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FIRE TESTS ON REINFORCED CONCRETE COLUMNS SPECIMENS NO. 10-12, PHASE II

by T.T. Lie, T.D. Lin and R. McGrath

Checked by: T.Z.H. **Approved by:** L.W. Gold **Date:** January 1985

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ABSTRACT

Results of fire tests on three reinforced concrete columns are given. These tests are a part of a series carried out in the second phase of a joint study of the fire performance of concrete columns by the National Research Council of Canada and Construction Technology Laboratories, a division of the Portland Cement Association. The columns were made with siliceous aggregate concrete. The section size of the columns was 406 × 406 mm (16 × 16 in.). They were tested to study the effect of cover to steel and of heavy reinforcement (about 4%) on the fire resistance of the columns.

FIRE TESTS ON REINFORCED CONCRETE COLUMNS
SPECIMENS NO. 10-12, PHASE II

by

T.T. Lie, T.D. Lin[1] and R. McGrath[2]

Tests were carried out on a series of reinforced concrete columns as part of a study to develop methods for the determination of the fire resistance of such columns. The study was a cooperative effort between the National Research Council of Canada (NRCC) and Construction Technology Laboratories, a division of the Portland Cement Association (PCA). The second phase of the study involves the fire testing of 12 columns. The columns were designed and manufactured by PCA in Skokie, Illinois, and tested in the NRCC laboratories in Ottawa. The test specimens, method of testing and test results are described in successive reports.

This report describes tests on columns 10, 11 and 12 of the second phase. Columns 10 and 11 were tested to study the effect of heavy reinforcement, and columns 11 and 12, the effect of thickness of concrete cover to steel, on the fire resistance of the columns.

Only test results will be given in this report. The results will be analyzed later, and discussed in subsequent papers.

TEST SPECIMENS

The specimens consisted of square tied reinforced concrete columns. Details of these specimens and their fabrication are given below.

Dimensions

Section Size: 406 × 406 mm (16 × 16 in.)
Height: 3810 mm (12 ft 6 in.)

Materials

Cement

Type I, a general purpose cement for the construction of reinforced concrete structures, was used.

Aggregate

Siliceous sand and gravel from Eau Claire, Wisconsin. The maximum size of the aggregate was 19 mm ($\frac{3}{4}$ in.). The gradation curve is shown in Fig. 1. Petrographic information on the aggregate, obtained according to ASTM C295-79[1], is given in Table 1.

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[1]Portland Cement Association, Skokie, Illinois
[2]Canadian Portland Cement Association, Ottawa, Canada

Physical properties of aggregates

Specific gravity of sand (2.63); specific gravity of gravel (2.57); moisture content of sand (4.0%); moisture content of gravel (1.0%); saturated surface dry unit weight of gravel (1678 kg/m^3) (104.9 lb/ft^3); fineness modulus of fine aggregate (2.96); fineness modulus of coarse aggregate (1.73).

Steel reinforcement

Deformed bars meeting the requirements of ASTM Designation A615-80[2], were used for main and tie bars. The longitudinal bars in column 10 were 25M (No. 8), and those in columns 11 and 12 were 30M (No. 10). The ties in all columns were 10M (No. 3). The yield stress of the 25M bars was 443.7 MPa (64.3 ksi) and that of the 10M bars, 426.5 MPa (61.8 ksi). The ultimate strengths of the 25M and 10M bars were 730 MPa (105.8 ksi) and 671 MPa (97 ksi), respectively. No tensile test was performed on the 30M bar, which had a specified minimum yield stress of 414 MPa (60 ksi).

Concrete mix

The concrete mix was designed to produce a 34.5 MPa (5000 psi) strength non-air-entrained concrete. A water/cement ratio of 0.43 was used. Batch quantities are as follows: cement, 325 kg/m^3 (546 lb/yd^3); coarse aggregate, 1058 kg/m^3 (1780 lb/yd^3); sand, 874 kg/m^3 (1470 lb/yd^3); water, 140 kg/m^3 (236 lb/yd^3). The measured average properties of the fresh concrete were: air content, 2.7%; unit weight, 2390 kg/m^3 (149 lb/ft^3); compressive strength at 28 days, 39.8 MPa (5763 psi); slump, 86.4 mm (3.4 in.).

Fabrication

Casting

The columns were cast in a specially designed form. At the start of casting, the front of the form was left open for depositing fresh concrete. As the casting progressed upwards, the window pieces were successively closed and tightly bolted to the form to avoid possible moisture leaks. Lifting hooks were embedded on opposite sides of the test specimen 800 mm (2 ft 7½ in.) from the top of the column. A brass tubing humidity well[3] with an inner diameter of 4 mm (5/32 in.) was positioned at mid-height of the column for measuring internal concrete relative humidity at mid-depth.

Reinforcing cage

The reinforcing cage was assembled by welding each end of eight longitudinal main reinforcing bars to a steel end plate. The bars were cut to 3800 mm (12 ft 5½ in.) and machined at both ends, along a length of 32 mm (1¼ in.) to a diameter of 19 mm (¾ in.). Figure 2* shows details of the finished bars. The dimensions of the end plates were 863 × 635 × 38 mm (34 × 25 × 1½ in.) at the top and 863 × 863 × 38 mm (34 × 34 × 1½ in.) at

*Metric measurements in the figures and text have been converted from the original imperial measurements, and rounded off to the nearest millimetre (except in Figs. 4 and 5).

the bottom. Eight holes were drilled in each plate, one in each corner and two on each centerline of the plate to accommodate the longitudinal bars. The holes were 20.6 mm (13/16 in.) in diameter and the centers of the holes were spaced 142.9 mm (5 5/8 in.) from the centerlines of the plates. In this way a column was obtained with a section of 406 × 406 mm (16 × 16 in.) and cover of 47.6 mm (1 7/8 in.) to the main reinforcing bars and 38.1 mm (1½ in.) to the stirrups. The main bars and stirrups were tied together to complete the steel cage which, including the steel plates, was 3810 mm (12 ft 6 in.) long.

Welding

The provisions of AWS Designation D12.1-75[4] were followed when welding plates and bars. These members were preheated with a propane torch to 288°C (550°F), to prevent brittle failure during welding. The side fillet weld was done around bars on the inner face of the bottom plate. McKay E10018-D2 and DYTRON-579 welding rods were used. Both types of welding rods have tensile strength of 835 MPa (121 000 psi). Mild-steel welding rods were used to fill up the 6 mm (¼ in.) deep holes on the outer faces of the plate. The rough surfaces of the welded joints on the outer face of the plate were ground to a smooth finish.

The welding of the top steel plate was done after the casting of the columns. Before positioning the top plate, a 6 mm (¼ in.) layer of mortar was spread over the top of the column to ensure good contact between steel and concrete. The mortar was made of one part cement and three parts siliceous sand. Using the same procedure as for the bottom plate, the top plate was welded on the outer side to the bars and smoothed.

Curing

The concrete was cured in the column formwork for 7 days, at 21 to 24°C (70 to 75°F). The forms were then stripped and the columns conditioned in an atmosphere controlled at 21 to 24°C and 30 to 40% relative humidity.

The columns were transported in February 1982, about a year after their fabrication, from PCA, Skokie to NRCC, Ottawa. The columns were kept in the NRCC laboratory, in an atmosphere of about 20°C (68°F) and 50% R.H., until they were tested.

Thermocouples

Butt-welded chromel-alumel thermocouples with a thickness of 0.912 mm (0.359 in.) were used to make thermocouple frames for measuring concrete temperatures at different locations in the mid-height section of the columns. Each frame consisted of a number of thermocouples tied to steel rods that were firmly secured to the main reinforcing bars. The thermocouples were arranged to measure temperatures along the whole length of a centerline and a diagonal of the section. The locations of the thermocouples in the concrete and their numbering are shown in Figs. 3, 4 and 5.

In addition, a number of thermocouples were mounted on the reinforcing steel bars and ties. The locations of the thermocouples on the steel are shown in Figs. 6 and 7, and in more detail in Fig. 8.

All thermocouples were installed in such a way that the wire followed an isotherm for at least 12.7 mm (½ in.) from the junction.

Test Apparatus

The test was 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 the conditions to which a member might be exposed during a fire, i.e. temperatures, structural loads, and heat transfer. It consists of a steel framework supported by four steel columns, with the furnace chamber inside the framework (Fig. 9). The characteristics and instrumentation of the furnace are described in detail in reference 5. Only a brief description of the furnace and the main components will be given here.

Loading Device

Three hydraulic jacks produce forces along the three principal axes. The jack acting along the axis of the test column is located at the bottom of the furnace chamber. The plate on top of this jack can be used as a platform to which the column can be attached.

Furnace Chamber

The furnace chamber has a floor area of 2642 × 2642 mm (8 ft 8 in. × 8 ft 8 in.) and is 3048 mm (10 ft) high. The interior faces of the chamber are lined with insulating materials that will efficiently transfer heat to the specimen. There are 32 propane gas burners in the furnace chamber, arranged in eight columns, each containing four burners. The total capacity of the burners is 4700 kW (16 million Btu/h). 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. It was set somewhat lower than atmospheric pressure.

Instrumentation

The furnace temperatures are measured using eight chromel-alumel thermocouples. The junction of each thermocouple was located 305 mm (1 ft) from the test specimen, at various heights. Two thermocouples were placed opposite each other at intervals of 610 mm (2 ft) along the height of the furnace chamber. The locations of their junctions and their numbering are shown in Fig. 10. Thermocouples 4 and 6 were located at a height of 610 mm from the floor, thermocouples 2 and 8 at 1220 mm (4 ft), thermocouples 3 and 5 at 1830 mm (6 ft) and thermocouples 1 and 7 at 2440 mm (8 ft). The temperatures measured by the thermocouples are averaged automatically and the average temperature used as the criterion for controlling the furnace temperature.

The loads are controlled and measured using pressure transducers. The accuracy of controlling and measuring loads is about 20 kN (5 kips) at lower load levels and relatively better at higher loads.

The axial deformation of the test specimen is determined by measuring the displacement of the jack that supports the column. The displacement is measured using transducers with an accuracy of 0.002 mm (7.87×10^{-5} in.).

Test Conditions and Procedure

The columns were installed in the furnace by bolting their end plates to a loading head at the top and a hydraulic jack at the bottom. Eight 19 mm ($\frac{3}{4}$ in.) bolts, spaced regularly around the column 63.5 mm ($2\frac{1}{2}$ in.) from the sides were used at each end.

Prior to the tests, the moisture condition in the centre of the columns was measured with a Monfore humidity gauge.[3] The relative humidity measured in column 10 was 80%, in column 11, 75% and in column 12, 68%. The ambient temperature at the start of the test of column No. 10 was 20°C; it was 25°C at the start of the test of column No. 11 and 19°C at the start of the test of column No. 12.

Column No. 10 was cast on April 10, 1981 and tested on September 21, 1984. It was subjected to an axial load of 2418 kN (544 kips). The cylinder strengths of the concrete on the test date, measured on two cylinders, were 36.5 MPa (5288 psi) and 41.2 MPa (5977 psi).

Column No. 11 was cast on November 4, 1981 and tested on August 8, 1984. It was subjected to an axial load of 2795 kN (629 kips). The cylinder strengths of the concrete on the test date, measured on two cylinders, were 39.3 MPa (5695 psi) and 37.6 MPa (5447 psi).

