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DEPARTMENT OF REGISTRATION AND EDUCATION
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DIVISION OF THE
STATE GEOLOGICAL SURVEY
M. M. LEIGHTON, *Chief*
URBANA

REPORT OF INVESTIGATIONS—NO. 175

VISCOSITY STUDIES OF SYSTEM $CaO-MgO-Al_2O_3-SiO_2$: IV, 60 and 65% SiO_2

BY

J. S. MACHIN AND TIN BOO YEE

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VISCOSITY STUDIES OF SYSTEM $CaO—MgO—Al_2O_3—SiO_2$: IV, 60 and 65% SiO_2

Variation of Viscosity when CaO, MgO, and/or Al_2O_3 are Constant

By

J. S. Machin and Tin Boo Yee

Abstract

In this final paper of a series on viscosity in the system CaO—MgO—Al_2O_3—SiO_2 data are presented for melts containing 60 and 65% SiO_2. There also are diagrammatic presentations of the systems of isokoms at intervals on planes parallel to the zero alumina, zero lime, and zero magnesia faces of the tetrahedron, the apices of which represent 100% of each of the four oxides that make up the system.

I. Introduction

This is the final paper in a series, the first three of which have appeared in this *Journal.*[1] The experimental methods were described in the earlier reports.

Tables I and II list the experimental values for the viscosity of melts containing 60 and 65% SiO_2, respectively. The percentages of CaO, MgO, and Al_2O_3 are such as to cover at 5% intervals that part of the compositional field which can be completely melted at 1500°C. These data are shown graphically in figs. 1 and 2. The isokoms have the same general direction as at lower silica levels, differing in that they are more nearly parallel to the lines along which the percentage of alumina is constant.

II. Effect of Al_2O_3 on Viscosity

Figures 3, 4, and 5 show the pattern of the isokoms when the percentage of Al_2O_3 is constant. The lines show less curvature in general than do isokoms drawn parallel to any of the other basal planes of the compositional tetrahedron. The variation of viscosity on these planes (constant Al_2O_3) is controlled mostly by the SiO_2 content, the increase of which increases the viscosity at a moderate rate for low Al_2O_3 content. As the Al_2O_3 content mounts, the rate of increase of viscosity with increasing SiO_2 is accelerated. The effect of increasing CaO and MgO is to cause moderate lowering of the viscosity. This effect is slightly more pronounced at higher Al_2O_3 contents.

At 0% Al_2O_3 content the isokoms are nearly straight lines which make rather small angles with the lines along which the silica content is constant. When the Al_2O_3 content increases to 10%, the isokoms are still rather straight, but the angle with the constant silica lines has increased. At 20% Al_2O_3 this angle has increased still more and the lines have developed noticeable curvature.

III. Variation of Viscosity with Changing Lime Content (Figs. 6, 7, and 8)

The isokoms on sections of the compositional tetrahedron cut parallel to the

Table I. Viscosity Data for the System: Lime—Magnesia—Alumina—Silica (SiO_2 = 60%)

Melt No.	Composition (wt. %)			Viscosity (poises) at °C.					
	Al_2O_3	CaO	MgO	1500	1450	1400	1350	13.00	1250
173	0	40	0	8.99	14.4				
170	0	35	5	8.83	12.8	19.1	30.3		
167	0	30	10	8.85	12.6	19.3	30.1		
155	0	25	15	8.72	12.2	18.2	27.7		
158	0	20	20	7.80	11.0	16.9	26.8		
162	0	15	25	7.25	10.6	17.9			
165	0	10	30	7.62					
129	5	35	0	17.1	25.0	39.4			
204	5	30	5	17.6	25.7	40.0	67.1	120	240
205	5	25	10	17.3	26.2	35.7	54.1	94.9	180
206	5	20	15	15.7	23.3	36.2	57.9	105	
207	5	15	20	13.9	20.6	31.7	52.0		
208	5	10	25	13.6	19.6				
243	5	5	30	11.6					
124	10	30	0	32.6	51.7	81.6	126	220	421
209	10	25	5	36.6	57.8	92.4	158	297	619
210	10	20	10	32.5	50.4	79.7	139	259	537
211	10	15	15	28.5	42.7	71.0	122	227	478
212	10	10	20	24.9	38.3	62.3	111		
213	10	5	25	22.6	35.1				
213.5	10	0	30	20.4					
119	15	25	0	77.7	128	214	390	730	1,560
214	15	20	5	82.9	132	225	417	831	1,820
215	15	15	10	69.1	112	194	352	693	1,550
216	15	10	15	53.8	87.2	149	273	530	1,180
236	15	5	20	45.1	75.1	121	236		
236.5	15	0	25	40.7	68.6	118			
115	20	20	0	204	353	663	1260	2530	5,750
237	20	15	5	183	323	597	1190	2670	6,290
238	20	10	10	137	238	440	856	1880	4,420
239	20	5	15	84.1	140	258	491	1030	2,330
239.5	20	0	20	86.8	148	269	538		
138	25	15	0	621	1200	2600			
240	25	10	5	349	667	1350	2930	7210	18,000
241	25	5	10	228	413	815	1720	4060	12,000
241.5	25	0	15	175	318	612	1310	3040	8,260

zero lime face are gently curved and are roughly parallel to the lines along which the MgO content is constant, provided the lime content is high (40%). As the lime content decreases, the angle between the isokoms and the constant MgO lines increases slowly.

IV. Variation of Viscosity with Changing MgO Content

The zero magnesia basal plane of the compositional tetrahedron was considered in paper II of this series [1(b)]. Figure 1 of that paper shows the isokoms to be roughly parallel to those compositional lines along which the CaO is constant. The viscosity decreases rather rapidly at low lime content and less rapidly at higher lime content as the lime content increases.

When the MgO content becomes 10% (fig. 9, this paper), the parallelism of the isokoms with the constant lime lines

Table II. Viscosity Data for the System: Lime—Magnesia—Alumina—Silica (SiO_2 = 65%)

Melt No.	Composition (wt. %)			Viscosity (poises) at °C.					
	Al_2O_3	CaO	MgO	1500	1450	1400	1350	1300	1250
172	0	35	0	21.4					
128	5	30	0	42.2	69.9				
217	5	25	5	46.2	66.1				
218	5	20	10	39.8	66.1				
219	5	15	15	36.7	64.0				
123	10	25	0	94.6	152	256	460	854	1,780
221	10	20	5	114	193	318	578	1,120	2,480
222	10	15	10	97.2	157	269	505	1,010	
223	10	10	15	86.4	136	236			
224	10	5	20	74.6	125				
114R	15	20	0	311	574	1040	1960	4,500	
225	15	15	5	257	444	821	1590	3.380	8,530
226	15	10	10	224	391	720	1420	2,920	6,820
227	15	5	15	181	307	557	1120	2,450	
249	15	0	20	126	216	392	778	1,770	
113	20	15	0	940	1590	3210	6440	14,700	31,200
228	20	10	5	671	1200	2410	5150	11,900	30,300
229	20	5	10	419	737	1430	3010	6,910	17,500
248	20	0	15	263	488	956	1980	4,070	12,400
112	25	10	0	1900	3960				
230	25	5	5	1030					
247	25	0	10	568	1100	2340			

persists in the high-lime low-viscosity areas but is less noticeable in the low-lime areas where the viscosity is higher. The same tendencies are more marked when the MgO content is increased to 20% (fig. 10). The viscosity at constant lime content decreases as the magnesia content increases and the silica remains constant. When both silica and alumina remain constant, increase of magnesia decreases the viscosity only in slight degree for amounts of magnesia up to 10%. As magnesia is increased to 20%, the decrease in viscosity for the same silica and alumina value is more marked.

The rate of change of viscosity with respect to variation of lime and alumina content is less as the magnesia content increases. McCaffery[2] pointed this out and suggested that advantage might be taken of the fact to minimize viscosity variation of the slag in iron blast-furnace operation.

