A UNITED STATES
DEPARTMENT OF
COMMERCE
PUBLICATION

DEPARTMENT OF COMMERCE • UNITED STATES OF AMERICA

NBS MONOGRAPH 135

Properties of Glasses in Some Ternary Systems Containing BaO and SiO_2

U.S.
DEPARTMENT
OF
COMMERCE
National
Bureau
of
Standards

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of a Center for Radiation Research, an Office of Measurement Services and the following divisions:

Applied Mathematics — Electricity — Mechanics — Heat — Optical Physics — Linac Radiation[2] — Nuclear Radiation[2] — Applied Radiation[2] — Quantum Electronics[3] — Electromagnetics[3] — Time and Frequency[3] — Laboratory Astrophysics[3] — Cryogenics[3].

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials and the following divisions:

Analytical Chemistry—Polymers—Metallurgy—Inorganic Materials—Reactor Radiation—Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations leading to the development of technological standards (including mandatory safety standards), codes and methods of test; and provides technical advice and services to Government agencies upon request. The Institute also monitors NBS engineering standards activities and provides liaison between NBS and national and international engineering standards bodies. The Institute consists of a Center for Building Technology and the following divisions and offices:

Engineering and Product Standards—Weights and Measures—Invention and Innovation—Product Evaluation Technology—Electronic Technology—Technical Analysis—Measurement Engineering—Building Standards and Code Services[4]—Housing Technology[4]—Federal Building Technology[4]—Structures, Materials and Life Safety[4]—Building Environment[4]—Technical Evaluation and Application[4]—Fire Technology.

THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus within the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Center consists of the following offices and divisions:

Information Processing Standards—Computer Information—Computer Services —Systems Development—Information Processing Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world, and directs the public information activities of the Bureau. The Office consists of the following organizational units:

Office of Standard Reference Data—Office of Technical Information and Publications—Library—Office of International Relations.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
[2] Part of the Center for Radiation Research.
[3] Located at Boulder, Colorado 80302.
[4] Part of the Center for Building Technology.

Properties of Glasses in Some Ternary Systems Containing BaO and SiO_2

Given W. Cleek

Institute for Materials Research
National Bureau of Standards
Washington, D.C. 20234

C. L. Babcock

Optical Sciences Center
University of Arizona
Tuscon, Ariz. 85721

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, *Secretary*
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, *Director*

Issued September 1973

Library of Congress Catalog Number: 73-600135

National Bureau of Standards Monograph 135
Nat. Bur. Stand. (U.S.), Monogr. 135, 42 pages (Sept. 1973)
CODEN: NBSMA6

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.44:135). Price 70 cents.
Stock Number 0303–01157

Properties of Glasses in Some Ternary Systems Containing BaO and SiO_2*

G. W. Cleek and C. L. Babcock**

The glass forming regions in six ternary oxide systems containing BaO, SiO_2, and a third oxide have been determined. The properties of the resulting glasses were measured and the results reported. The data on refractive indices, dispersions, and specific volumes were evaluated by computer methods in an attempt to identify "substructures" containing the cations present in the glasses.

Key words: Barium glasses; barium silicates; glass properties; glass property factors; oxide glasses; silicate substructures; ternary glasses.

1. Introduction

During the course of several years, while working on the development of special purpose oxide glasses for various applications, surveys of the regions of glass formation in some ternary systems containing BaO and SiO_2 have been made. The systems surveyed are as follows:

1. BaO-TiO_2-SiO_2
2. BaO-La_2O_3-SiO_2
3. BaO-Ta_2O_5-SiO_2
4. BaO-ZnO-SiO_2
5. BaO-Nb_2O_5-SiO_2
6. BaO-Al_2O_3-SiO_2

It was believed that the properties measured on the glasses are of sufficient interest to glass technologists to be made generally available and are published here.

2. Experimental Procedure

The experimental glasses were normally made in 500 g melts from batch materials of sufficient purity to satisfy the requirements for the production of optical glass. The standard procedure was to melt the batches in platinum crucibles, 6.5 cm in diameter by 7.5 cm deep. After the batch was melted, the melt was stirred for 2 h with a motor driven platinum-10-percent-rhodium, double-bladed propeller-type stirrer. The furnace used for melting was heated by silicon carbide resistance elements so that the furnace atmosphere was not contaminated by combustion products. After the melt was stirred, it was poured into a heated metal mold to form a block about 7.5 cm by 7.5 cm by 2.0 cm thick. When sufficiently rigid, the glass block was transferred to an electric muffle furnace, which was cooled to room temperature in approximately 18 h.

Only those compositions that could be melted below 1500 °C and in which no appreciable devitrification occurred during cooling were considered to produce glasses. These experimental conditions were used to define the regions of glass formation in the ternary systems studied, and no attempt was made to enlarge these regions by melting at a higher temperature or by cooling the melts more rapidly to avoid devitrification.

The properties determined for most of the experimental glasses included the following:

(1) Sag Point [1] [1]
(2) Refractive index for the C ($\lambda=0.6563$ μm), D ($\lambda=0.5893$ μm), and F ($\lambda=0.4861$ μm) spectral lines. From these the reciprocal dispersive power, commonly known as the Nu value, ν, was calculated.

$$\nu=\frac{n_D-1}{n_F-n_C}$$

(3) Liquidus temperature [2]
(4) Infrared transmittances for 2 mm thickness from 1 to 6 μm.

For the more promising glasses certain other properties were measured. These included infrared transmittances for greater thicknesses, usually 8 mm, so that absorption coefficients could be computed; infrared refractive indices; linear coefficient of thermal expansion; and deformation temperature. For some glasses density, chemical durability, and elastic constants were also measured.

In addition, data on refractive indices (n_D), dispersions and specific volume were evaluated, using previously described methods [3]. One purpose of this evaluation is to develop quantitative property-composition relations for use by technologists in formulating glasses for optical uses. A further purpose is to clarify presently incomplete knowledge of the ternary phase diagrams of these glass-forming systems and to identify, if possible, "substructures" containing the cations present in the glasses.

*Part of the work described in this report was sponsored by the Department of the Navy at the National Bureau of Standards, and by Project Themis, U.S. Air Force, at the University of Arizona.
**Address: Optical Sciences Center, University of Arizona, Tucson, Arizona 85721.
[1] The figures in brackets indicate the literature references at the end of the paper.

3. Glass-Forming Systems Investigated

Several ternary silicate systems were investigated as to the extent of the region of glass formation and the properties of the glasses obtained.

