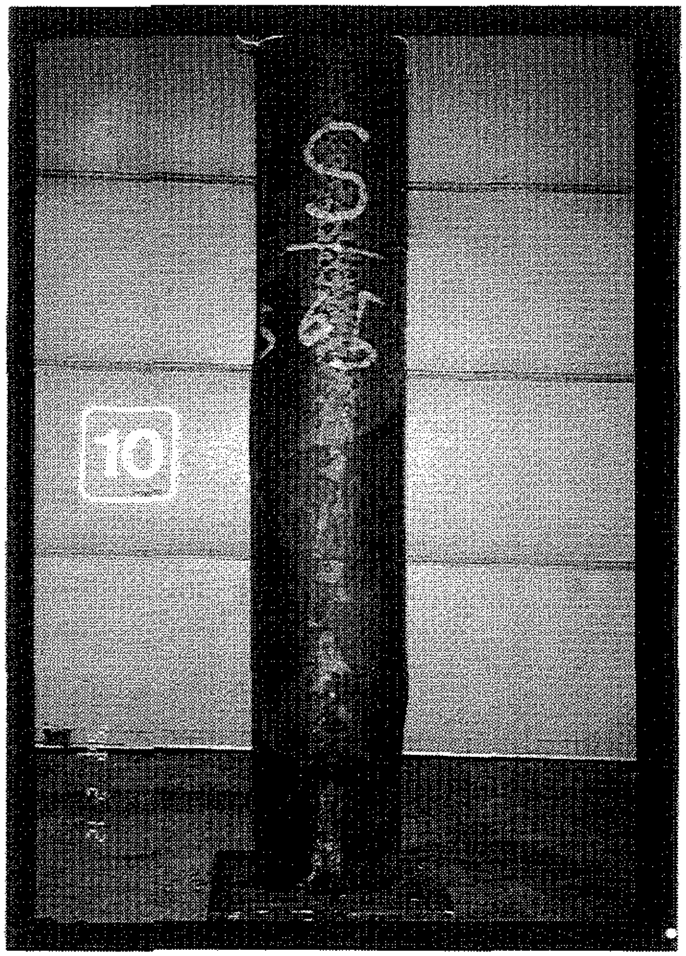


Figure B.4. Column No. C-65 after fire test

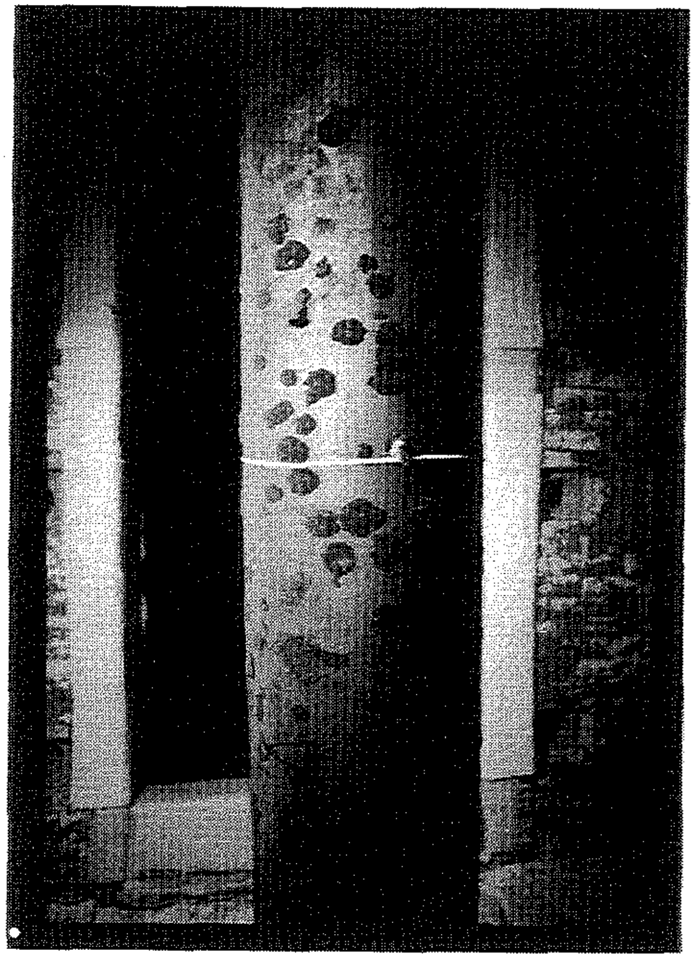


Figure B.5. Column No. C-66 after fire test

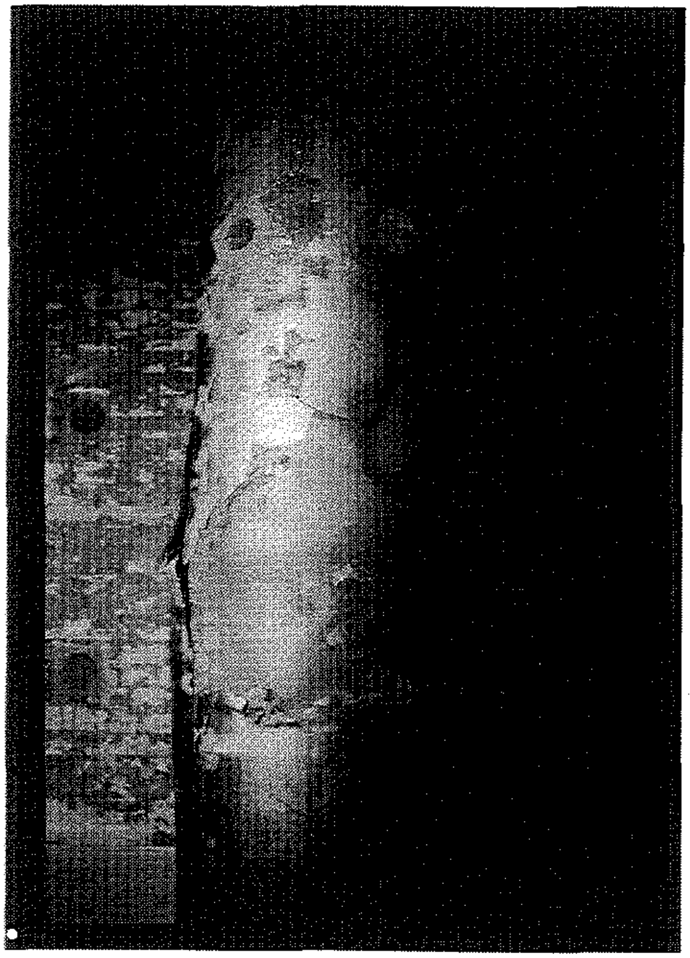


Figure B.6. Column No. C-67 after fire test