V. General Picture

In this $CaO-MgO-Al_2O_3-SiO_2$ system the viscosity is represented by a system of surfaces which, although not planes, curve only gently. If one takes a sheet of paper and bends it so that the edge is shaped like an integral sign ∫ and then twists the sheet so as to warp it a little, one will have an approximate representation of a surface within the compositional tetrahedron, all points on which have the same viscosity at a given temperature. The picture is possibly not quite so simple as this at very high viscosities, but for low and intermediate viscosities the general pattern of variation is not highly complicated. An attempt to represent this pictorially has been made in fig. 11, which is an oblique drawing of the tetrahedral solid with some typical isoviscous surfaces inscribed.

It has been suggested in the past that phase-field borderlines on the phase equilibrium diagrams might be expected to influence viscosity. This implies breaks in the isokoms when they cross phase-field borderlines. Figure 3 covers a phase-wise complicated part of the lime-magnesia-silica system[3] (see phase equilibrium diagram of Osborn), but there are no significant aberrations in the isokoms in this field.

Footnotes

[1] (a) J. S. Machin and D. L. Hanna, "Viscosity Studies of the System CaO—MgO—Al_2O_3—SiO_2: I, 40% SiO_2," *J. Am. Ceram. Soc.*, 28 [11] 310—16 (1945); *Illinois State Geol. Survey Rept. Investigations*, No. 111 (1945).

(b) J. S. Machin and Tin Boo Yee, "Viscosity Studies of the System CaO—MgO—Al_2O_3—SiO_2: II, CaO—Al_2O_3—SiO_2," *J. Am. Ceram. Soc.*, 31 [7] 200—204 (1948); *Illinois State Geol. Survey Rept. Investigations*, No. 137 (1948).

(c) J. S. Machin, Tin Boo Yee, and D. L. Hanna, "Viscosity Studies of the System CaO—MgO—Al_2O_3—SiO_2: III, 35, 45, and 50% SiO_2," *J. Am. Ceram. Soc.*, 35 [12] 322—25 (1952); *Illinois State Geol. Survey Rept. Investigations*, No. 163 (1953).

[2] R. S. McCaffery, J. F. Oesterle, and O. O. Fritsche, "Effect of Magnesia on Slag Viscosity," *Am. Inst. Mining Met. Engrs., Tech. Pub.*, No. 383, pp. 55-68 (1931); *Ceram. Abstr.*, 10 [6] 460 (1931).

[3] E. F. Osborn, "The Compound Merwinite (3CaO · MgO · SiO_2) and Its Stability Relations Within the System CaO—MgO—SiO_2 (Preliminary Report)," *J. Am. Ceram. Soc.*, 26 [10] 321—32 (1943).

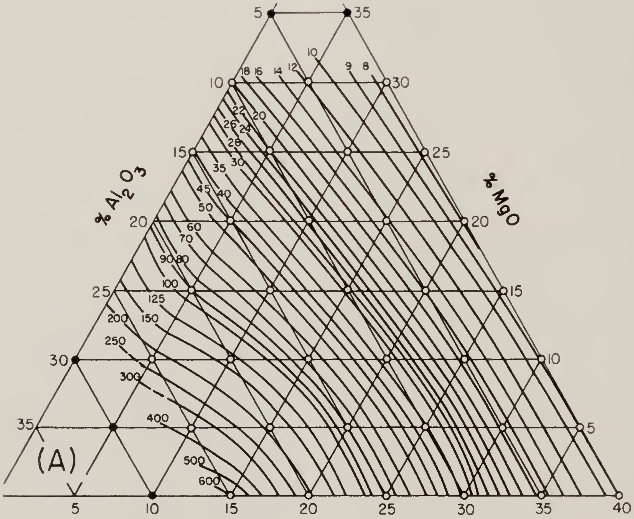


Fig. 1.—See opposite page.

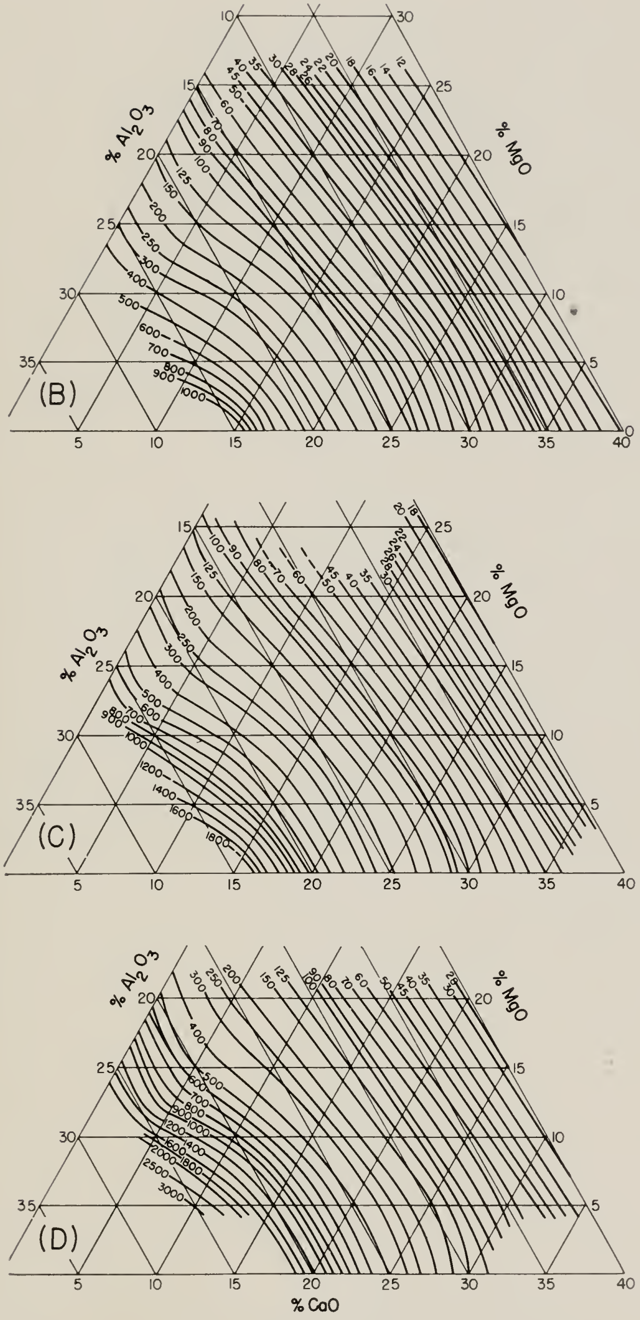


Fig. 1.—Isokoms (60% SiO_2) at (A) 1500° C., (B) 1450° C., (C) 1400° C., (D) 1350° C. In (A) solid circles indicate experimental compositions not molten at 1500° C.; hollow circles, compositions molten at 1500° C. or lower.