3.1. The $BaO-TiO_2-SiO_2$ System

In an effort to produce glasses having high values of refractive index at wavelengths of 2.0 to 2.5 μm, good infrared transmittances and good chemical durability melts were made in the ternary system $BaO-TiO_2-SiO_2$ [4]. Most high-index glasses presently available are either extra-dense flint glasses, which have a high PbO content, or rare-earth borate glasses [5]. The extra-dense flint glasses have fairly good infrared transmittances, cutting off, as do most silicate glasses, at about 5 μm. They have high refractive indices, but their chemical durability is rather poor and they have low deformation temperatures. The B_2O_3 content of most rare-earth glasses makes them useless for infrared applications.

The phase equilibrium diagram for the ternary system $BaO-TiO_2-SiO_2$ has not been determined, but information is available on the binary sides of the ternary system [6, 7, 8]. Rase and Roy have determined the liquidus temperatures and phase relations along the line $BaO \cdot TiO_2-SiO_2$ in the ternary diagram [9]. This information was very useful in selecting compositions in the ternary system that could be melted and cooled as glasses.

The composition of all melts made in the ternary system are given in table 1 and are plotted in the ternary diagram in figure 1. As may be seen from the figure, the longest BaO isopleth along which glasses were formed is the 25 mol percent line. Although glasses are not formed on this line to the $BaO-SiO_2$ binary, glass formation begins at about the 20 mol percent of TiO_2 and extends to relatively high concentrations of TiO_2. This line of glass formation seems to follow a valley in the liquidus surface, as may be seen from table 1.

The color of the glasses changed very markedly as the TiO_2 content was increased. Those containing up to about 15 mol percent of TiO_2 were nearly colorless, whereas those containing intermediate amounts from 20 to 35 mol percent of TiO_2, were orange colored, and the others having about 40 mol percent of TiO_2 were dark brown to black. Evidently, as the TiO_2 content is increased, the absorption increases at the shorter wavelengths in the visible region, and at higher TiO_2 concentrations very little visible light is transmitted.

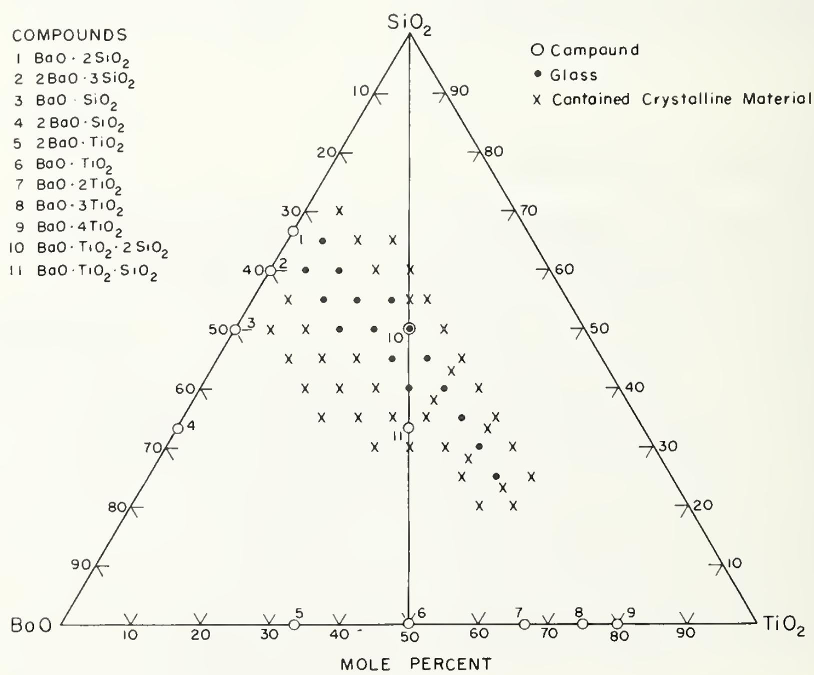


FIGURE 1. *Compositions studied in the system* $BaO-TiO_2-SiO_2$.

TABLE 1. *Ternary* BaO-TiO_2-SiO_2 *compositions*

Melt No.	Composition			n_C	n_D	n_F	ν	Density ρ	Liquidus temp. °C	Sag point °C	Coef. of thermal exp.	Remarks
	SiO_2 Mol %	BaO Mol %	TiO_2 Mol %									
F294	65	20	15						1468			Devit in mold.
F293	60	20	20						1484			Do.
F292	55	20	25						1462			Do.
F291	50	20	30						1464			Do.
F300	45	20	35						1488			Do.
F316	40	20	40						> 1447			Do.
F331	35	20	45						> 1440			Do.
F332	30	20	50						> 1440			Do.
F337	25	20	55						> 1440			Do.
F363	55	22.5	22.5						> 1440			Do.
F364	42.5	22.5	35						1248			Some devit.
F365	32.5	22.5	45									Considerable devit.
F151	70	25	5						1408			Do.
F150	65	25	10						1345	860		Do.
F149	60	25	15						1265	850		Opal in center.
F148	55	25	20	1.72414	1.73021	1.74562	34.0	3.699	1250	840		Glass.
F147	50	25	25	1.77046	1.77760	1.79589	30.6	3.804	1248	835		Do.
F146	45	25	30	1.81406	1.82236	1.84382	27.6	3.887	1233	835		Do.
F145	40	25	35	1.85733	1.86682	1.89161	25.3	3.954	1218	835		Do.
F289	35	25	40						1242			Dark brown glass.
F317	30	25	45						1260			Do.
F333	25	25	50						1305			Black glass.
F367	22.5	25	52.5						1310			Considerable devit.
F336	20	25	55						1333			Do.
F366	27.5	27.5	45						1266			Considerable devit.
F368	37.5	27.5	35						1288			Do.
F152	65	30	5	1.62772	1.63139	1.64037	49.9		1356	820		Glass.
F 35	60	30	10	1.66807	1.67250	1.68347	43.7	3.743	1301	820	9.2×10^{-6}	Do.
F 49	55	30	15	1.70750	1.71276	1.72596	38.6	3.859	1330	815		Do.
F 40	50	30	20	1.74790	1.75412	1.76986	34.3	3.945	1342	815	9.9×10^{-6}	Do.
F 95	45	30	25	1.78860	1.79585	1.81434	30.9	4.004	1344	815		Do.
F138	40	30	30	1.82865	1.83697	1.85847	28.1	4.079	1350	820	10.0×10^{-6}	Do.
F139	35	30	35	1.87050	1.87998	1.90465	25.8	4.159	1337	820		Some devit. in end of block.