Column No. 12 was cast on January 6, 1982 and tested on April 29, 1983. It was subjected to an axial load of 2978 kN (670 kips). The cylinder strengths of the concrete on the test date, measured on two cylinders, were 46.6 MPa (6756 psi) and 46.1 MPa (6685 psi).

The loads were concentric and applied at least 40 minutes before the start of the test.

In the tests the columns were exposed to heating controlled so that the average temperture in the furnace followed as closely as possible the ASTM-E119[6] or ULC-S101[7] standard temperature-time curve. This curve can be approximately described by the following equation:[8]

$$T_f = 20 + 750\left[1-\exp(-3.79553\sqrt{\tau})\right] + 170.41\sqrt{\tau} \qquad (1)$$

where T_f = temperature in °C, and
τ = time in h

or by

$$T_f = 68 + 1350\left[1-\exp(-3.79553\sqrt{\tau})\right] + 306.74\sqrt{\tau} \qquad (2)$$

where T_f = temperature in °F.

During the tests, temperatures in the furnace and in the columns were measured at the locations described earlier. The axial strain of the columns was also measured. The columns were regarded to have failed and the tests were terminated, when the hydraulic jack, which has a maximum speed of 76 mm/min (3 in./min), could no longer maintain the applied load.

TEST RESULTS

Measured Temperatures

Tables 2-4 provide measured steel temperatures, for columns 10-12, at various test times. The measured concrete temperatures are given in Tables 5-7. Table 8 gives the measured average furnace temperatures for columns 10-12.

Measured Deformations

The measured axial deformations during the tests of columns 10-12 are given in Table 9.

Observations

Column No. 10

Test time Hr:Min	
0:00	Fire started after subjecting the column to a preload of 2418 kN (544 kips) for 1 hour and 40 minutes.
1:35	Fine cracks were visible on all four faces, as indicated in Fig. 11.
2:20	Maximum crack width on the east and west faces of the column was approximately 6 mm (¼ in.).
3:20	Two 600 mm (2 ft) long cracks developed in the lower quarter of the column on the east and south faces.
3:58	Large cracks had developed on all four faces of the column. The cracks on the south and east faces of the column had widened to about 25 mm (1 in.), exposing the corner reinforcing bar.
4:22	The column failed in compression. Figure 12 shows the column after the fire test.

Column No. 11

Test time Hr:Min	
0:00	Fire started after subjecting the column to a preload of 2795 kN (629 kips) for 40 minutes.
1:40	Fine cracks developed on the east and south faces of the test column.
2:20	Cracks on the east face of the column lengthened to 100-200 mm (4-8 in.). The maximum crack width on the east face was about 3 mm (1/8 in.). Small cracks also developed on the north and west faces.
3:00	Two 600 mm (2 ft) long cracks developed in the lower quarter of the column on the east and south faces.
3:20	The longest crack on the east face extended to about 750 mm (2½ ft). Cracks on other faces also lengthened.
4:00	The worst crack on the east face opened up to nearly 6 mm (¼ in.) wide (see Fig. 13).

4:17 All cracks continued to widen. The crack on the east face was about 25 mm (1 in.) wide.
4:45 Test column failed in compression. Figure 14 shows the column after the fire test.

Column No. 12

Test time
Hr:Min

0:00 Fire started after subjecting the column to a preload of 2978 kN (670 kips) for 40 minutes.
0:28 A hairline crack developed on the east face of the column in the area near the upper one-quarter point.
0:40 The crack rapidly grew to a length of about 450 mm (18 in.) long. Additional hairline cracks developed.
1:10 More hairline cracks, some 100-200 mm (4-8 in.) long, developed on all four sides in the area 50-75 mm (2-3 in.) from the edges.
2:15 Major cracks had a maximum width of about 6 mm (¼ in.) (see Fig. 15).
3:00 Most cracks became stable.
3:33 The combustion air fan motor burned out and the fire was automatically shut off. Figure 16 shows the column shortly after the fire test.

On the third day after the test the column was subjected to a load of 4089 kN (922 kips) without failure of the column. After the load test, the load was removed. Seventy-six days after the test the same column (Figure 17) was again subjected to a load test. In this test, the load was gradually increased until the column failed at 3204 kN (721 kips).

SUMMARY

Three reinforced concrete columns with a cross section of 406 × 406 mm (16 × 16 in.) were tested. Two of these columns were tested to study the effect of heavy reinforcement (about 4%) on the fire resistance of the columns. The results indicated that increasing the steel reinforcement percentage is beneficial for the fire resistance of the columns.

One column was tested to study the effects of a high percentage of steel reinforcement (about 4%) in combination with a large cover thickness to steel (63 mm [2.5 in.]) on the fire performance of the column. These have been considered to be the primary factors that promote spalling of a column exposed to fire. Although no spalling occurred during the fire test, it could not be continued after about 3½ hours of testing, due to fan failure. The test provided additional information, however, on the residual strength of the column after the exposure to fire. After cooling and subjecting the column to a load test, about 2½ months after the fire test, the residual strength of the column was found to be about 10% higher than the maximum allowable load that was applied to the column during the fire test.

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TABLE 1. PETROGRAPHY OF SAND AND GRAVEL USED AS AGGREGATE

Component	Composition of Sieve Fraction, Percent on Sieve of Size Indicated											Percent Passing through No. 200
	19 mm	12.5 mm	9.5 mm	6 mm	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	
Granite	37.9	32.9	25.5	31.3	27.0	27.6	12.3	7.4	1.9	4.4	0.6	--
Quartzite	21.6	29.2	34.8	24.6	24.5	20.0	12.3	12.6	10.9	3.1	2.2	--
Quartz	6.3	3.1	4.9	4.8	5.5	18.8	52.2	62.0	73.1	79.5	74.2	92.0
Chert[a]	10.8	7.0	5.2	8.1	9.8	5.9	7.7	3.5	2.0	0.8	2.8	2.0
Sandstone-Quartz Conglomerate	1.9	0.8	3.1	5.1	5.5	8.3	--	--	--	--	--	--
Rhyolite-Dacite	13.9	6.2	2.2	5.1	7.2	4.1	0.8	2.6	1.6	0.8	0.9	--
Feldspar	--	--	--	--	--	--	1.3	5.0	6.6	5.0	10 8	4.0
Diorite	1.9	1.4	3.1	1.8	1.2	--	--	--	--	--	--	--
Graywacke[b]	1.3	9.5	5.8	5.4	4.3	6.5	2.3	1.5	0.3	--	0.6	--
Gneiss-Schist	2.5	5.1	10.5	9.3	7.5	4.1	6.4	1.8	0.9	1.1	0.6	--
Basalt	1.9	4.5	4.0	3.9	6.9	3.2	2.6	2.4	0.7	--	0.3	--
Misc. Igneous Rocks and[c] Opaque Minerals	--	0.3	0.9	0.6	0.6	1.5	2.1	1.2	2.0	5.3	7.0	2.0

Particle Shape	19 to 6 mm (%)	No. 4 to No. 16 (%)	No. 30 to No. 200 (%)
Subrounded to rounded	30	20	10
Subrounded to subangular	40	40	40
Angular	30	40	50

[a] "Ironstone," made up of jasper and hematite, is included in the chert classification.
[b] Includes metagraywacke.
[c] The miscellaneous igneous rocks were severely altered and positive identification was impossible. The opaque minerals occurred in the No. 50 and smaller sieve sizes and were largely magnetite.

TABLE 2. MEASURED STEEL TEMPERATURES (COLUMN NO. 10)

Time (min)	Temperature (°C) Measured at Thermocouple No:															
	1	2	3	4	5	6	7	8	9	10	11	12	45	46	47	48
0	21	21	20	20	18	18	17	17	21	25	18	19	20	20	18	18
5	23	23	23	25	22	24	19	20	34	25	21	22	26	23	22	27
10	34	38	35	44	34	49	28	36	65	25	41	38	49	40	43	56
15	48	82	57	97	52	101	45	68	101	25	90	85	103	88	94	106
20	82	108	76	111	79	117	65	105	110	25	115	108	111	107	114	119
25	103	109	94	119	95	124	83	124	133	25	117	114	122	115	117	133
30	102	121	114	135	103	144	100	139	157	25	131	127	140	126	130	156
35	102	141	123	157	110	165	112	158	182	25	150	146	160	146	148	180
40	107	163	143	181	117	193	121	181	206	25	178	166	184	168	177	209
45	115	186	165	207	130	224	134	205	229	25	207	189	210	193	207	239
50	124	209	188	235	154	254	147	229	250	25	237	216	238	220	237	270
55	134	233	209	263	178	284	160	255	270	26	265	242	266	247	265	299
60	145	256	229	290	199	311	173	279	288	26	292	269	293	274	292	326
70	168	300	265	341	237	362	199	326	324	26	341	319	344	324	340	376
80	192	341	296	386	270	407	224	367	357	26	385	364	389	368	383	421
90	216	378	324	427	298	447	247	404	388	26	424	405	430	408	420	461
100	240	413	349	465	324	485	270	437	418	26	458	442	468	445	455	497
110	263	446	372	499	347	519	291	466	447	26	490	476	503	479	487	530
120	286	476	393	529	368	549	310	490	475	26	520	506	533	509	517	561
130	308	503	413	556	388	581	330	514	501	27	547	532	561	535	545	589
140	329	528	432	583	408	615	349	536	525	27	578	558	585	560	576	618
150	350	551	449	608	426	650	367	556	548	27	608	582	618	585	607	650
160	371	576	465	631	443	691	385	577	571	27	637	606	656	609	636	683
170	391	601	481	654	460	729	403	597	593	27	665	628	693	633	665	715
180	411	626	496	678	477	755	420	616	615	27	694	649	723	658	694	738
190	431	650	511	703	493	759	437	634	635	27	710	668	744	686	709	739
200	450	676	526	725	509	761	453	651	655	27	726	686	762	712	724	739
210	470	703	540	737	525	768	469	669	674	27	741	702	772	730	747	747
220	489	716	554	734	540	*	484	685	692	27	749	710	769	736	753	755
230	509	734	569	735	555	765	499	699	709	27	759	717	759	741	753	762
240	527	770	584	750	571	767	514	709	723	27	773	744	752	747	755	771
250	545	789	598	762	586	772	527	721	739	27	788	766	749	752	760	780
260	563	801	612	769	601	777	541	738	756	28	806	776	753	761	768	787

*Measurement not reliable

TABLE 3. MEASURED STEEL TEMPERATURES (COLUMN NO. 11)