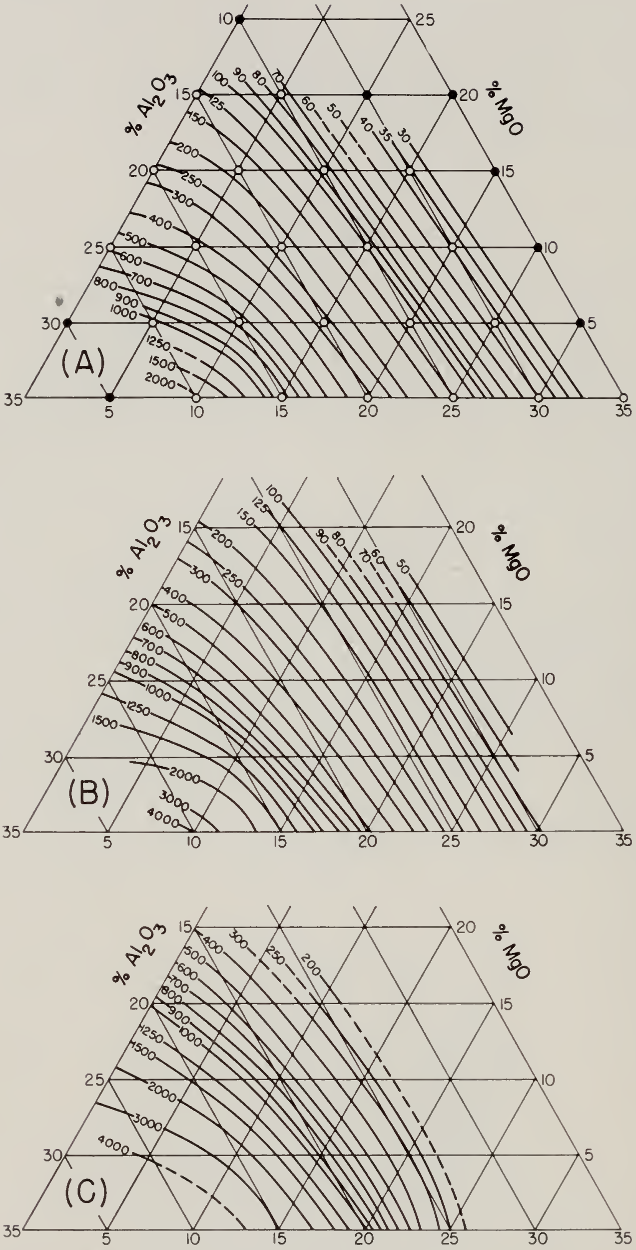


FIG. 2.—Isokoms (65% SiO_2) at (A) 1500° C., (B) 1450° C., (C) 1400° C., (D) 1350° C. In (A) solid circles indicate experimental compositions not molten at 1500° C.; hollow circles, compositions molten at 1500° C. or lower.

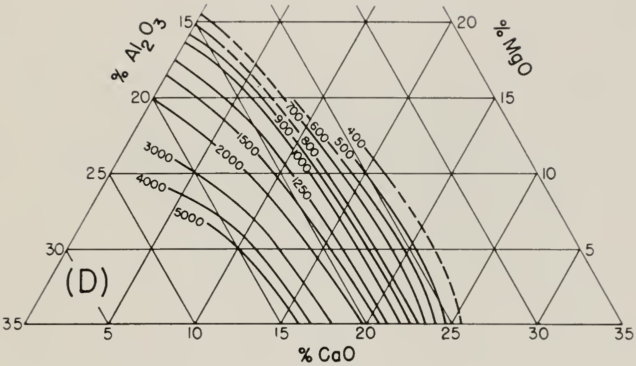


Fig 2.—Continued.

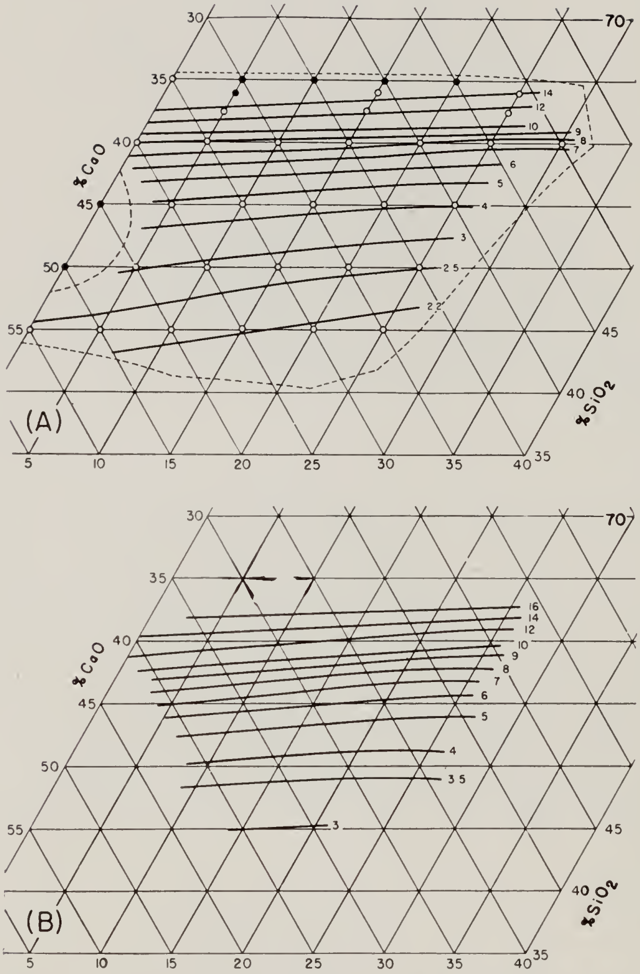


Fig. 3.—Isokoms (0% Al_2O_3) at (A) 1500° C., (B) 1450° C., (C) 1400° C. In (A) solid circles indicate experimental compositions not molten at 1500° C.; hollow circles, compositions molten at 1500° C. The dashed isotherm is from Osborn, footnote 3.

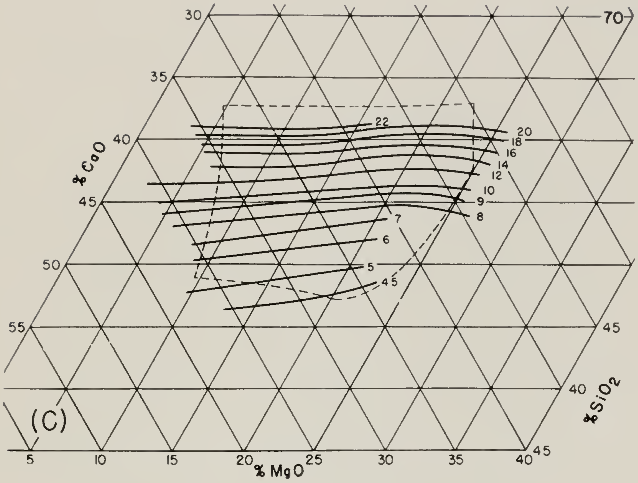
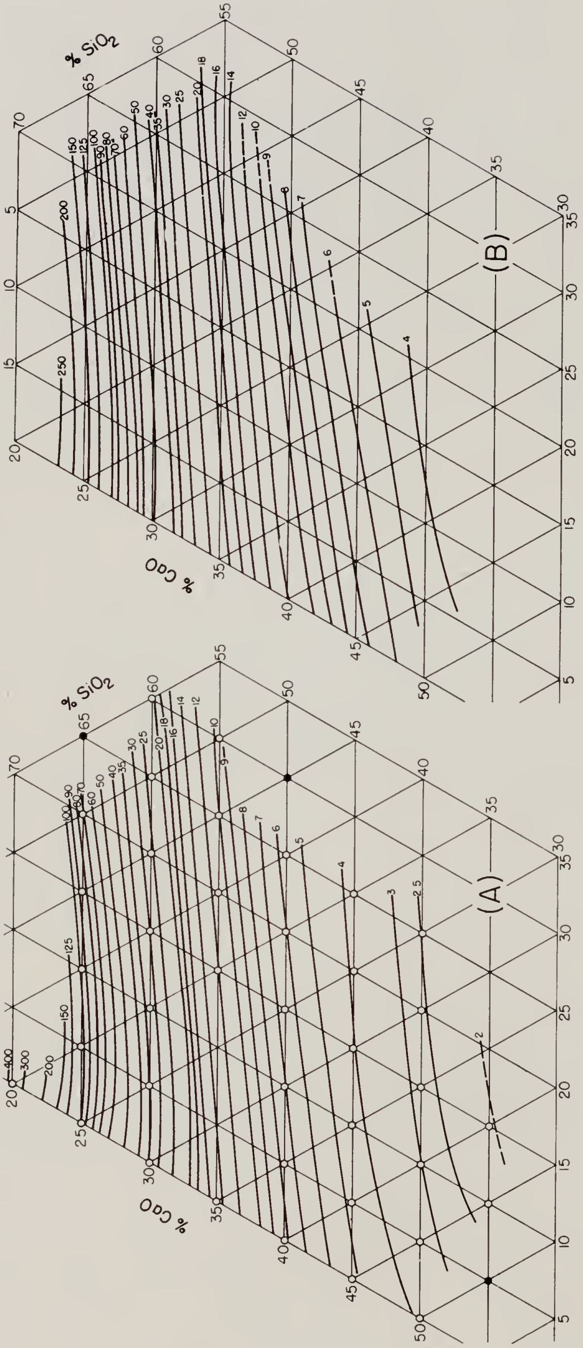


Fig. 3.—Continued.