TABLE 1. *Ternary* BaO-TiO_2-SiO_2 *compositions* – Continued

Melt No.	Composition			n_C	n_D	n_F	ν	Density ρ	Liquidus temp. °C	Sag point °C	Coef. of thermal exp.	Remarks
	SiO_2 Mol %	BaO Mol %	TiO Mol %									
F288	35	30	35						1354			Some devit.
F290	30	30	40						1313			Considerable devit.
F334	25	30	45						1331			Do.
F335	20	30	50						1302			Do.
F353	33.3	33.3	33.3						1405			Devit. in mold.
F144	60	35	5	1.63026	1.63399	1.64310	49.4	3.634	1367	860		Glass.
F143	55	35	10	1.68703	1.69148	1.70306	43.1	3.968	1354	860		Do.
F142	50	35	15	1.72494	1.73037	1.74401	38.3	4.047	1393	840		Do.
F141	45	35	20						1415	835		Considerable devit.
F140	40	35	25						1420			Do.
F315	35	35	30						1423			Devit. in mold.
F287	30	35	35						1441			Do.
F282	55	40	5						1375			Cloudy.
F283	50	40	10						1401			Some devit.
F284	45	40	15						1441			Considerable devit.
F295	40	40	20						1462			Devit. in mold.
F285	35	40	25						1468			Do.
F286	30	40	30						1484			Do.
F296	50	45	5						1404			Devit. in mold.
F297	45	45	10						1462			Do.
F298	40	45	15						1462			Do.
F299	35	45	20						1488			Do.

The liquidus temperature [2] for each composition is given in table 1. It will be noticed from the table that in no case was a glass formed from a composition that had a liquidus temperature greater that 1400 °C. The lowest liquidus temperatures were found along the 25 mol percent BaO isopleth, which is also the longest line of glass formation in the system. Furthermore, the shape of the liquidus curve of the 25 mol percent BaO series in the areas of best glass formation is relatively flat, indicating a high degree of dissociation of the primary phase at the liquidus temperature. Probably, the ease of glass formation is related to the degree of dissociation of the primary phase in the melt, because similar observations have been made for this and other glass forming systems [10]. In the BaO-B_2O_3-SiO_2 system, the glasses whose compositions lie in the $3BaO \cdot 3B_2O_3 \cdot 2SiO_2$ primary field, which has a flat liquidus curve, were the ones that were melted and homogenized with the least difficulty and had the least tendency to devitrify.

The refractive index, n_D, and ν are plotted in figure 2 for the three BaO isopleths along which glasses were obtained. The values of n_D varied from 1.63139 to 1.87988, and ν from 49.9 to 25.3. The refractive index appears to be a linear function of composition. The plots of ν definitely show curvature.

Figures 3 to 9, inclusive, give the transmittances for 2-mm thicknesses of the ternary glasses over the spectral range 1 to 5 μm. The figures compare glasses of constant TiO_2 content. In general the glasses giving the highest transmittance at 4 μm lie on the 30-mol percent BaO isopleth up to a TiO_2 concentration of 25 mol percent, then the compositions shift to the 25-mol-percent BaO iospleth. There are considerable differences in the transmittances of the various glasses, but no simple relationship between transmittance and composition is readily evident.

The values of chemical durability [11] of five representative ternary glasses are given in table 2

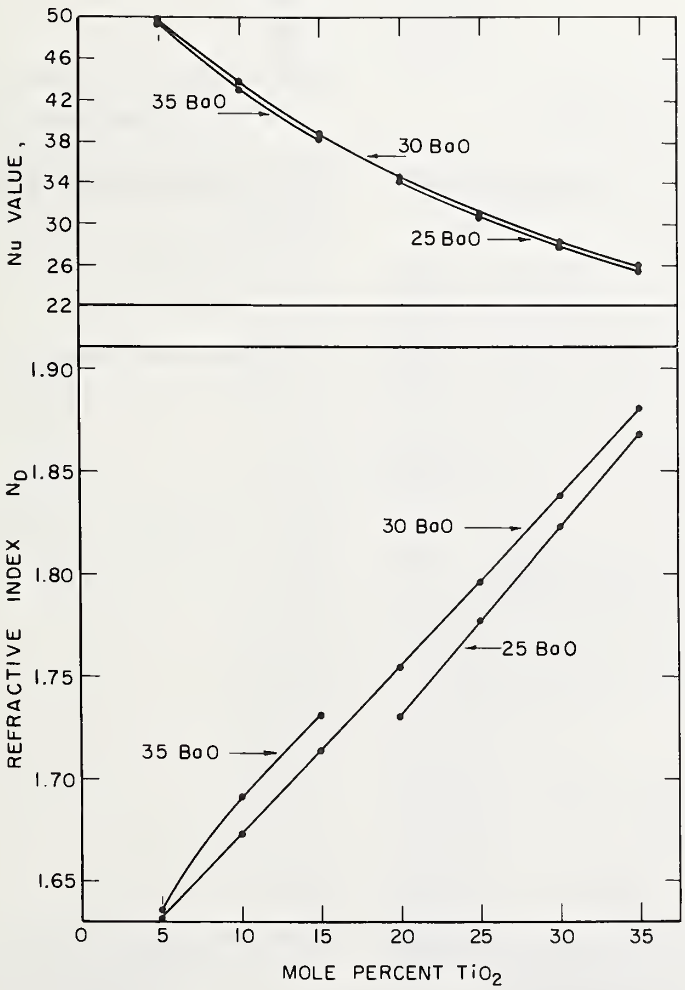


FIGURE 2. *Plot of refractive index and* ν *as a function of composition for the glass-forming compositions in the* BaO-TiO_2-SiO_2 *system.*

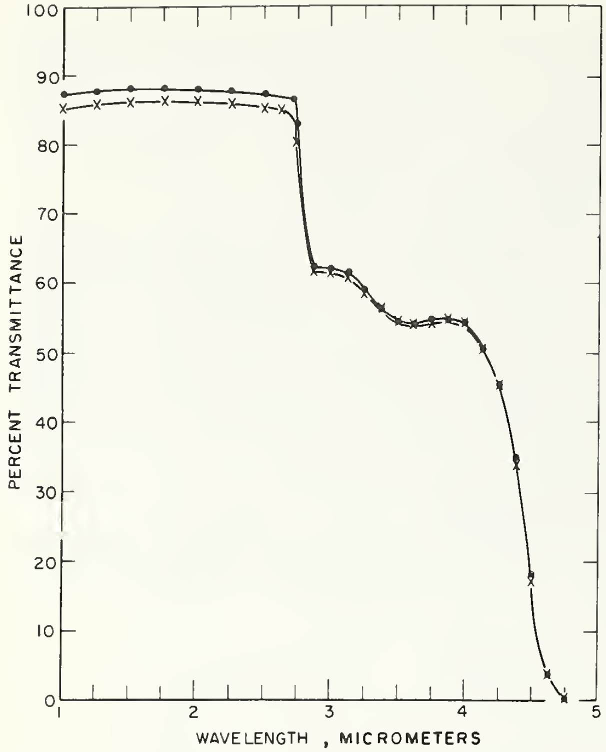


FIGURE 3. *Spectral transmittance of 2-mm thickness of two glasses containing 5 mol percent of* TiO_2. ● F152, × F144.