Time (min)	Temperature (°C) Measured at Thermocouple No:															
	1	2	3	4	5	6	7	8	9	10	11	12	45	46	47	48
0	25	24	24	24	22	22	22	22	24	26	21	23	23	23	22	22
5	28	28	28	27	24	24	23	24	34	26	22	24	28	25	23	24
10	45	45	53	44	34	35	29	35	63	26	30	38	49	38	30	35
15	69	81	87	90	51	70	41	66	104	26	61	77	95	77	59	79
20	82	111	104	109	73	103	58	105	121	27	95	105	100	105	91	106
25	93	114	108	113	85	105	75	103	149	27	102	107	117	107	100	104
30	102	127	106	123	100	109	93	107	181	28	108	111	128	106	107	114
35	108	144	104	143	104	122	109	120	215	28	111	129	147	124	108	124
40	127	164	147	165	115	140	118	136	249	28	125	151	171	145	121	141
45	156	186	164	189	138	160	126	153	281	28	142	174	186	168	138	160
50	175	210	178	215	153	181	140	171	309	29	163	163	223	192	156	180
55	190	235	193	242	167	202	154	191	335	29	184	224	251	217	176	203
60	205	259	207	269	180	223	166	211	358	29	205	250	278	242	196	223
70	231	305	234	320	204	264	189	249	399	30	245	299	329	290	235	264
80	256	347	260	367	227	302	210	284	434	30	284	344	375	334	272	304
90	279	386	283	409	250	338	230	317	464	30	319	385	416	372	307	341
100	301	421	304	446	272	372	251	349	492	30	353	421	452	406	340	375
110	311	437	314	463	282	388	261	363	504	31	369	438	469	422	356	392
120	342	482	343	508	314	433	290	406	538	31	414	483	513	466	400	438
130	362	510	362	534	334	462	309	433	559	31	443	509	540	493	429	467
140	382	535	381	559	352	489	327	458	581	31	470	533	566	517	455	484
150	401	558	399	583	370	513	345	482	601	31	495	556	591	540	480	519
160	419	580	418	607	388	536	363	506	620	31	518	578	614	562	504	542
170	436	601	437	630	405	559	380	527	638	32	540	600	636	583	826	565
180	454	622	456	654	421	585	397	547	656	32	561	620	655	604	547	587
190	471	641	474	677	438	*	413	568	673	32	583	640	675	624	570	610
200	488	661	492	699	454	647	429	587	690	32	605	658	684	624	581	621
210	506	680	510	718	471	677	445	607	705	32	626	675	711	661	613	653
220	516	689	521	727	479	691	452	616	712	32	636	683	721	670	623	664
230	543	718	572	741	502	721	475	643	730	32	664	704	742	694	652	696
240	562	736	632	735	517	731	489	661	742	33	681	708	742	702	670	715
250	582	746	682	729	531	737	504	677	746	33	698	711	737	708	687	733
260	603	756	710	730	545	742	518	691	746	33	713	716	734	716	703	747
270	626	772	732	740	566	744	532	706	751	33	718	724	735	728	710	753
280	650	794	754	754	597	750	541	720	760	33	725	733	740	742	717	760
285	664	805	764	761	708	*	552	766	764	33	749	738	744	750	752	965

*Measurement not reliable

TABLE 4. MEASURED STEEL TEMPERATURES (COLUMN NO. 12)

Time (min)	Temperature (°C) Measured at Thermocouple No: 1	2	3	4	5	6	7	8	9	10	11	12	45	46	47	48
0	22	21	21	18	19	19	20	19	22	19	19	20	20	20	19	19
10	*	25	23	19	22	23	23	37	*	25	21	22	24	22	21	22
15	*	31	27	20	24	27	28	46	*	31	24	26	29	27	25	27
20	*	36	29	22	27	31	32	52	*	35	27	30	33	30	28	30
25	*	42	34	24	31	36	38	90	*	41	32	36	39	36	33	35
30	*	52	39	27	37	44	45	107	*	54	38	42	47	43	39	43
35	*	75	46	32	45	55	61	129	*	70	48	56	65	56	49	55
40	*	101	59	38	55	76	87	175	*	98	65	79	91	80	67	75
45	*	110	71	46	68	102	107	321	*	109	92	102	106	103	93	105
50	*	*	88	61	87	*	*	469	*	*	97	*	*	*	99	*
55	*	*	102	77	102	*	*	526	*	*	98	102	*	*	100	*
60	*	113	108	93	114	104	*	569	*	131	102	104	*	105	102	*
70	106	134	109	116	125	124	108	633	123	175	118	108	115	107	113	125
80	125	165	126	127	148	154	136	701	142	213	142	131	144	126	139	155
90	146	201	147	150	178	188	178	746	170	247	171	168	184	165	172	188
100	169	239	173	175	207	223	220	787	196	281	204	208	227	204	206	224
110	193	277	198	200	236	259	260	813	224	313	238	247	267	242	240	259
120	216	313	222	223	264	293	297	837	249	344	272	282	304	278	273	293
130	235	348	245	244	290	325	331	858	273	374	305	316	339	312	305	325
140	258	381	267	264	314	356	363	878	298	402	336	348	371	343	335	356
150	276	413	288	283	338	385	393	*	*	*	*	*	402	374	363	385
160	296	444	309	301	359	411	423	911	349	454	392	407	432	402	390	411
170	315	473	329	318	380	437	451	926	372	476	417	435	459	429	414	437
180	335	500	348	335	399	461	477	937	395	498	441	460	485	455	438	461
190	351	526	367	351	418	484	500	948	418	519	464	484	509	479	461	484
200	365	550	386	367	436	506	522	959	438	539	486	506	531	500	482	506
210	380	573	405	382	456	527	542	970	460	563	506	526	550	520	503	527
220	416	596	423	397	480	547	561	*	504	593	426	544	570	539	522	547
240	450	622	451	416	500	581	587	*	530	612	555	571	592	566	552	579
255	461	*	458	416	*	584	*	*	*	*	563	575	*	570	560	581

*Measurement not reliable

TABLE 5. CONCRETE TEMPERATURES MEASURED AT MID-HEIGHT (COLUMN NO. 10)

Time (min)	Temperature (°C) Measured at Thermocouple No:																															
	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
0	21	20	19	19	19	19	19	19	20	19	19	19	19	20	23	25	23	20	19	19	19	19	19	19	19	19	19	20	20	21	26	36
5	109	75	54	34	21	19	19	19	19	19	21	28	72	109	181	234	130	88	65	39	21	19	19	19	19	19	20	33	77	122	197	259
10	186	130	106	67	28	20	19	19	20	20	34	66	135	192	308	380	230	150	113	78	31	20	19	19	19	19	33	79	142	214	350	413
15	271	192	145	102	42	22	19	19	20	25	75	111	200	283	424	505	330	220	165	109	48	23	19	19	19	23	81	116	216	314	470	529
20	346	253	189	121	60	27	20	19	21	45	106	114	264	361	510	586	411	286	220	130	71	28	19	19	21	43	108	137	282	392	550	609
25	407	306	232	145	83	34	21	20	24	57	107	129	324	427	576	659	468	337	264	158	89	36	20	19	25	59	108	188	343	455	616	674
30	456	349	270	177	92	43	23	21	28	70	110	170	382	486	630	714	510	378	301	188	96	45	23	20	31	68	106	234	398	512	673	783
35	498	391	311	220	93	50	26	22	34	76	118	197	435	535	673	725	545	414	337	222	101	53	26	21	37	73	115	271	447	562	718	760
40	532	428	348	253	99	56	30	25	40	79	131	224	480	576	711	749	574	445	368	250	111	60	30	24	43	77	133	300	490	606	*	778
45	562	459	379	280	107	62	34	28	45	83	147	252	518	607	711	776	600	471	395	274	127	66	34	27	49	81	157	327	526	644	739	803
50	587	486	405	303	116	68	39	32	50	87	167	278	550	637	722	799	621	494	418	296	144	70	39	31	54	86	183	353	558	677	722	823
55	609	509	429	324	125	74	44	36	55	91	188	305	583	661	741	320	641	514	438	316	161	75	44	36	59	90	208	378	589	*	733	841
60	629	530	450	342	135	80	48	40	60	98	210	329	612	689	757	838	660	533	457	335	176	80	48	40	63	93	231	400	616	706	746	857
70	662	565	485	374	156	94	58	49	71	115	253	375	661	733	772	863	690	567	491	368	205	92	57	49	72	104	273	444	*	703	758	871
80	691	597	517	403	179	106	69	58	85	133	292	417	701	769	762	859	715	598	522	399	232	105	67	58	82	117	312	482	691	732	772	806
90	716	625	543	428	202	117	81	68	100	148	327	456	729	798	770	845	739	625	549	426	257	117	77	68	94	133	345	515	693	753	785	792
100	738	650	568	451	224	128	96	81	109	164	358	490	754	823	783	827	761	649	576	451	281	128	88	79	107	152	374	546	717	769	793	800
110	760	672	592	473	245	139	108	96	119	179	385	523	778	845	793	803	782	672	600	474	303	139	100	93	117	173	397	573	737	781	800	805
120	777	692	613	493	265	148	116	107	127	195	411	553	800	863	798	802	800	692	622	496	325	150	111	105	127	193	415	595	748	785	801	803
130	794	711	633	511	285	162	121	117	133	215	434	581	819	880	800	799	816	712	643	517	344	162	118	114	135	211	429	614	751	786	801	800
140	703	726	650	528	304	177	127	122	139	234	456	605	834	891	798	796	829	726	660	535	363	175	123	120	144	228	444	618	752	786	798	798
150	707	742	667	544	322	191	133	127	169	259	477	630	847	902	795	790	842	744	677	553	380	188	130	126	154	244	459	649	752	787	795	796
160	712	757	683	560	339	205	139	133	419	362	498	673	846	905	787	755	697	756	693	570	397	203	144	142	160	260	475	665	758	788	791	793
170	720	772	698	576	356	218	145	139	641	599	521	727	776	851	758	750	693	755	708	587	414	222	187	207	181	293	493	682	760	786	787	787
180	728	788	713	592	372	231	151	143	714	724	575	755	738	772	765	779	691	743	725	607	443	269	320	343	327	460	512	738	743	765	772	760
190	735	793	727	608	389	244	158	147	749	759	710	772	755	768	786	803	700	729	737	641	521	408	524	501	609	661	552	736	745	742	742	744
200	744	722	744	625	405	258	169	149	752	777	756	774	761	770	783	814	718	728	737	683	636	573	650	610	756	758	685	783	779	764	762	777
210	749	727	757	623	423	273	180	153	756	790	764	766	776	770	753	810	745	735	735	725	720	677	711	678	799	791	757	808	805	788	787	805
220	755	733	771	638	440	287	192	159	772	784	766	766	791	769	757	785	766	742	734	750	756	718	737	720	819	799	785	820	824	804	306	824
230	758	737	783	652	458	304	206	168	787	777	773	777	797	773	774	766	778	752	744	769	771	734	742	739	826	803	798	828	833	809	816	837
240	762	740	795	665	476	320	221	183	796	786	785	789	797	787	788	775	784	766	457	780	776	749	748	753	828	809	801	831	833	812	819	843
250	766	797	794	796	493	337	236	200	796	797	794	796	800	800	798	784	783	779	766	785	778	765	758	765	826	813	800	829	829	816	822	837
260	767	748	819	694	509	353	252	219	786	801	801	800	801	808	802	789	779	792	772	790	782	779	770	776	825	817	798	829	826	822	824	823

*Measurement not reliable

TABLE 6. CONCRETE TEMPERATURES MEASURED AT MID-HEIGHT (COLUMN NO. 11)