% SiO2
70
65
60
55
50
45
40
35
30
5
10
15
20
% CaO
25
30
35
40
45
50
35
30
25
20
15
10
5
150
125
100
90
80
70
60
50
40
35
30
25
20
18
16
14
12
10
9
8
7
6
5
4
200
250
(B)
% SiO2
70
65
60
55
50
45
40
35
30
20
% CaO
25
30
35
40
45
50
35
30
25
20
15
10
5
100
90
80
70
60
50
40
35
30
25
20
18
16
14
12
10
9
8
7
6
5
4
3
2.5
2
125
150
200
300
400
(A)

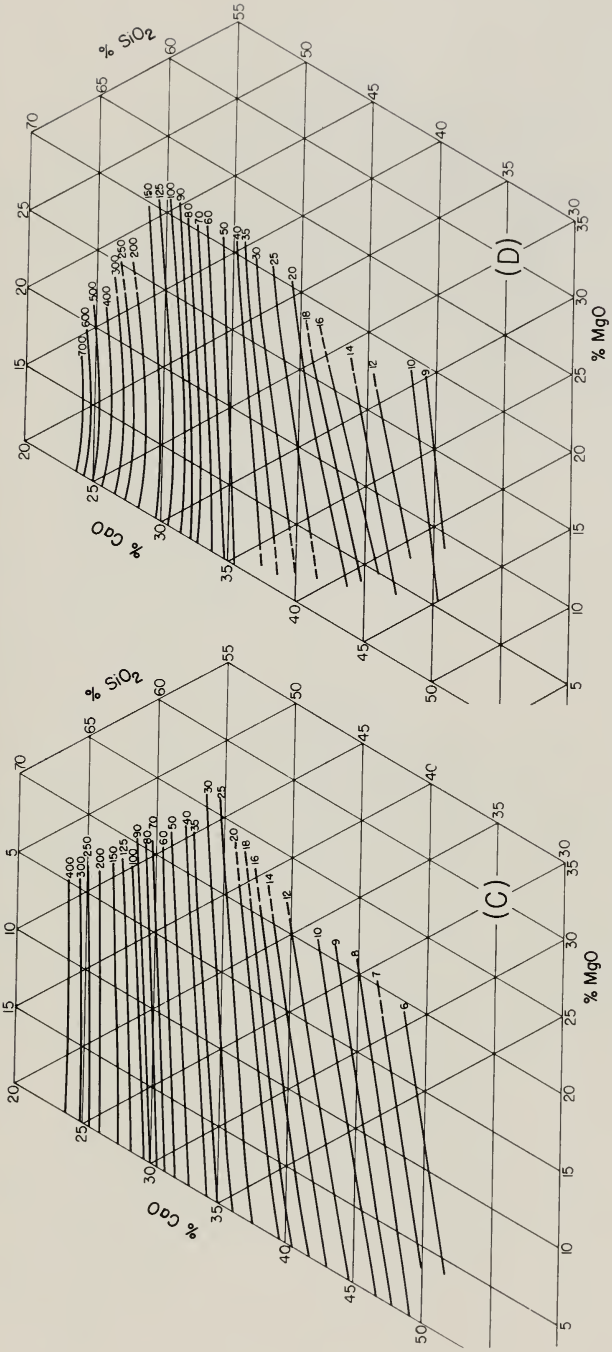
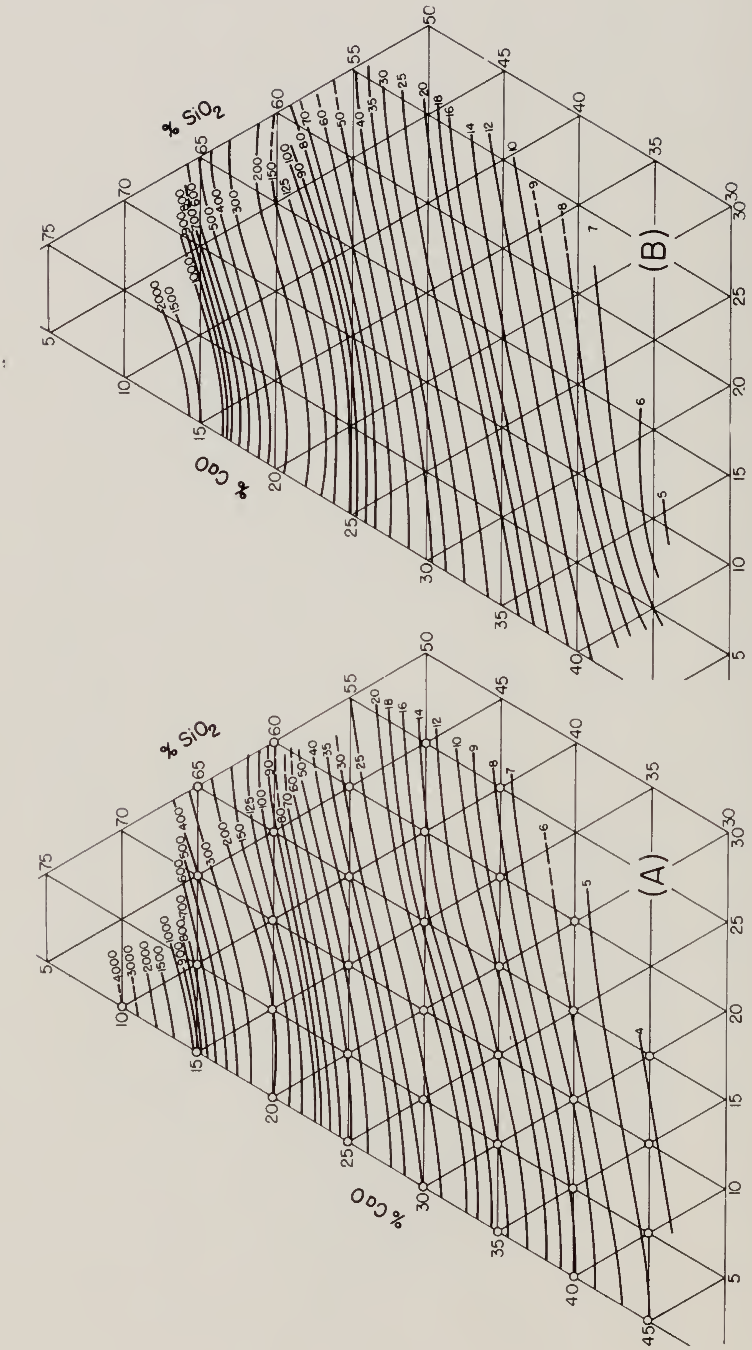


Fig. 4.—Isokoms (10% Al_2O_3) at (A) 1500° C., (B) 1450° C., (C) 1400° C., (D) 1350° C.