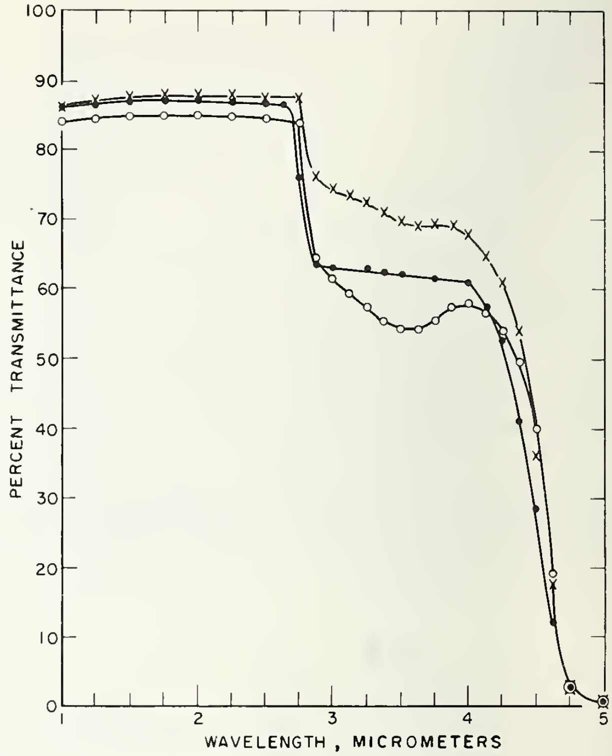


FIGURE 5. *Spectral transmittance of 2-mm thickness of three glasses containing 15 mol percent of* TiO_2. ● F149, ○ F142, × F49.

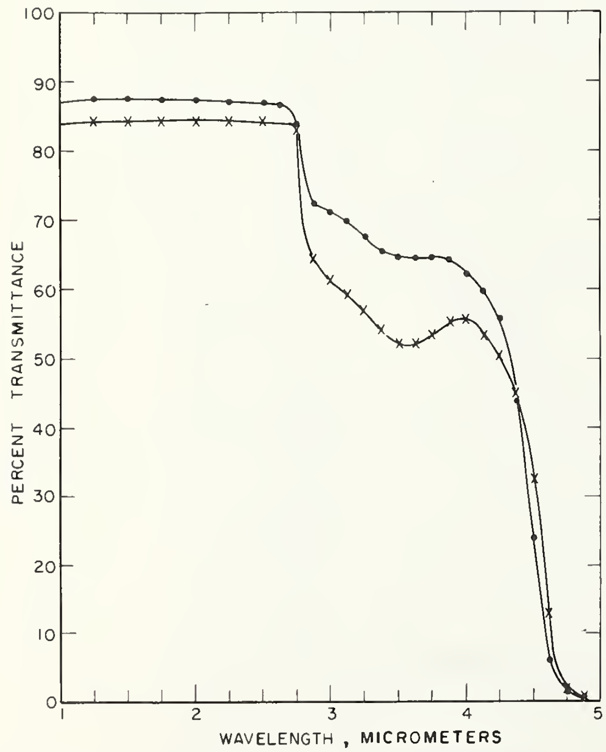


FIGURE 4. *Spectral transmittance of 2-mm thickness of two glasses containing 10 mol percent of* TiO_2. ● F35, × F143.

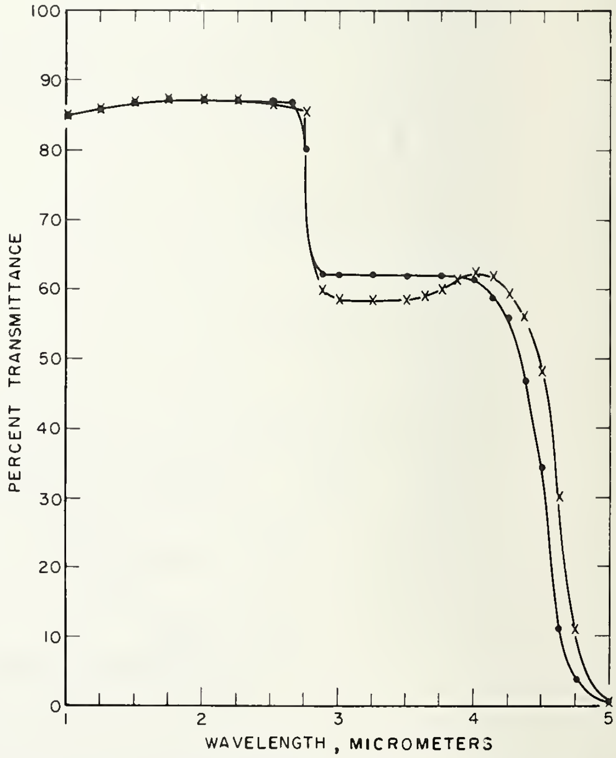


FIGURE 6. *Spectral transmittance of 2-mm thickness of two glasses containing 20 mol percent of* TiO_2. ● F148, × F40.

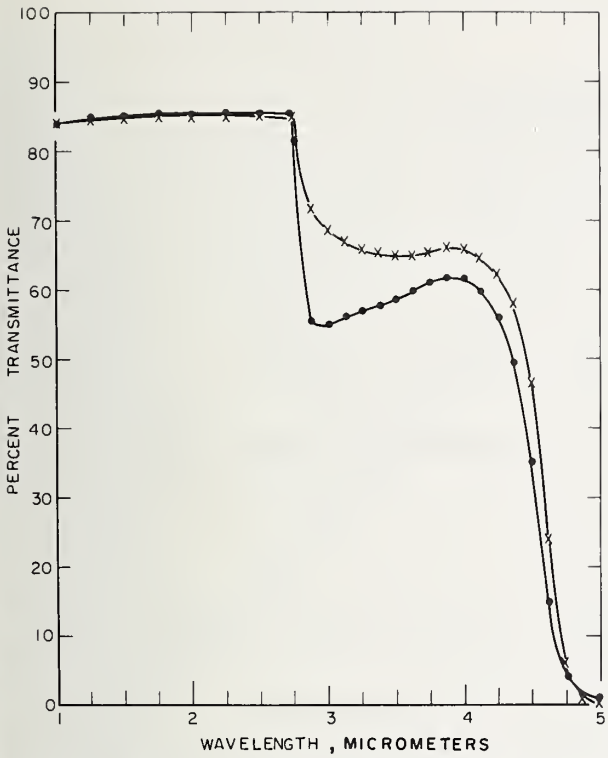


FIGURE 7. *Spectral transmittance of 2-mm thickness of two glasses containing 25 mol percent of* TiO_2. ● F147, × F95.