Time (min)	Temperature (°C) Measured at Thermocouple No: 13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
0	26	24	23	22	22	22	22	23	23	22	22	22	23	23	27	29	26	24	23	22	22	22	22	22	22	*	22	23	24	25	30	34
5	123	91	58	41	24	22	22	23	23	22	23	33	70	101	174	230	124	96	70	44	24	22	22	*	22	*	23	35	70	112	171	235
10	210	150	108	78	33	23	22	23	23	23	30	77	140	179	299	376	222	170	128	87	34	23	22	*	22	*	30	84	134	200	314	407
15	311	226	152	117	53	26	23	23	23	26	68	111	199	266	414	510	321	247	183	120	48	26	22	*	22	*	78	120	205	305	444	539
20	395	296	205	150	78	31	23	23	24	37	102	132	270	351	493	600	405	318	241	155	65	32	23	*	23	*	100	144	274	388	533	619
25	462	358	256	187	103	43	24	23	26	48	101	143	332	422	565	654	468	375	290	190	102	42	24	*	25	*	102	192	338	459	603	681
30	515	408	299	219	111	56	26	24	30	58	106	214	386	479	610	*	516	420	331	223	103	51	26	*	30	*	104	246	397	516	655	*
35	555	448	337	253	112	64	30	25	35	65	104	264	437	524	656	730	552	459	369	265	101	57	29	*	35	*	106	293	446	564	687	754
40	588	484	374	291	143	69	34	28	41	71	109	306	483	567	695	743	587	495	406	306	101	62	34	*	40	*	112	329	487	608	710	741
45	618	516	409	325	173	73	39	31	46	77	120	342	521	605	728	763	618	526	440	340	108	66	38	*	45	*	129	362	523	645	728	760
50	644	545	439	354	193	78	43	35	52	83	134	373	553	642	755	779	646	555	469	368	117	72	42	*	50	*	141	393	555	671	765	773
55	665	568	464	378	212	84	48	39	57	91	150	400	587	668	776	780	668	580	494	392	127	78	45	*	55	*	162	419	587	699	785	776
60	687	592	487	399	229	90	53	44	62	100	167	425	615	696	698	756	691	604	516	412	137	85	51	*	60	*	181	442	616	717	751	843
70	720	630	525	436	261	103	62	53	76	117	202	470	652	708	830	763	722	641	552	446	158	99	61	*	72	*	217	482	662	758	771	873
80	748	662	558	469	289	115	73	62	91	131	235	508	688	738	855	779	746	670	584	473	179	110	75	*	83	*	250	517	701	789	784	897
90	774	690	588	496	313	128	86	74	104	141	264	542	729	759	877	791	769	695	609	496	201	122	90	*	94	*	283	548	733	816	790	916
100	797	714	614	518	277	136	101	95	113	151	289	572	756	774	894	799	784	714	631	515	222	132	104	*	106	*	313	579	760	838	796	732
110	812	729	630	530	310	144	118	113	122	164	321	602	780	785	905	805	804	731	648	532	243	144	115	*	119	*	345	608	784	858	801	942
120	830	747	650	550	350	154	127	121	133	182	352	628	802	792	912	809	821	747	666	547	263	156	124	*	130	*	374	632	806	877	802	952
130	847	765	670	572	378	169	131	126	138	203	382	652	821	792	869	809	836	762	682	563	282	165	130	*	138	*	402	653	824	892	803	958
140	863	783	689	593	398	184	135	132	144	225	410	673	839	791	805	808	849	776	697	579	303	172	135	*	149	*	427	676	841	905	802	963
150	877	800	707	611	415	201	138	134	154	249	437	693	855	789	804	807	863	791	713	596	325	181	140	*	157	*	450	696	857	919	799	965
160	889	816	723	628	431	217	144	137	164	267	461	711	870	787	801	805	873	806	728	612	345	197	144	*	164	*	472	714	868	929	793	729
170	899	830	738	644	446	233	141	140	172	284	483	727	884	784	498	803	765	820	743	628	365	211	150	*	169	*	493	732	775	922	786	786
180	875	843	752	659	461	248	159	146	181	299	505	743	892	782	794	802	767	834	758	644	384	223	156	*	175	*	512	748	775	776	781	780
190	772	854	765	674	477	263	171	152	193	314	527	755	898	780	793	799	765	846	771	659	404	235	161	*	185	*	532	763	774	774	776	777
200	786	867	780	688	492	279	182	159	207	331	547	760	900	778	793	801	766	860	785	675	423	249	167	*	198	*	551	777	772	772	774	777
210	788	876	793	702	507	294	194	167	225	349	569	758	774	776	792	802	764	871	798	689	442	264	176	*	211	*	572	790	771	771	775	775
220	800	874	807	716	531	311	206	176	261	372	593	755	871	769	774	798	766	885	812	704	462	282	188	*	224	*	593	803	770	770	774	772
230	802	855	818	729	730	32	664	704	802	855	818	729	537	330	221	190	766	895	824	718	482	305	203	*	239	*	613	816	770	767	772	767
240	802	837	826	740	551	356	243	218	446	459	658	753	783	735	744	740	766	901	836	729	501	339	222	*	255	*	628	824	767	761	767	761
250	804	797	823	748	583	396	283	272	545	539	685	752	719	723	727	722	765	759	846	739	521	397	247	*	271	*	641	832	765	759	764	759
260	788	723	798	749	623	466	366	373	625	604	707	756	721	721	720	719	762	755	849	748	543	476	664	*	288	*	658	840	766	762	766	765
270	741	713	754	738	671	579	529	533	689	671	731	765	732	729	728	730	666	744	790	752	567	561	685	*	319	*	677	830	770	769	771	775
280	721	721	733	727	712	686	679	668	733	718	752	777	747	743	743	747	707	732	732	760	602	633	719	*	539	*	698	765	776	776	777	784
285	721	728	729	720	729	711	710	694	746	731	760	780	753	748	740	752	724	843	721	961	640	653	747	*	*	*	717	973	973	784	786	790

*Measurement not reliable

TABLE 7. CONCRETE TEMPERATURES MEASURED AT MID-HEIGHT (COLUMN NO. 12)

Time (min)	Temperature (°C) Measured at Thermocouple No:																														
	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
0	24	23	21	20	20	19	20	19	20	*	19	19	20	22	24	27	23	21	20	20	17	19	19	19	19	*	19	20	22	24	27	31
10	66	60	50	37	24	20	20	20	20	*	24	32	54	69	86	100	60	50	41	33	17	20	19	19	19	*	26	36	55	72	89	105
15	*	77	65	48	29	22	20	20	20	*	31	44	73	92	117	128	76	63	53	42	18	21	19	19	19	*	34	49	73	95	114	133
20	*	87	74	55	33	24	20	20	20	*	36	52	85	106	127	145	86	72	60	48	18	22	19	19	19	*	39	57	85	108	129	148
25	*	138	108	70	38	27	20	20	21	*	45	64	109	148	201	256	141	105	83	59	19	24	20	19	20	*	49	71	112	155	209	270
30	*	168	136	99	49	30	21	20	22	*	59	88	151	197	252	294	165	131	105	83	21	27	20	19	21	*	67	100	151	201	255	302
35	*	205	163	116	62	35	22	21	24	*	80	113	182	243	310	368	200	157	126	101	25	31	21	20	23	*	86	123	181	242	305	365
40	*	260	203	136	75	44	24	21	26	*	105	138	222	302	386	456	264	199	154	116	67	37	23	21	26	*	107	144	221	301	385	460
45	*	389	285	168	94	52	26	23	30	*	119	148	269	394	539	671	412	285	205	137	*	45	25	22	31	*	115	161	284	375	529	652
50	*	513	386	225	115	64	29	24	35	*	*	169	356	513	691	820	532	382	278	179	85	60	28	24	35	*	*	203	370	481	669	791
55	*	562	445	274	124	75	34	27	40	*	*	206	430	587	745	833	572	437	333	221	110	74	32	26	40	*	*	251	441	554	725	810
60	685	601	486	312	139	86	*	30	45	*	139	244	484	640	786	*	609	477	372	256	118	86	42	30	46	*	*	295	495	610	768	838
70	731	656	546	372	176	101	51	39	60	*	222	326	564	720	*	878	661	533	429	312	165	95	62	41	62	*	211	380	575	691	820	*
80	788	711	601	419	209	101	62	51	74	*	282	398	638	777	795	931	718	588	480	366	212	102	72	53	75	*	284	455	645	757	839	*
90	818	746	645	461	241	101	72	63	84	*	331	459	701	824	805	*	756	635	528	414	247	108	81	65	87	*	336	516	712	810	*	*
100	847	775	677	496	270	107	81	77	91	*	373	511	750	840	806	*	788	668	568	453	276	118	89	76	100	*	379	566	760	847	*	*
110	*	798	704	527	297	121	96	90	98	*	412	555	790	*	*	*	811	699	602	485	302	130	98	90	107	*	417	611	796	873	*	*
120	*	820	727	553	323	145	103	100	105	*	446	598	821	*	*	*	833	724	631	514	325	145	104	99	113	*	450	650	825	895	*	*
130	*	842	750	581	349	167	108	105	113	*	478	637	846	*	*	*	854	747	656	538	346	161	111	104	120	*	481	685	849	913	*	*
140	*	860	771	606	374	184	112	109	123	*	506	670	*	*	*	*	871	767	678	560	365	177	118	107	128	*	507	714	869	929	*	*
150	*	*	*	630	398	205	117	113	134	*	530	699	*	*	*	*	886	785	698	582	385	193	125	110	136	*	536	739	888	942	*	*
160	*	*	809	653	421	225	125	117	145	*	554	725	*	*	*	*	901	802	716	603	402	209	133	115	145	*	562	761	905	953	*	*
170	*	*	827	674	442	243	135	124	157	*	579	749	*	*	*	*	915	818	734	622	419	225	141	123	157	*	586	781	920	962	*	*
180	*	*	843	693	462	262	146	134	170	*	604	770	*	*	*	*	928	833	750	640	436	242	151	132	173	*	608	798	933	970	*	*
190	*	*	853	712	481	281	157	145	185	*	626	790	*	*	*	*	940	846	766	658	452	259	162	142	191	*	629	815	947	977	*	*
200	*	*	*	729	500	299	168	155	201	*	646	808	*	*	*	*	952	859	781	675	468	277	174	152	208	*	648	830	959	983	*	*
210	763	768	753	746	517	317	179	165	218	*	667	825	781	778	765	790	964	751	796	691	484	295	185	163	225	*	667	844	971	987	782	781
220	730	736	730	744	534	335	194	175	235	*	685	839	769	772	749	779	838	730	779	699	499	312	198	173	241	*	685	855	958	934	778	778
240	625	628	628	643	534	369	226	194	271	*	627	789	710	721	695	720	644	629	651	625	505	345	227	194	273	*	682	784	789	723	723	722
255	567	569	570	584	519	387	250	208	292	*	617	723	669	677	656	675	563	571	583	574	493	364	251	213	296	*	652	710	688	673	672	672

*Measurement not reliable

TABLE 8. AVERAGE FURNACE TEMPERATURES

Time (min)	Average Temperature (°C) Column No. 10	Column No. 11	Column No. 12
0	48	77	55
5	557	555	*
10	667	663	*
15	732	735	*
20	775	782	*
25	808	813	540
30	828	836	568
35	850	859	*
40	866	876	625
45	883	890	858
50	893	900	936
55	904	916	897
60	921	928	922
70	928	945	935
80	945	952	985
90	964	968	990
100	981	988	1011
110	992	999	1011
120	994	1007	1026
130	998	1018	1035
140	1019	1027	1045
150	1030	1037	1053
160	1040	1046	1059
170	1046	1056	1067
180	1054	1064	1077
190	1054	1072	1085
200	1063	1080	1094
210	1079	1087	1103
220	1085	1098	785
230	1091	1103	646
240	1103	1109	555
250	1107	1119	485
260	1111	1130	454
270		1132	
280		1138	

TABLE 9. MEASURED AXIAL DEFORMATION (COLUMNS 10-12)

Time (min)	Axial Deformation (mm)		
	Column No. 10	Column No. 11	Column No. 12
0	0.0	0.0	0.0
10	0.3	0.4	0.1
20	1.2	1.3	0.4
30	1.6	1.8	0.7
40	1.9	2.1	1.3
50	2.1	2.5	1.6
60	2.4	3.0	2.0
70	2.7	3.4	2.3
80	3.0	4.0	2.6
90	3.3	4.4	3.1
100	3.5	4.9	3.5
110	3.7	5.3	4.0
120	3.8	5.5	4.4
130	3.8	5.7	4.9
140	3.8	5.9	5.3
150	3.8	6.0	5.8
160	3.8	6.1	6.1
170	3.8	6.1	6.5
180	3.8	6.1	6.7
190	3.6	6.1	6.9
200	3.4	6.1	7.0
205	3.3	5.9	7.0
210	3.1	5.9	7.0
215	3.0	5.8	7.0
220	2.8	5.7	7.0
225	2.6	5.5	6.9
230	2.4	5.3	6.8
235	2.2	5.1	6.6
240	2.0	4.9	6.5
245	1.8	4.6	6.3
250	1.5	4.2	6.1
255	1.2	3.8	5.9
260	0.8	3.3	
265		2.8	
270		2.2	
275		1.6	
280		0.9	
285		-3.0	

(-) Sign indicates contraction of column past initial starting position.