% SiO₂
% CaO
(A)
(B)
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5

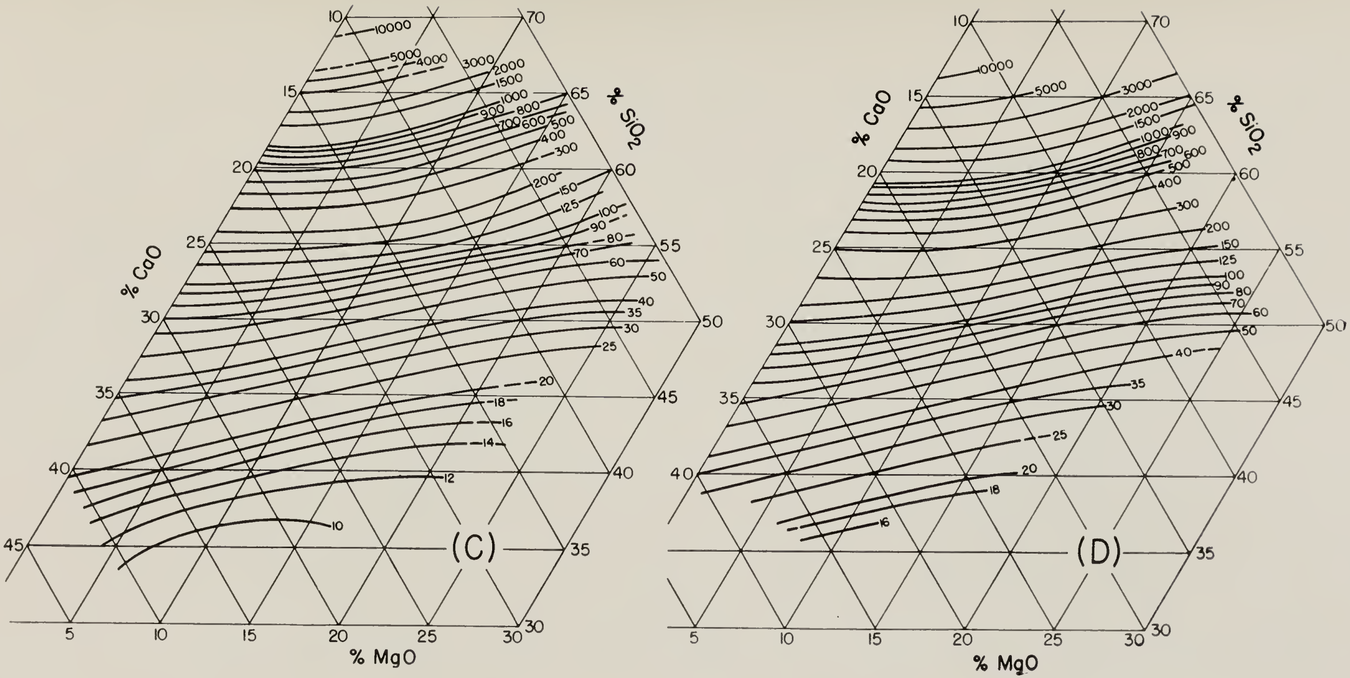
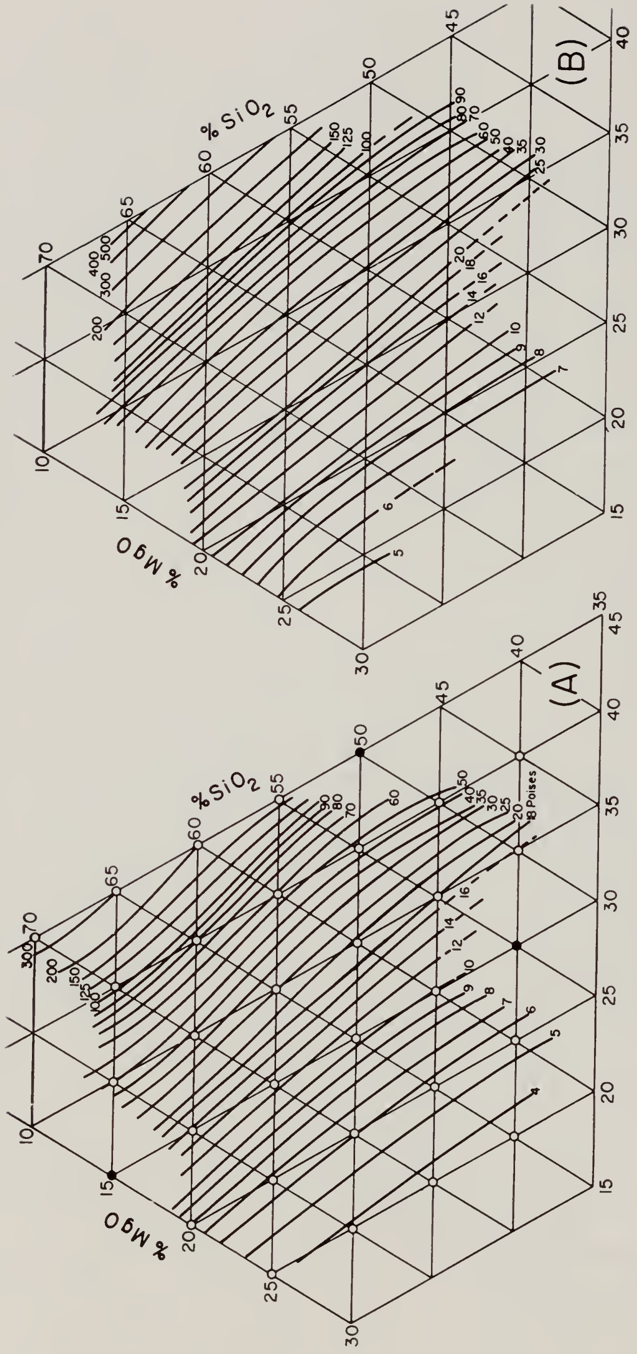


Fig. 5—Isokoms (20% Al_2O_3) at (A) 1500° C., (B) 1450° C., 1400° C., (D) 1350° C.


% SiO2
% MgO
(A)
(B)
10
15
20
25
30
35
40
45
50
55
60
65
70
18 Poises
300
200
150
125
100
90
80
70
60
50
40
35
30
25
20
16
14
12
10
9
8
7
6
5
4
400
500