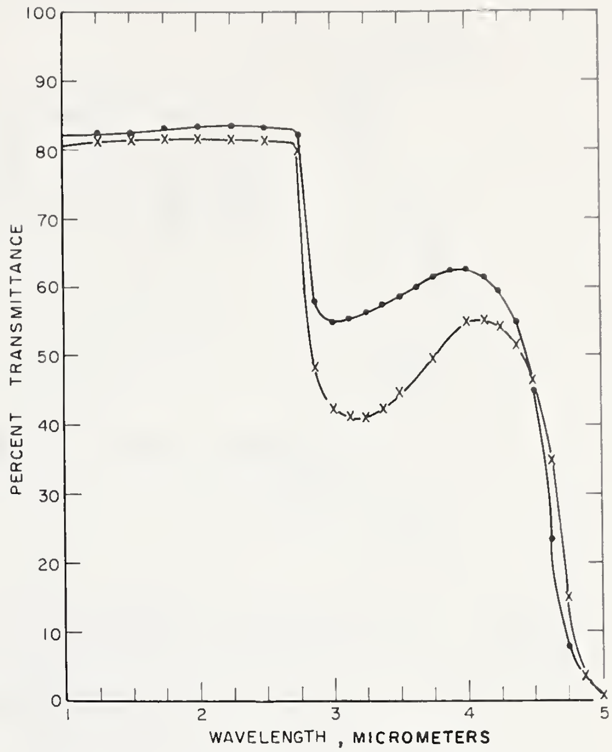


FIGURE 9. *Spectral transmittance of 2-mm thickness of two glasses containing 35 mol percent of* TiO_2. ● F145, × F139.

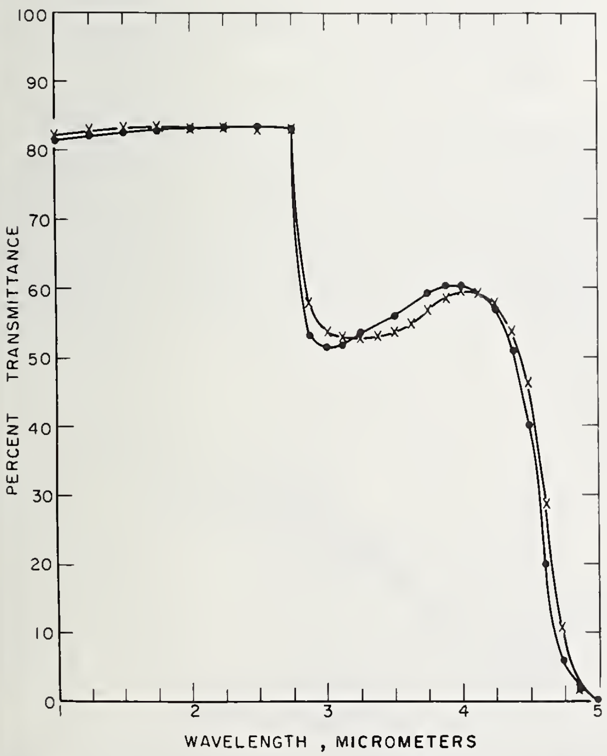


FIGURE 8. *Spectral transmittance of 2-mm thickness of two glasses containing 30 mol percent of* TiO_2. ● F146, × F138.

and are plotted as a function of pH in figure 10. All values are for 6 h of exposure at 80 °C. As may be seen from the figure, the glass containing 60 mol percent of SiO_2 is attacked in the alkaline range. As SiO_2 is replaced by TiO_2, the attack in this range is decreased, and although slight attack or swelling is noticed at pH 2, the glasses containing 20 mol percent and more of TiO_2 show no attack in the alkaline range.

The hygroscopicity [12], or the tendency of a powdered-glass sample to absorb water in a humid atmosphere, was very low for the samples of the ternary glasses on which determinations were made. The values obtained were, in all cases, equal or less than fused silica which was used for purposes of comparison. These data are given in table 2 and plotted in figure 11.

The resistance of these glasses to chemical attack and their low hygroscopicity make them unique as compared to known oxide glasses.

The linear coefficient of thermal expansion [13] has been determined for only three representative ternary glasses. The values obtained were 9 or $10 \times 10^{-6}/°C$, which is near the values of most commercial soda-lime-silica glasses. The deformation temperatures are somewhat higher than the usual values for silicate glasses. The expansion curves for three glasses are plotted in figure 12.

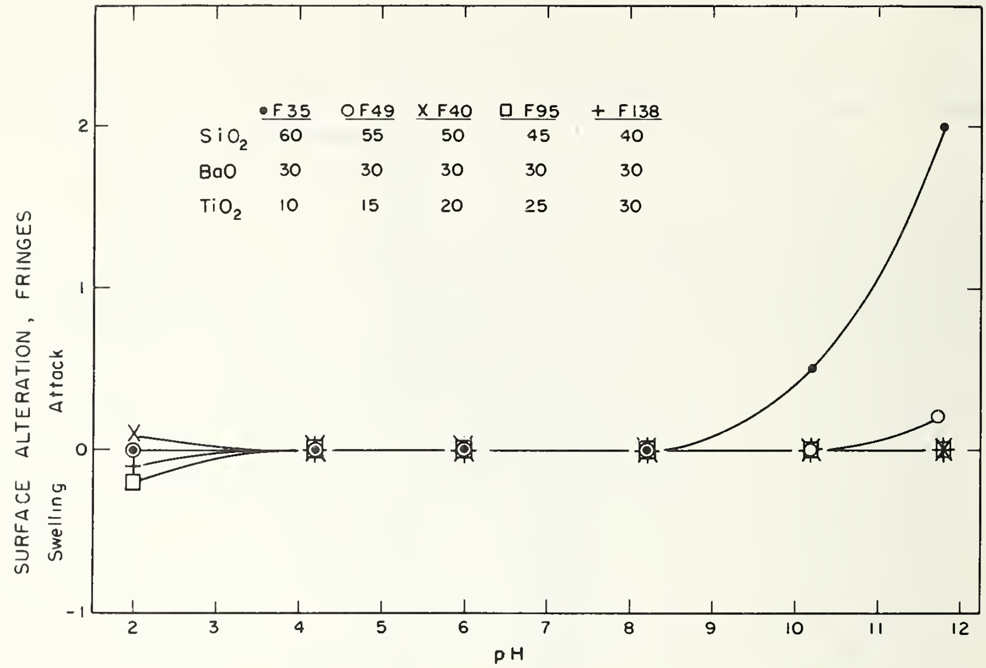


FIGURE 10. *Chemical durability of five* BaO-TiO₂-SiO₂ *glasses as a function of pH.*

TABLE 2. *Hygroscopicity and chemical durability of* BaO-TiO₂-SiO₂ *glasses*

Melt	Water sorbed		Surface alteration,[a] fringes, at pH— (exposures, 6 h at 80 °C)					
	1 h	2 h	2.0	4.1	6.0	8.2	10.2	11.88
	mg/cm³	*mg/cm³*						
F35	5.7	10.0	ND	ND	ND	ND	1/2 A	2 A
F49	6.1	9.1	ND	ND	ND	ND	ND	2/10 A
F40	5.2	8.2	1/10 A	ND	ND	ND	ND	ND
F95			2/10 S	ND	ND	ND	ND	ND
F138			1/10 S	ND	ND	ND	ND	ND
Corning 7740	15.9	28.3	ND	ND	ND	DA	1/4 A	1¾ A
Fused SiO_2	6.2	12.1	ND	ND	ND	ND	DA	1/2 A

[a] ND, No detectable attack; A, attack of surface; S, swelling of surface; DA, detectable, but not measurable attack.