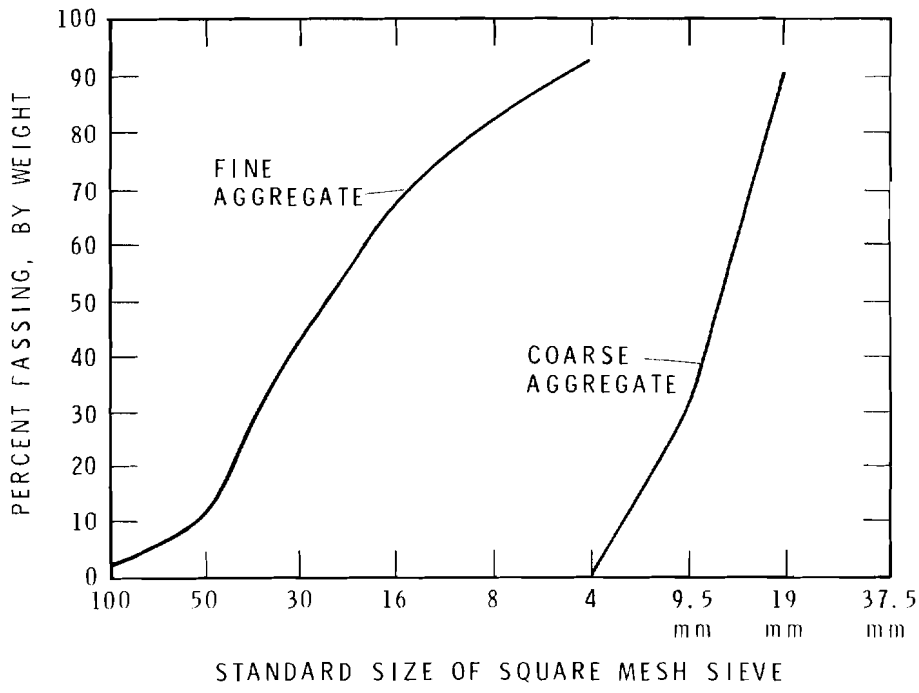

FIGURE 1

GRADATION CURVES OF SILICEOUS AGGREGATE

BR 6599-1

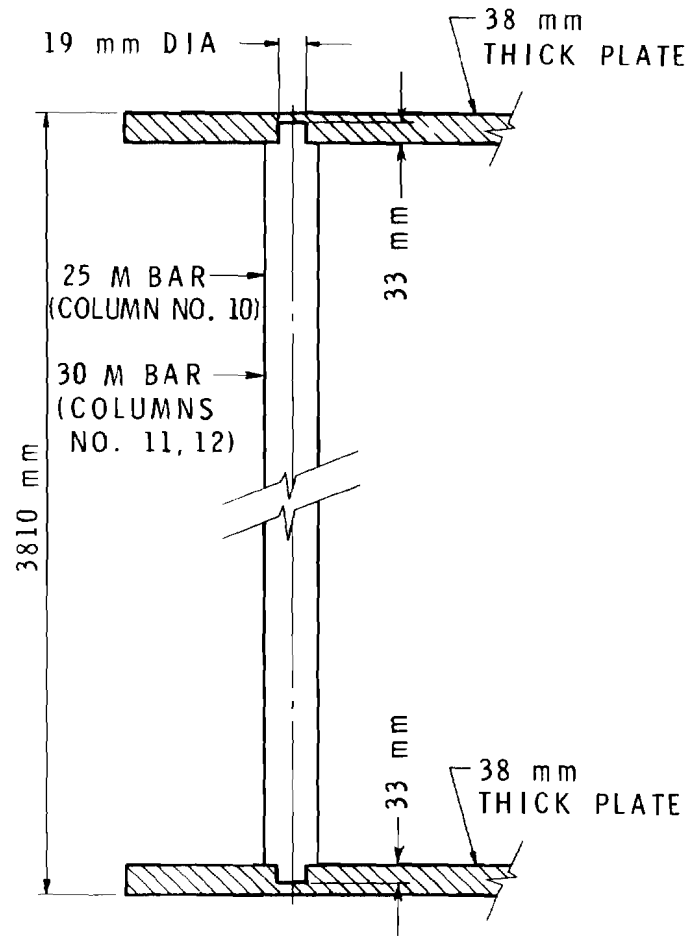

FIGURE 2

MAIN REINFORCING BARS

BR 6623-1

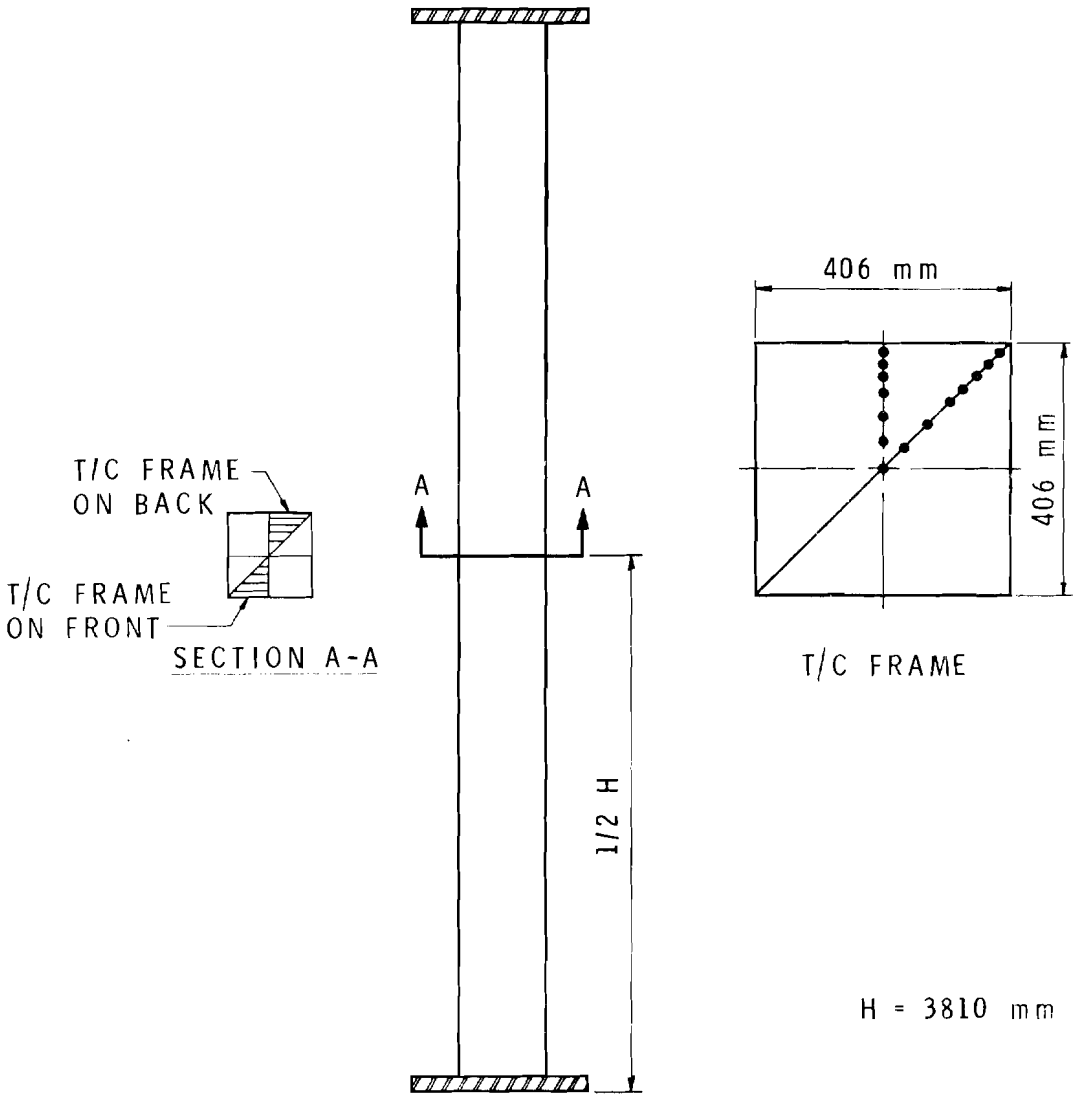

FIGURE 3

LAYOUT OF THERMOCOUPLE FRAMES (COLUMNS NO. 10, 11 AND 12)