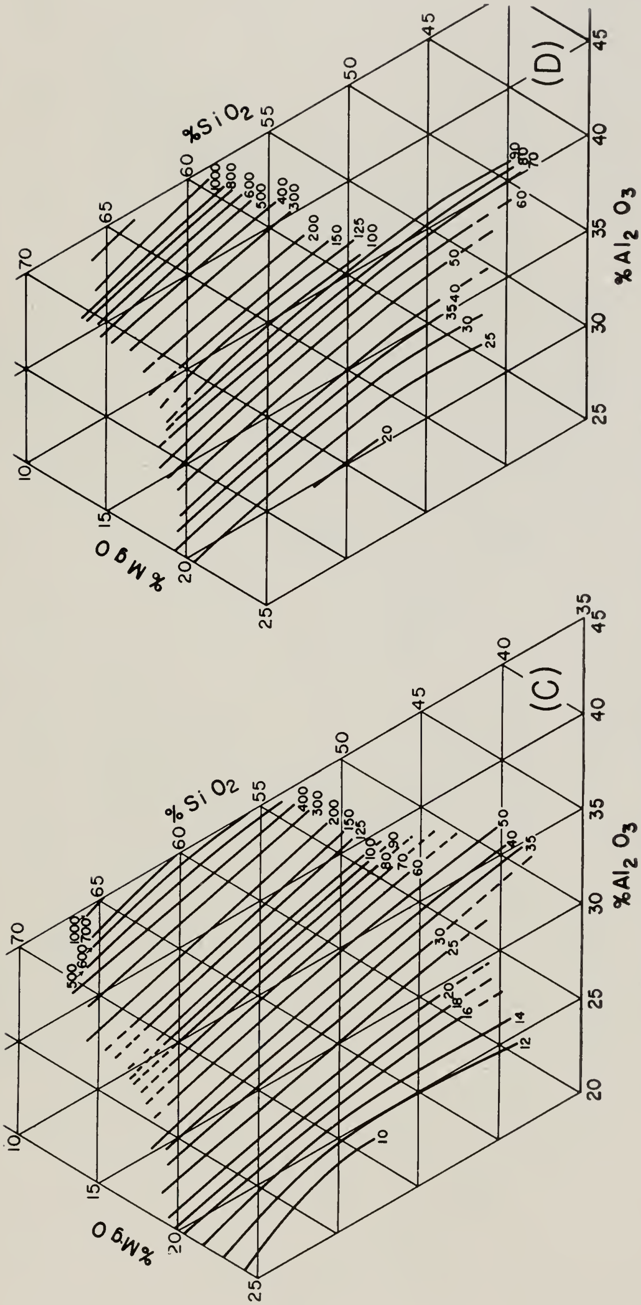
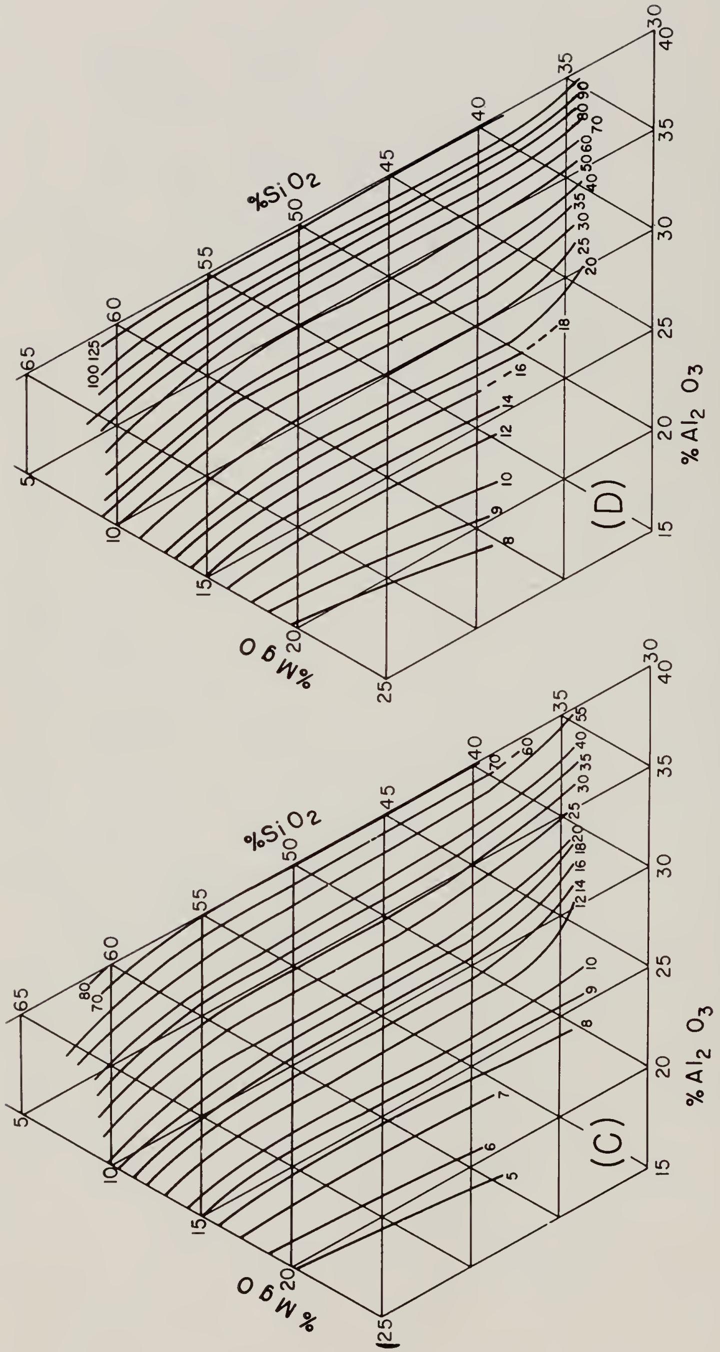


Fig. 6.—Isokoms (20% CaO) at (A) 1500° C., (B) 1450° C., (C) 1400° C., (D) 1350° C.


(D)
%SiO2
65
60
55
50
45
40
35
%MgO
5
10
15
20
25
% Al2 O3
15
20
25
30
35
40
30
100
125
8
9
10
12
14
16
18
20
25
30
35
40
50
60
70
80
90
(C)
%SiO2
65
60
55
50
45
40
35
%MgO
5
10
15
20
25
% Al2 O3
15
20
25
30
35
40
30
80
70
5
6
7
8
9
10
12
14
16
18
20
25
30
35
40
55
60
70

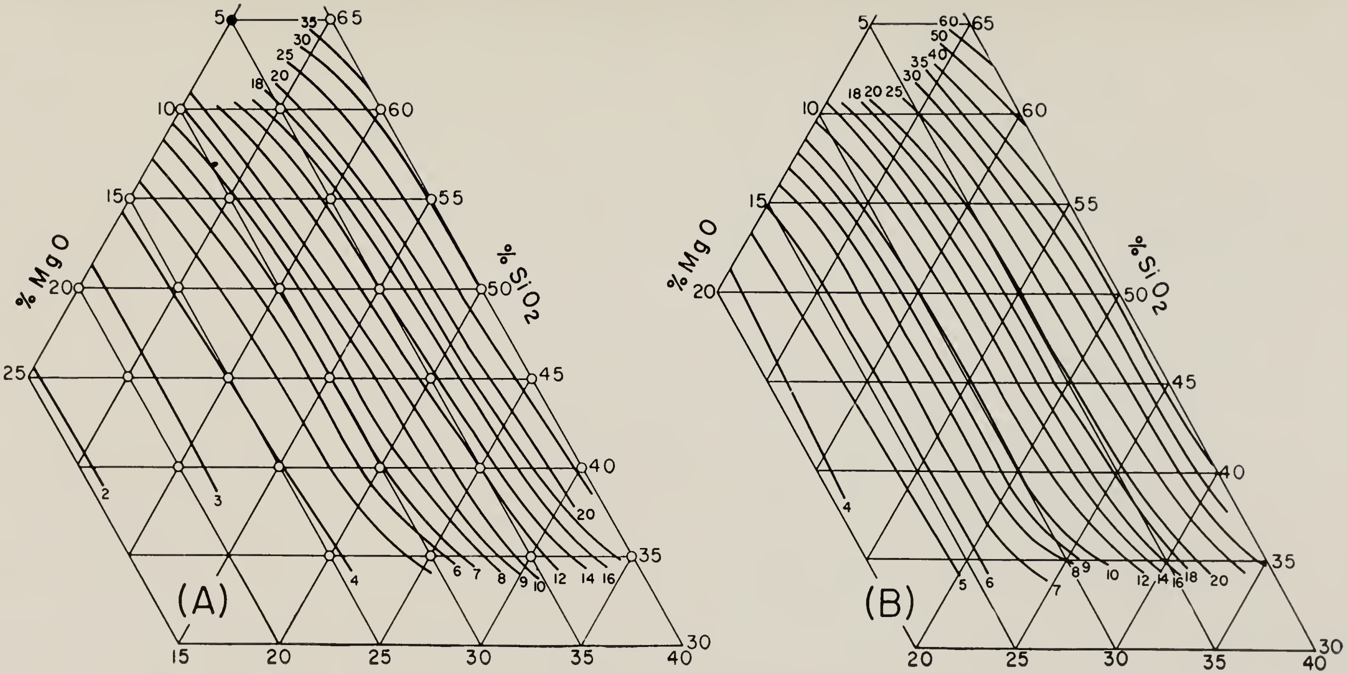


Fig. 7.—Isokoms (30% CaO) at (A) 1500° C., (B) 1450° C., (C) 1400° C., (D) 1350° C.

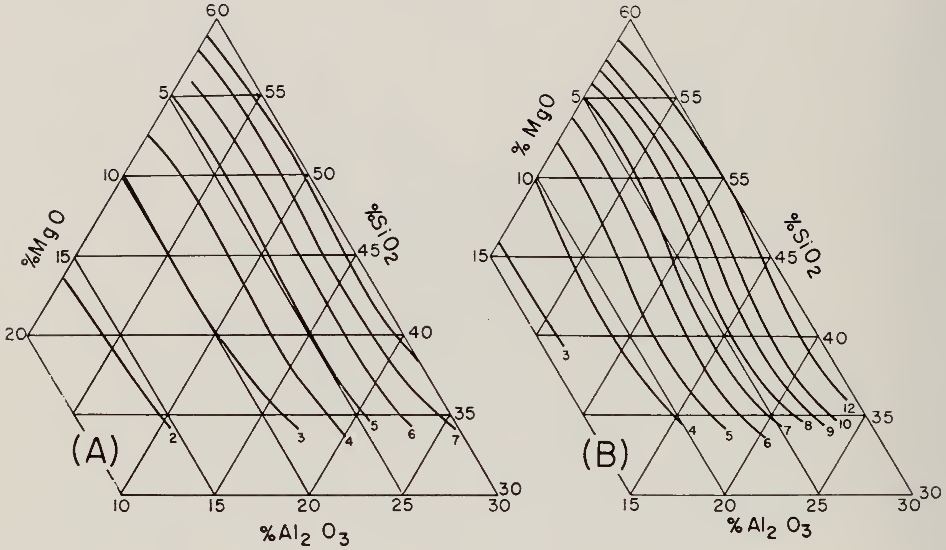


Fig. 8.—Isokoms (40% CaO) at (A) 1500° C., (B) 1450° C., (C) 1400° C.