The deformation temperatures varied from 767 °C for glass F35, containing 10 mol percent of TiO_2, to 791 °C for glass F138, having 30 mol percent of TiO_2. The high deformation temperatures of these glasses make them unique as compared to most commercial glasses. Other data given in table 1 are the densities of several of the glasses as well as their sag points.

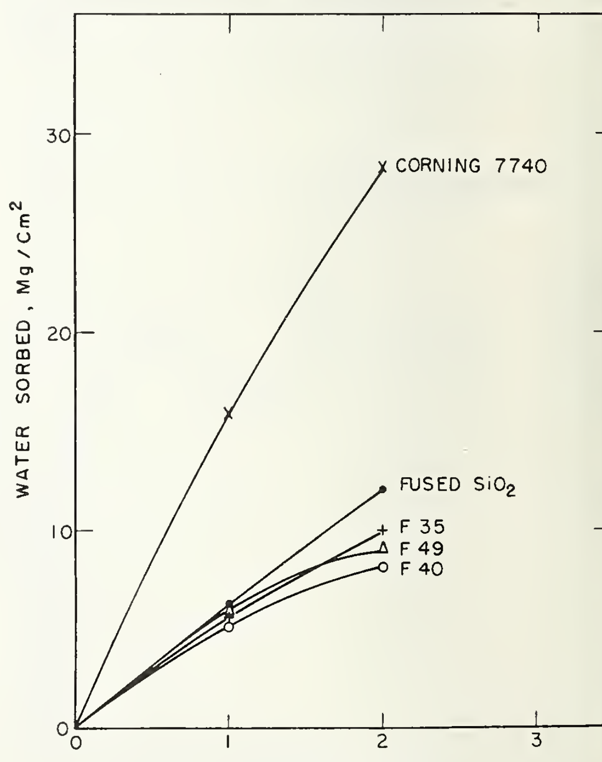


FIGURE 11. *Hygroscopicity of three* BaO-TiO₂-SiO₂ *glasses compared with Corning 7740 glass and fused* SiO₂.

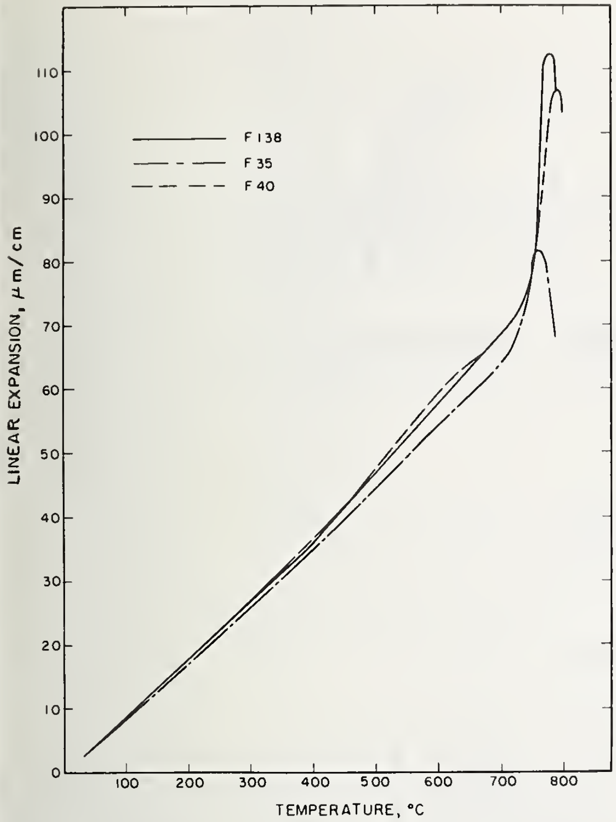


FIGURE 12. *Thermal expansion curves of three* BaO-TiO_2-SiO_2 *glasses as determined by an interferometric method.*

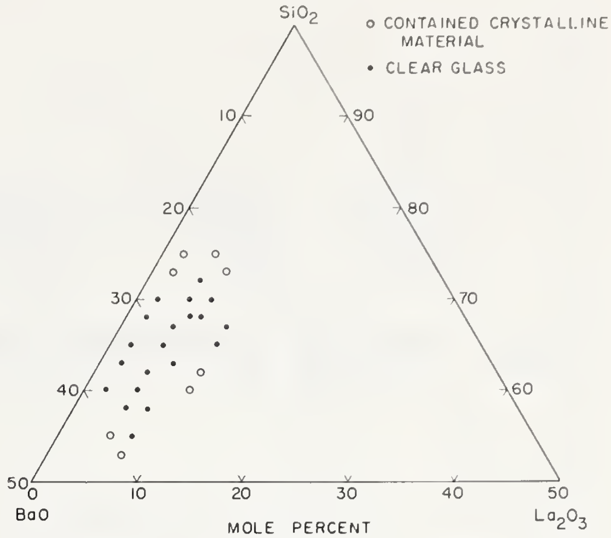


FIGURE 13. *Compositions studied in the system* BaO-La_2O_3-SiO_2.

3.2. The BaO-La_2O_3-SiO_2 System

Lanthanum oxide is used in optical glasses to produce relatively high values of refractive index with little or no increase in the dispersion values in the visible region. A survey of the glass forming region of the ternary system BaO-La_2O_3-SiO_2 was made. No data on the liquidus temperatures in the system were available except those in the binary BaO-SiO_2 system [8] which forms one side of the ternary system. Since then a tentative diagram for the BaO-La_2O_3 system [14] has been published. A eutectic point at about 1370 °C near the composition 30 mol percent $BaO-70$ mol percent SiO_2 served as a starting point.

The region of glass formation is shown in the triangular diagram in figure 13. Glasses were formed to the 12 mol percent La_2O_3 isopleth. While these compositions appear to contain rather small amounts of La_2O_3, it must be remembered that on a weight percent basis the La_2O_3 content amounts to about 35 percent. The compositions melted and the properties of the resulting glasses are listed in table 3.