BR 6599-3

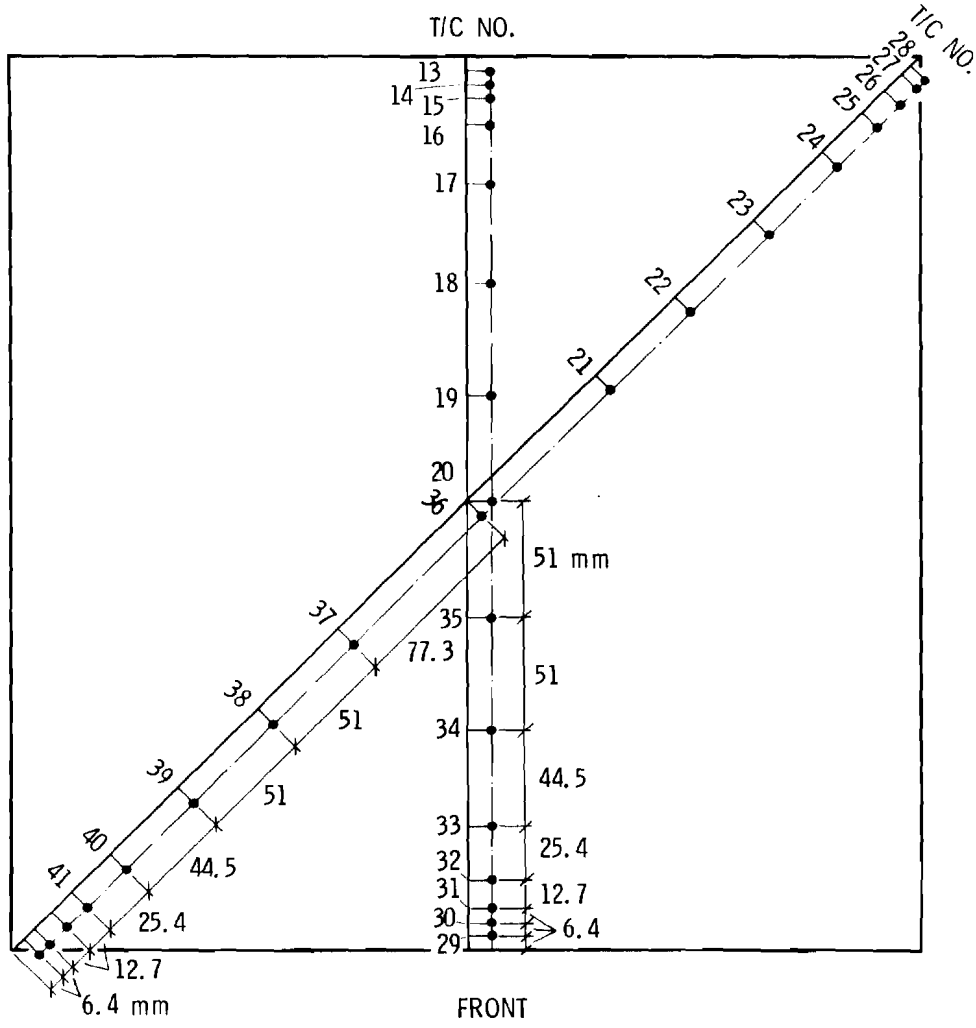

FIGURE 4

LOCATION AND NUMBERS OF THERMOCOUPLES IN SECTION OF COLUMNS NO. 10 AND 11

BR 6623-2

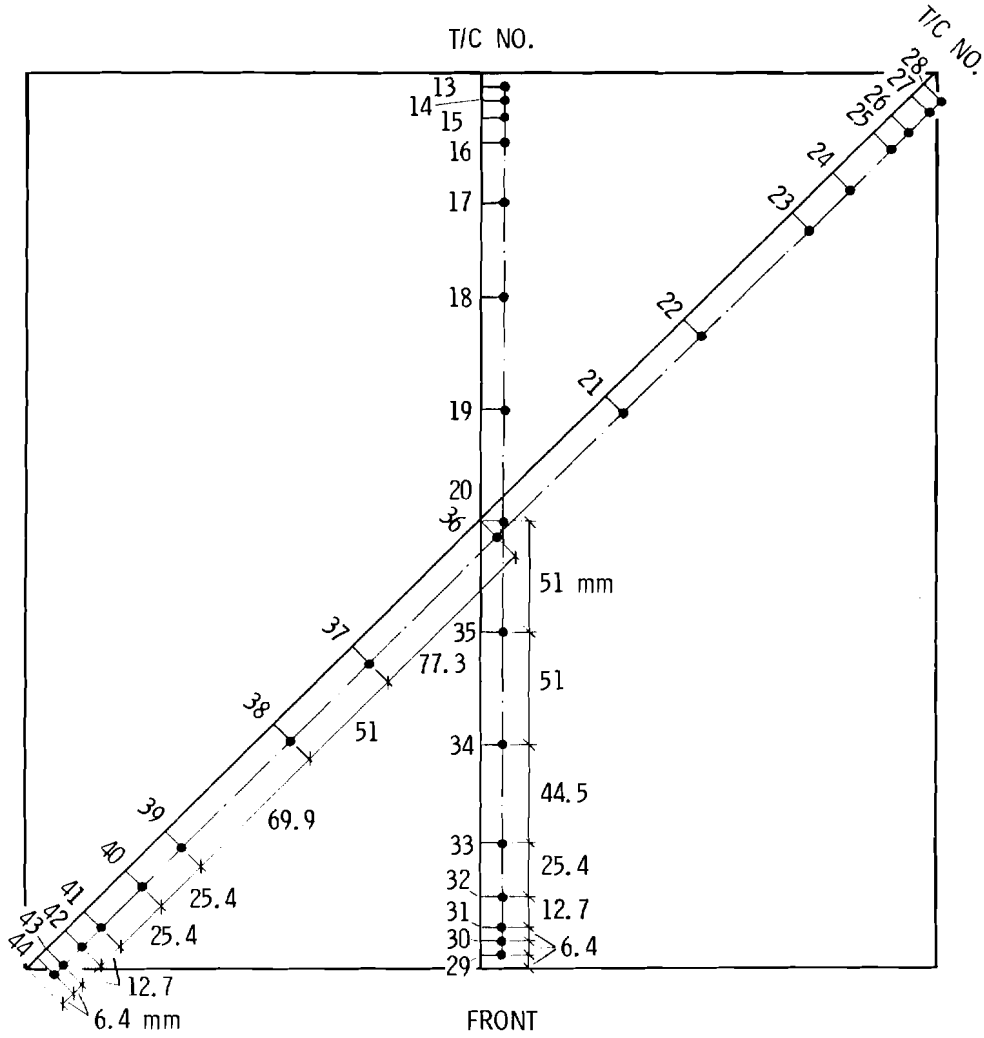

FIGURE 5

LOCATION AND NUMBERS OF THERMOCOUPLES IN SECTION OF COLUMN NO. 12

BR 6623-3

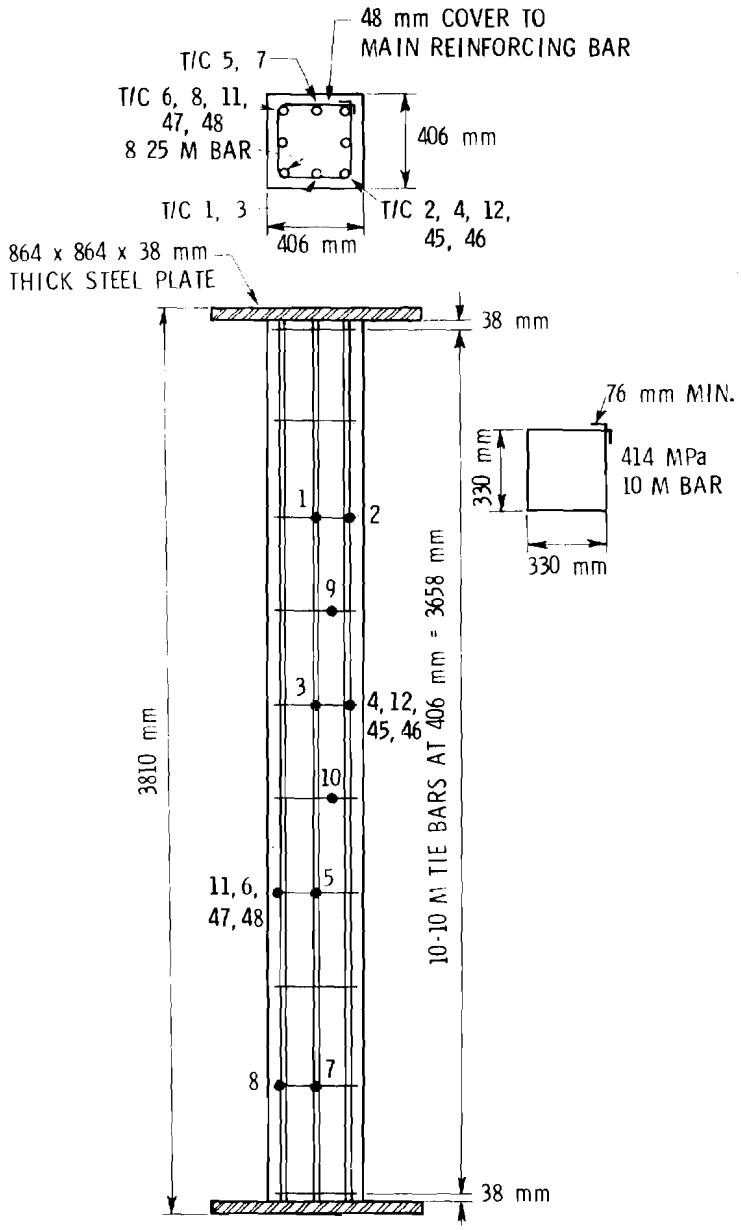

FIGURE 6

THERMOCOUPLES ON REINFORCING BARS
OF COLUMN NO. 10

BR 6623-4

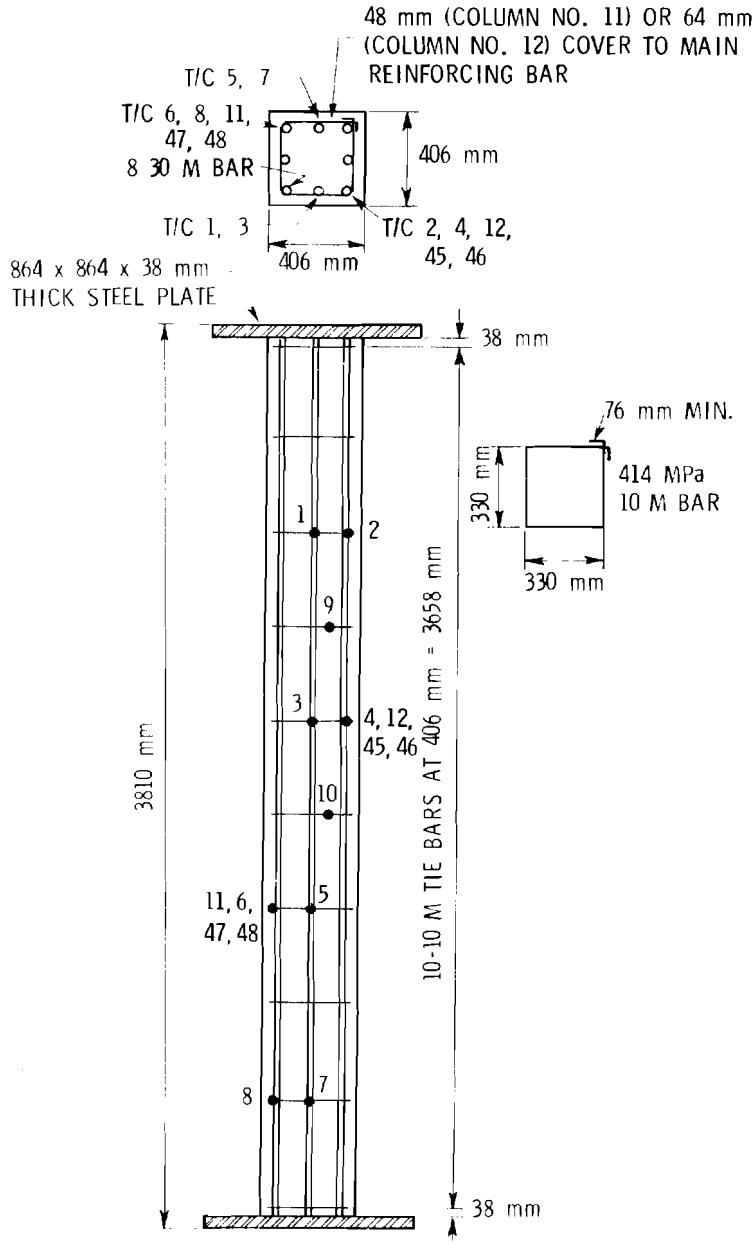

FIGURE 7

THERMOCOUPLES ON REINFORCING BARS OF COLUMNS NO. 11 AND 12