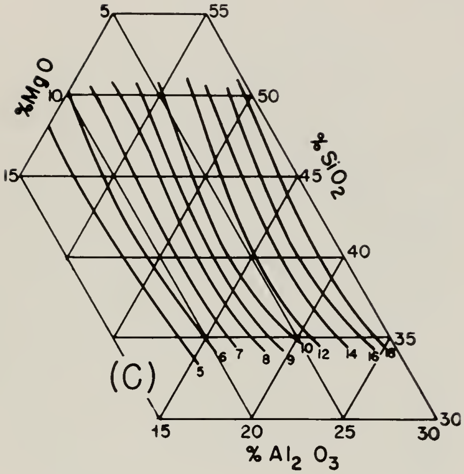
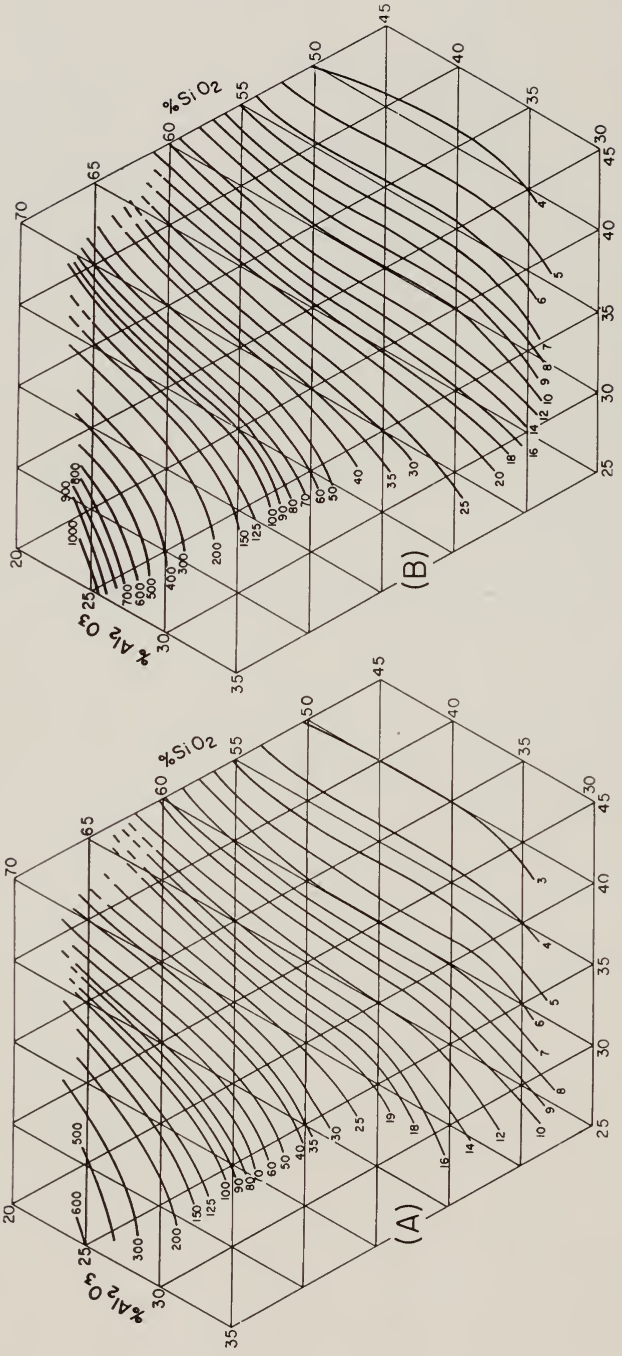


Fig. 8.—Continued.


(B)
% SiO2
% Al2 O3
70
65
60
55
50
45
40
35
30
25
20
1000
900
800
700
600
500
400
300
200
150
125
100
90
80
70
60
50
40
35
30
25
20
18
16
14
12
10
9
8
7
6
5
4
(A)
% SiO2
% Al2 O3
600
500
300
200
150
125
100
90
80
70
60
50
40
35
30
25
19
18
16
14
12
10
9
8
7
6
5
4
3

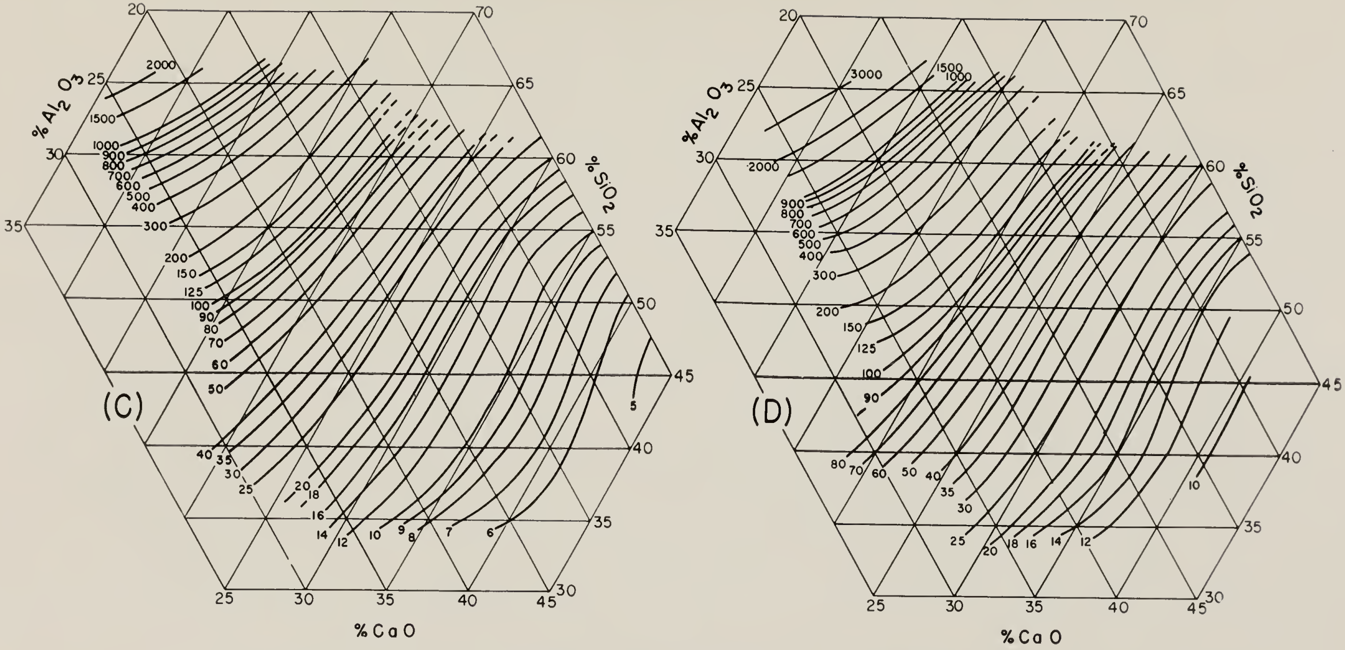
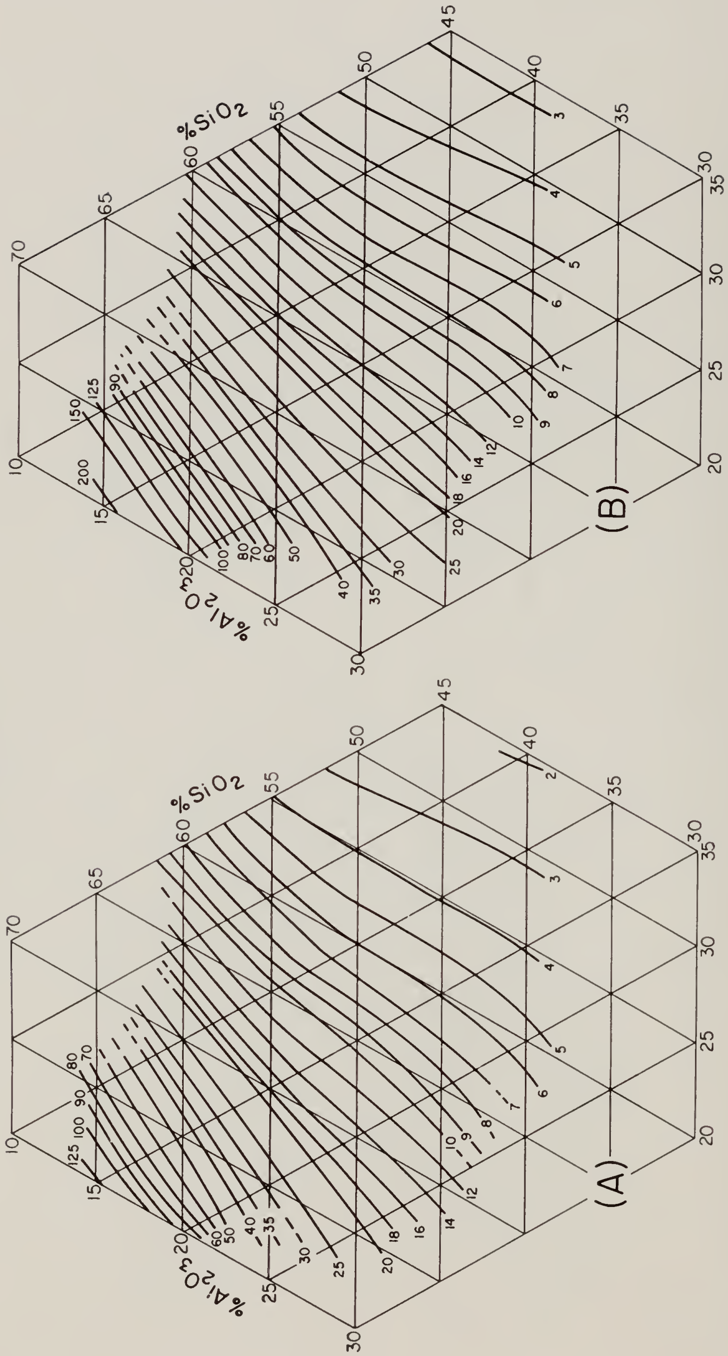