The refractive index, n_D, varied from 1.6097 to 1.7027 with ν from 56.0 to 50.8. The densities of the glasses ranged from 3.623 to 4.169 g/cm^3, and the coefficient of thermal expansion ranged from 8.4 to 11.4×10^{-6}/°C.

The coefficients of thermal expansion of the glasses are plotted as a function of the composition in figure 14. The plots show an anomolous behavior

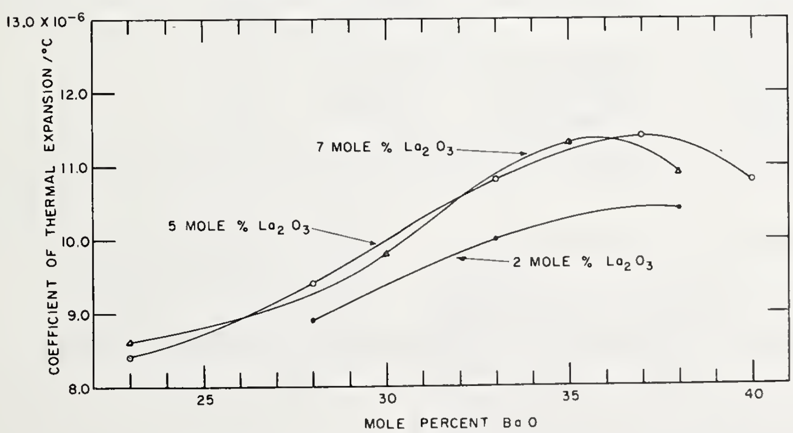


FIGURE 14. *Plot of linear coefficients of thermal expansion as a function of composition for glasses in the* BaO-La_2O_3-SiO_2 *system.*

TABLE 3. *Ternary* BaO-La_2O_3-SiO_2 *compositions*

Melt No.	Composition			n_C	n_D	n_F	ν	Density ρ	Sag point °C	Expansion per °C $\times 10^6$	Deformation point °C	Liquidus temp. °C	Remarks
	BaO Mol %	La_2O_3 Mol %	SiO_2 Mol %										
F547	23	2	75									> 1426	Opal glass.
F548	25	2	73						781			1338	Opal in center of block.
F518	28	2	70	1.60655	1.60974	1.61743	56.0	3.623	798	8.9	747	1355	Clear glass.
F634	30	2	68	1.61357	1.61685	1.62465	55.6		798			1351	Do.
F549	33	2	65	1.62518	1.62853	1.63662	54.9	3.819	790	10.0	742	1373	Do.
F558	35	2	63	1.63521	1.63865	1.64698	54.3	3.918	790			1392	Do.
F561	38	2	60	1.64261	1.64611	1.65462	53.8	3.997	798	10.4	755	1388	Do.
F550	20	5	75									> 1424	Opal glass.
F551	23	5	72	1.61743	1.62076	1.62864	55.4	3.663		8.4	775	1213	Clear glass.
F536	25	5	70	1.62824	1.63162	1.63978	54.8	3.768	798			1256	Do.
F559	28	5	67	1.63952	1.64299	1.65139	54.2	3.885	798	9.4	775	1261	Do.
F525	30	5	65	Striated				3.964	798			1275	Do.
F563	33	5	62	1.65768	1.66126	1.67007	53.3	4.076	810	10.8	775	1305	Do.
F527	35	5	60	1.66330	1.66700	1.67598	52.6	4.132	810			1307	Do.
F564	37	5	58	1.67280	1.67660	1.68584	51.9	4.243	810	11.4	775	1322	Do.
F528	40	5	55						835	10.8	777	1340	Contains some devit.
F562	20	7	73									1410	Opal glass.
F552	23	7	70	1.64081	1.64428	1.65270	54.2	3.849	848	8.6	793	1260	Clear glass.
F538	25	7	68	1.64872	1.65227	1.66086	53.8	3.923	835			1246	Do.
F530	30	7	63	1.66779	1.67152	1.68057	52.6	4.121	840	9.8	792	1335	Do.
F539	35	7	58	1.68199	1.68584	1.69530	51.5	4.276	835	11.3	794	1398	Do.
F553	38	7	55	1.69098	1.69496	1.70467	50.8	4.387	840	10.9	797	1405	Do.
F560	40	7	53									1422	Devitrified.
F627	20	10	70	1.66660	1.67032	1.67942	52.3		862			> 1421	Clear glass.
F554	23	10	67	1.67071	1.67445	1.68352	52.7	4.085	850			> 1427	Do.
F545	25	10	65	1.67861	1.68243	1.69172	52.0	4.169	868	9.3	817	1398	Do.
F555	28	10	62						860			1404	Contains some devit.
F526	30	10	60									> 1431	Devitrified.
F631	32	10	58	1.69872	1.70275	1.71255	50.8		880			> 1424	Contains some devit.
F632	35	10	55									> 1421	Devitrified.
F633	37	10	53									> 1421	Do.
F629	20	12	68									> 1424	Contains some devit.
F628	23	12	65	1.69550	1.69950	1.70927	50.8		855			> 1424	Clear glass.

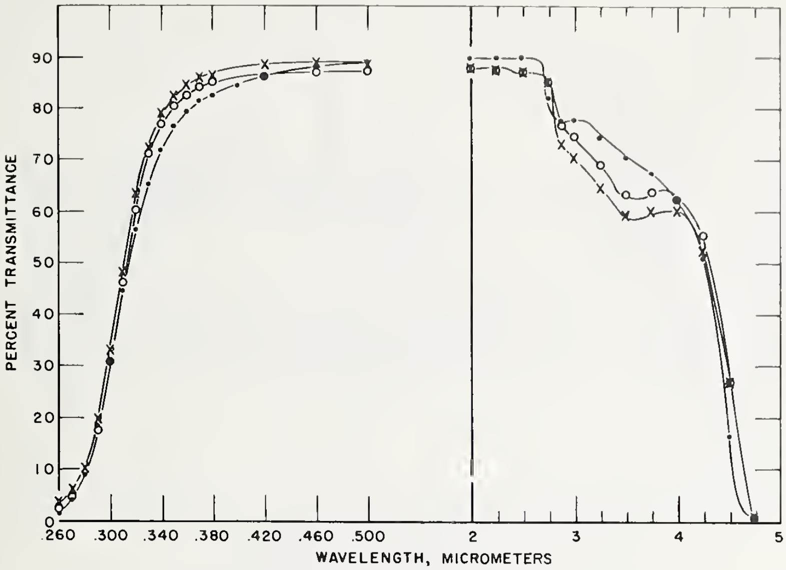


FIGURE 15. *Spectral transmittance of 2-mm thickness of glasses containing 2 mol percent of* La_2O_3. ● F558, ○ F548, × F634.

for the 5 and 7 mol percent La_2O_3 lines, and it is possible that the 2 mol percent line would show a similar behavior if data were obtained at higher BaO concentrations. The increase in the values of coefficient of expansion with increasing amounts of BaO, and decreasing SiO_2 content, is not surprising. But the curve reaches a maximum and then decreases as the SiO_2 content continues to decrease. An explanation for this behavior is not readily apparent.