BR 6623-5

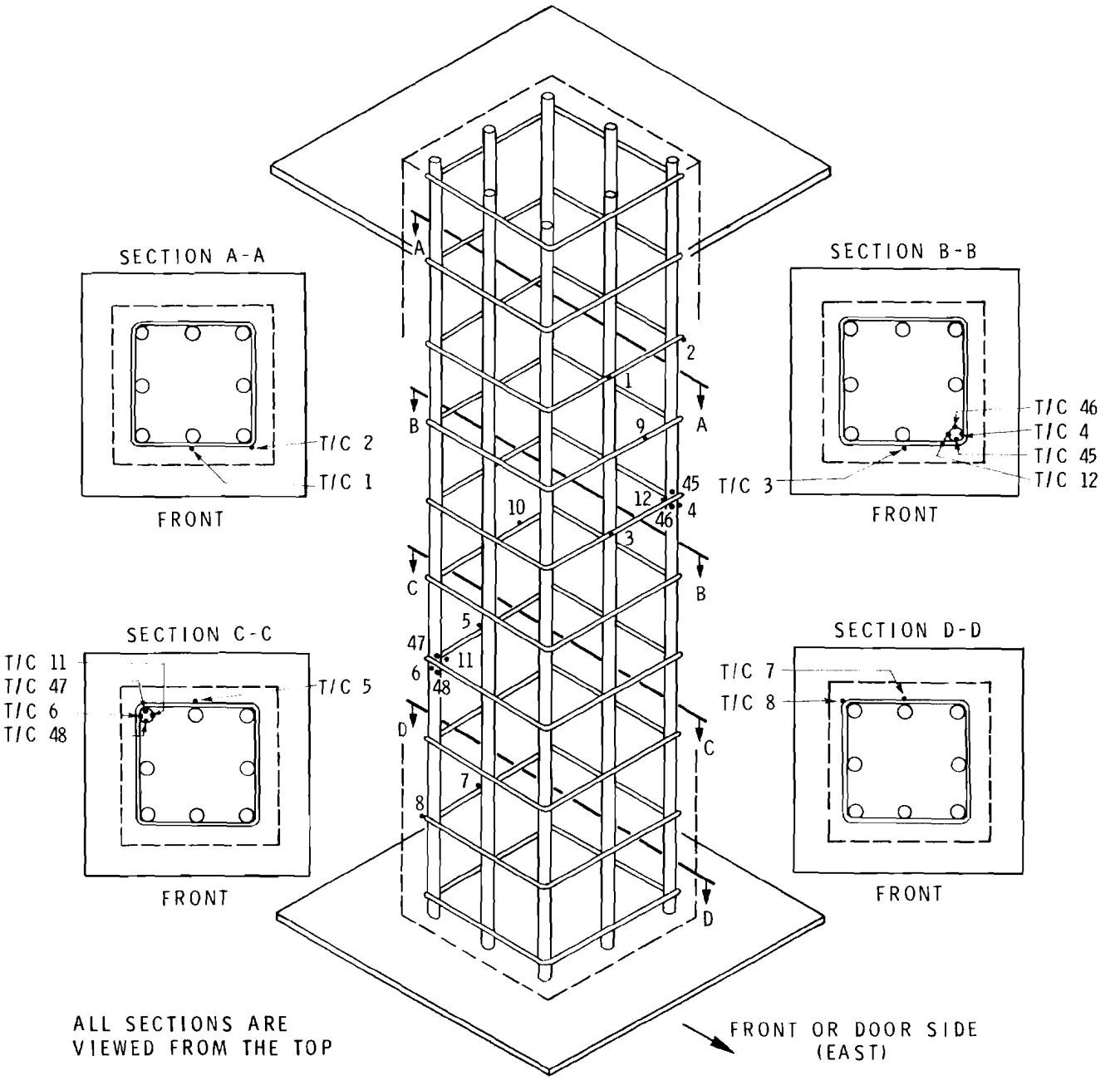

FIGURE 8

THERMOCOUPLES ON REINFORCING BARS OF COLUMNS NO. 10 - 12

BR 6623-6

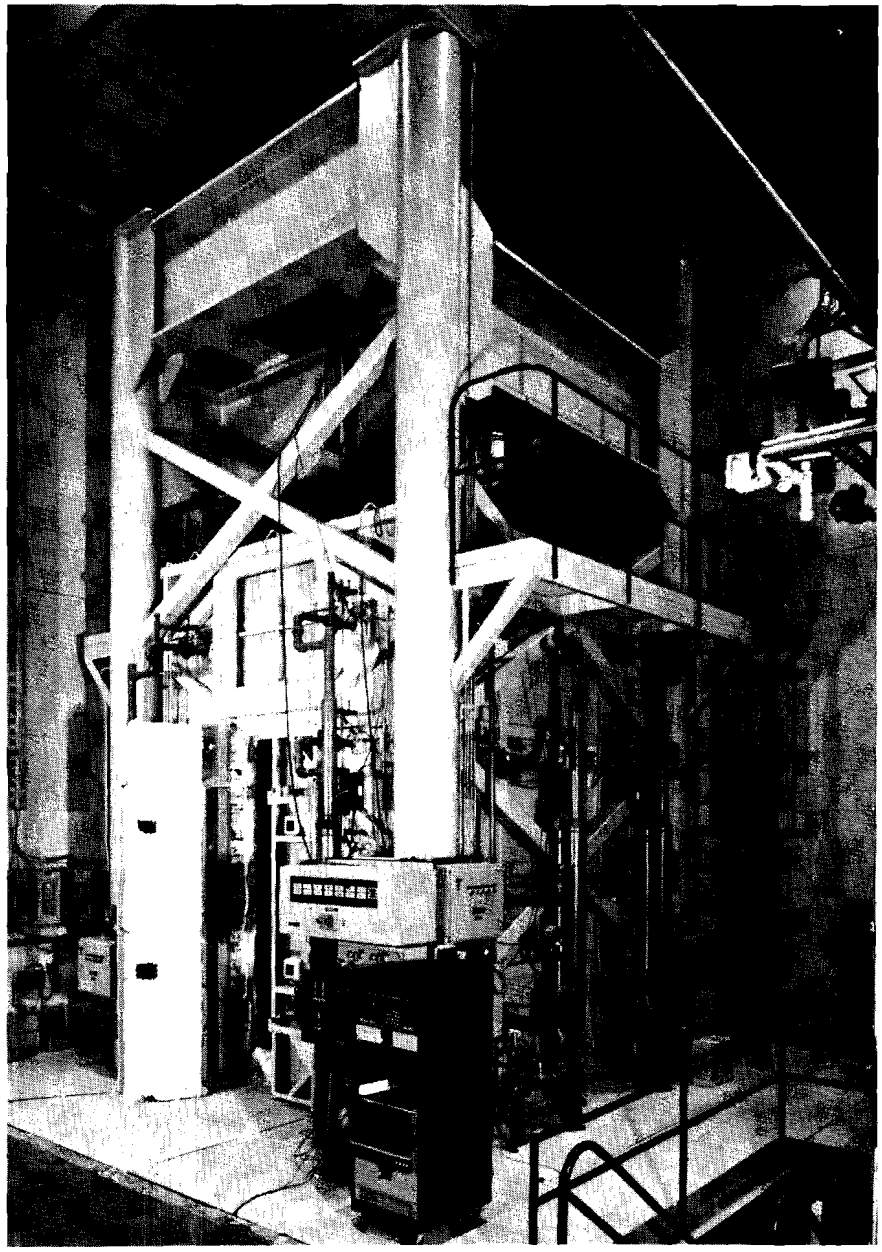

FIGURE 9

TEST FURNACE

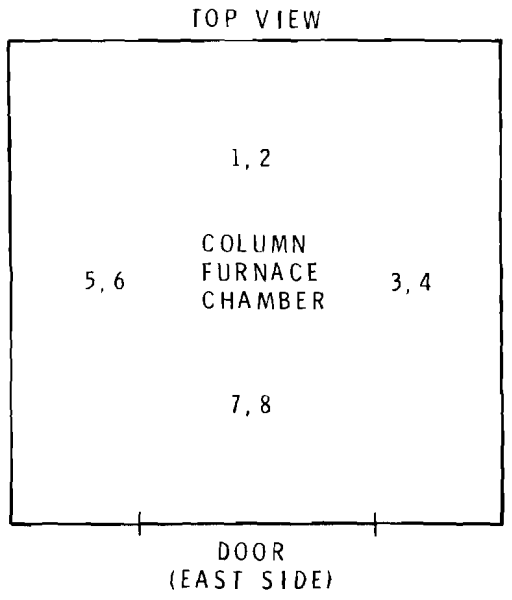

FIGURE 10

LOCATION AND NUMBERS OF THERMOCOUPLES IN COLUMN FURNACE CHAMBER

BR 6599-7

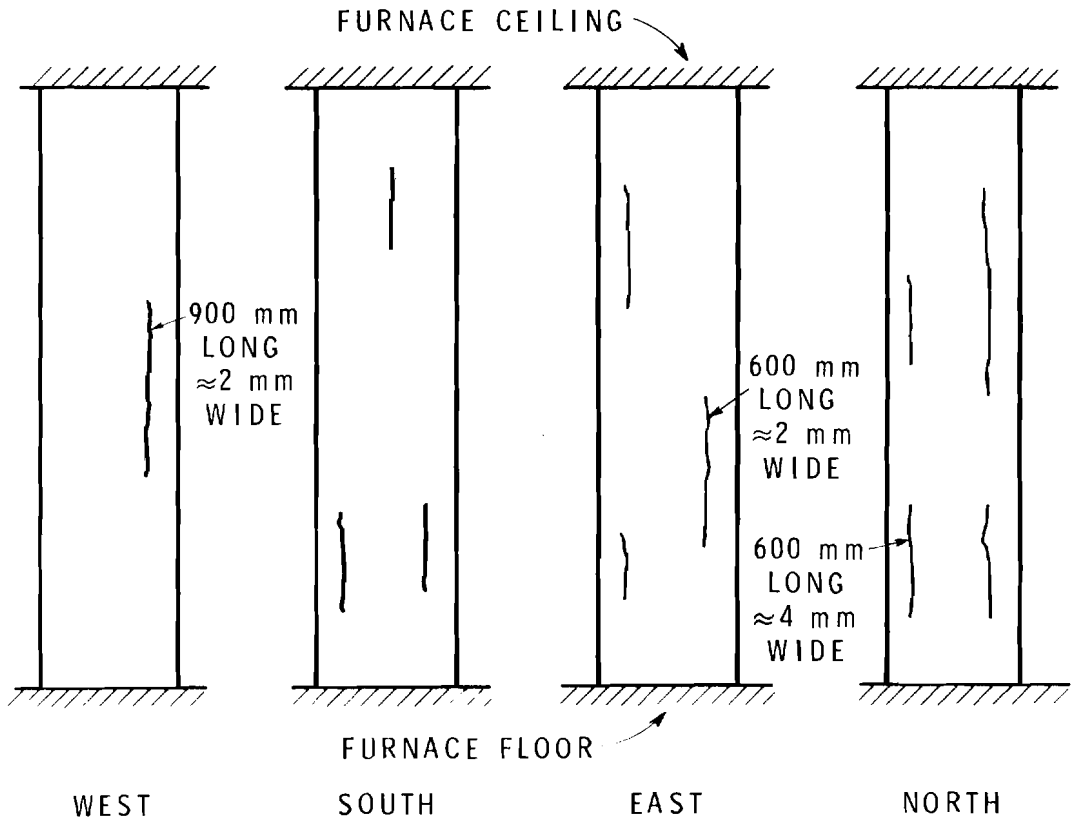

FIGURE 11

CRACKS IN COLUMN AT 1 h 35 min TEST TIME (COLUMN NO. 10, PHASE II)