Fig. 9.—Isokoms (10% MgO) at (A) 1500° C., (B) 1450° C., (C) 1400° C., (D) 1350° C.


(B)
%SiO2
%Al2O3
70
65
60
55
50
45
40
35
30
25
20
10
15
200
150
125
100
90
80
70
60
50
40
35
30
25
20
18
16
14
12
10
9
8
7
6
5
4
3
(A)
%SiO2
%Al2O3
2

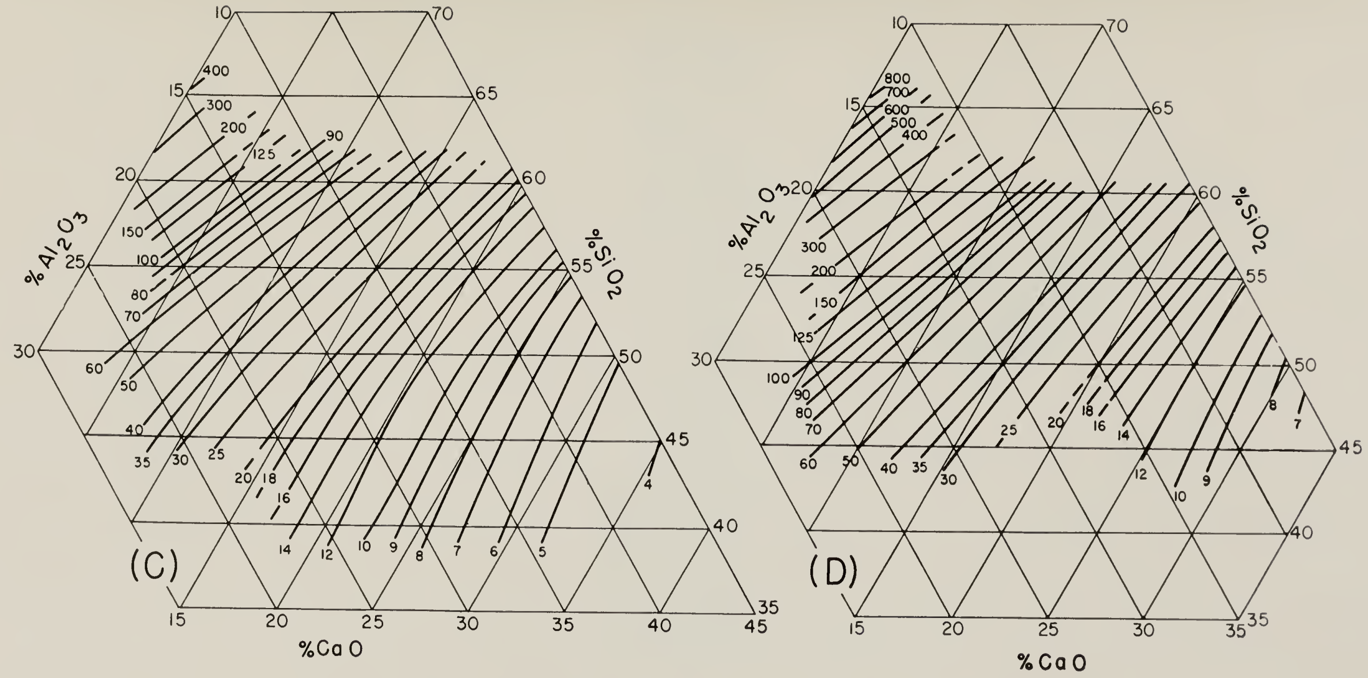


Fig. 10.—Isokoms (20% MgO) at (A) 1500° C., (B) 1450° C., (C) 1400°C., (D) 1350°C.

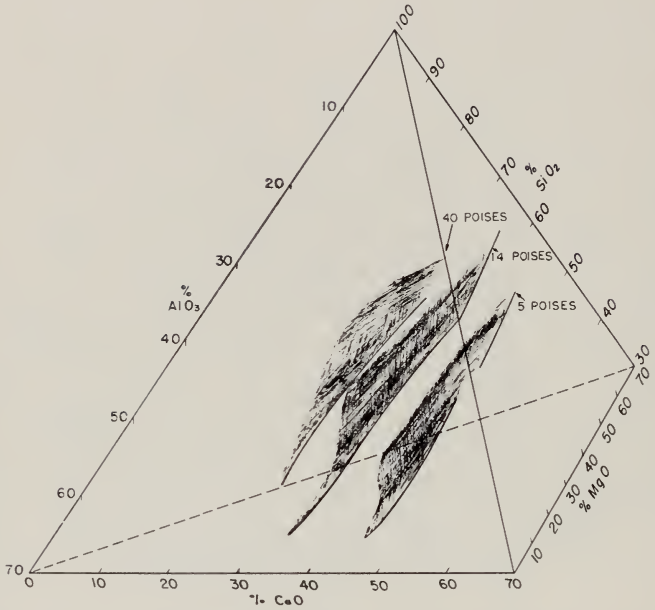


FIG. 11.—An oblique drawing of compositional tetrahedron with inscribed equiviscous surfaces. Front face is zero MgO; base is 30% SiO_2; right-hand face is zero Al_2O_3. Heavy lines at edges of shaded areas are intersections of equiviscous surfaces with faces of tetrahedron.

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