BR 6623-7

FIGURE 12

COLUMN AFTER FIRE TEST
(COLUMN NO. 10, PHASE II)

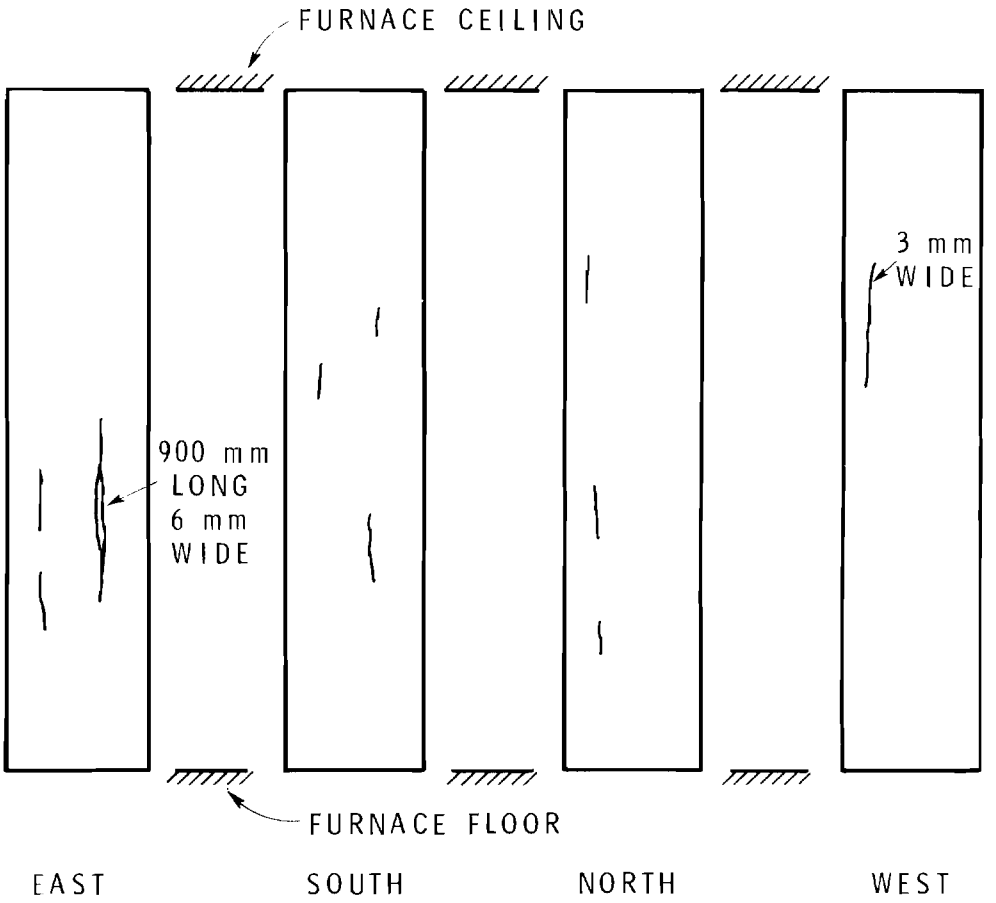

FIGURE 13

CRACKS IN COLUMN AT 4 h TEST TIME (COLUMN NO. 11, PHASE II)

BR 6623-8

FIGURE 14

COLUMN AFTER FIRE TEST
(COLUMN NO. 11, PHASE II)

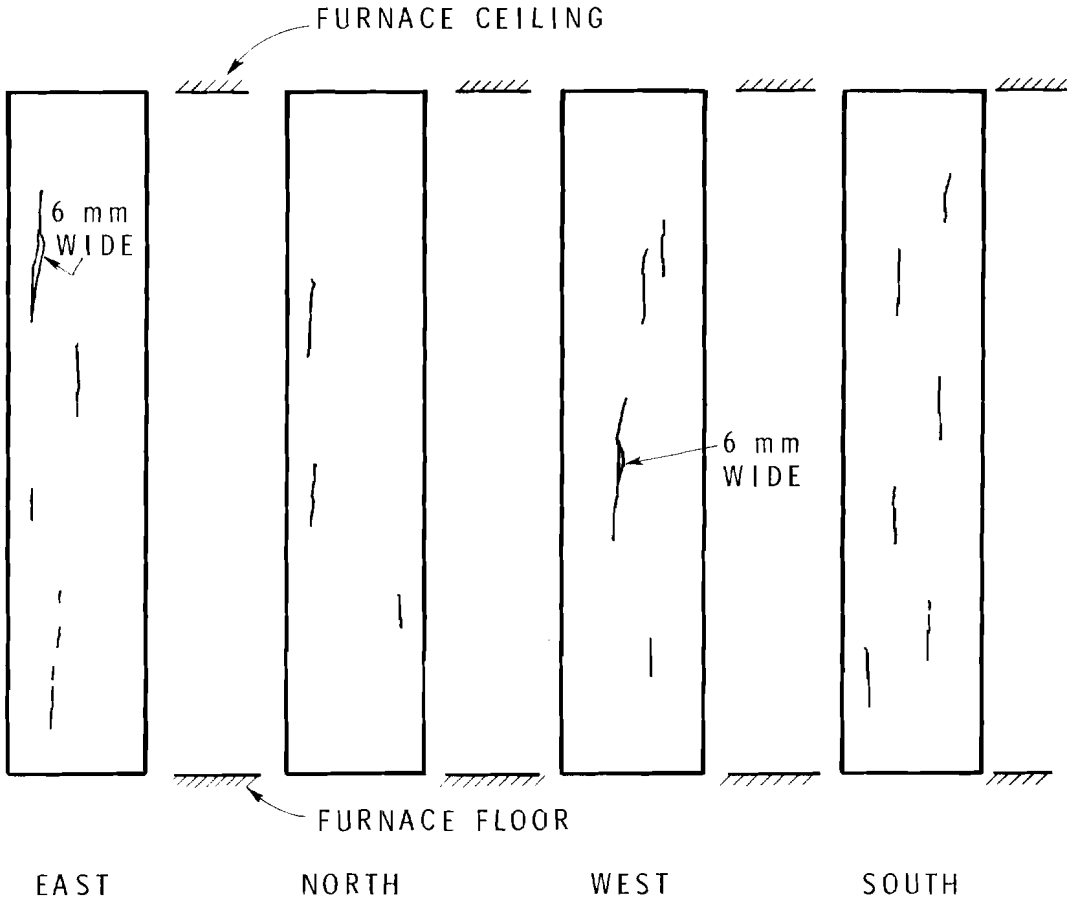

FIGURE 15

CRACKS IN COLUMN AT 2 h 15 min TEST TIME (COLUMN NO. 12, PHASE II)

BR 6623-9

FIGURE 16

COLUMN SHORTLY AFTER FIRE TEST
(COLUMN NO. 12, PHASE II)

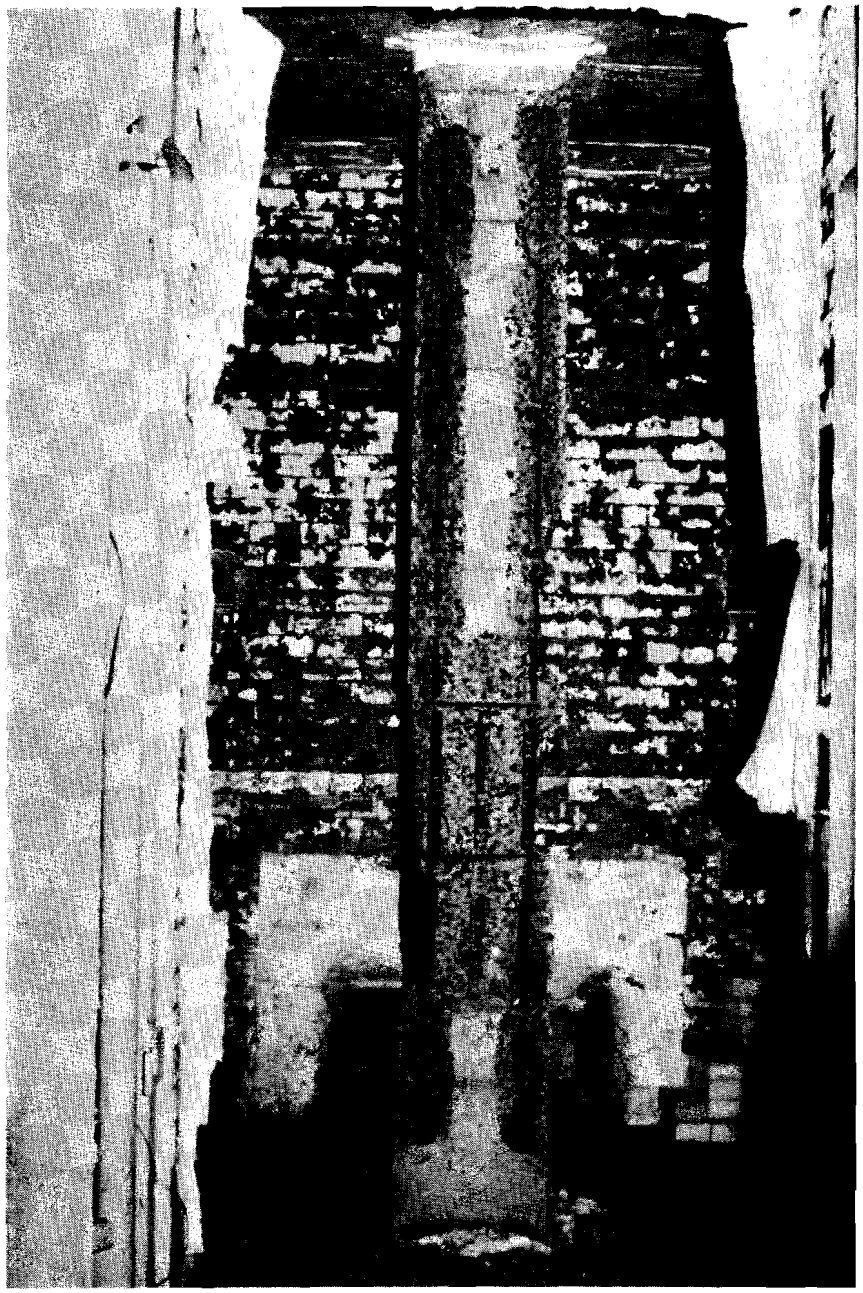

FIGURE 17

COLUMN 76 DAYS AFTER FIRE TEST
(COLUMN NO. 12, PHASE II)