At the same time, for each La_2O_3 isopleth, there is little change in deformation temperature, so that it does not appear that the increase in the coefficient of expansion is due solely to a loosening of the structure as more BaO is incorporated into the glass. As shown in the table the deformation temperatures of the glasses vary little within each series, but definitely increase as the La_2O_3 content of the glasses increases.

The transmittance curves for 2-mm thicknesses of glasses in the 2, 5, 7, and 10 mol percent La_2O_3 series are plotted in figures 15, 16, 17, and 18. The curves are plotted from the limit of transmittance in the ultraviolet to 0.5 μm and from 2.0 μm to the limit of transmittance in the infrared. While transmittance values have not been measured from 0.5 to 1.0 μm, there is no reason to expect any change in transmittance in this region because the glasses are clear and show no evidence of absorption. The ultraviolet limit of transmittance, about 0.260 μm, is somewhat beyond the usual run of glasses. Window glass, for instance, does not transmit beyond about 0.320 μm in 2.0 mm thicknesses. thicknesses. In the infrared there are variations in

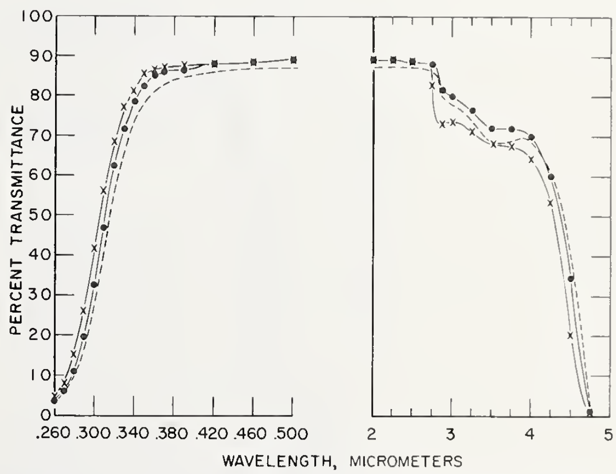


FIGURE 16. *Spectral transmittance of 2-mm thickness of glasses containing 5 mol percent of* La_2O_3. ● F525, × F551, — — F527.

the transmittance curves between 3 and 4 μm, but no simple relation with composition is readily evident.

3.3. The BaO-Ta_2O_5-SiO_2 System

Tantalum oxide, used as a component of glass, imparts higher refractive index values and higher dispersions than does La_2O_3. A survey of the glass-forming region of the BaO-Ta_2O_5-SiO_2 ternary system was made. Again no data were found on the liquidus temperatures in the systems except for the BaO-SiO_2 binary system [8]. The eutectic point in the binary system at about 1370 °C served again as a starting composition.

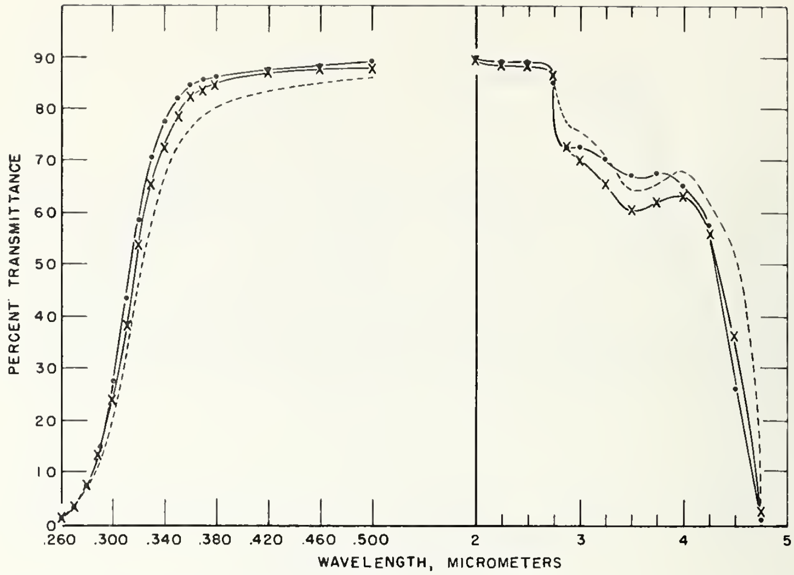


FIGURE 17. *Spectral transmittance of 2-mm thickness of glasses containing 7 mol percent of* La_2O_3. ● F552, × F530, — — F553.

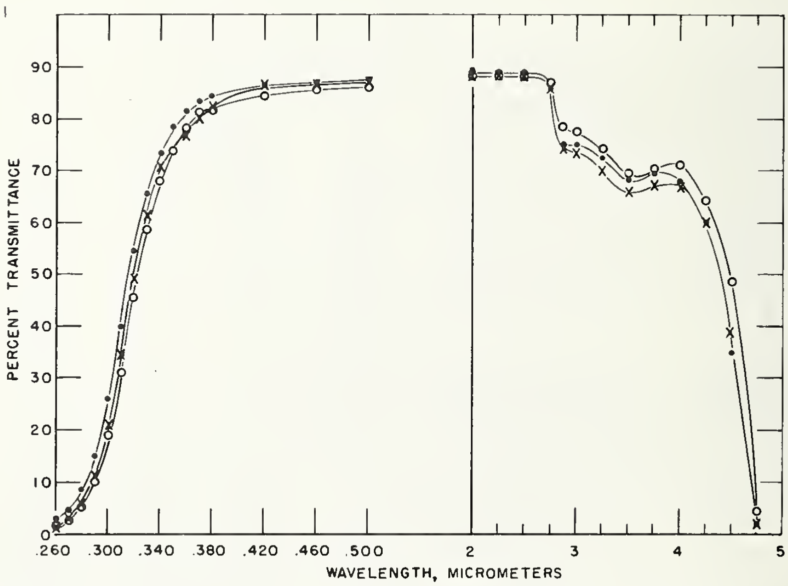


FIGURE 18. *Spectral transmittance of 2-mm thickness of glasses containing 10 mol percent of* La_2O_3. ● F554, × F545, ○ F555.

The region of glass formation is shown in the triangular diagram in figure 19. The compositions melted and the properties of the glasses are given in table 4. The glasses form series along the 2, 5, 7, and 10 mol percent Ta_2O_5 isopleths as may be seen from the figure. The refractive index, n_D, varied from 1.6112 to 1.7708 with ν from 53.5 to 39.4. The densities of the glasses ranged from 3.672 to 5.015 g/cm^3. The coefficients of thermal expansion were determined for only two glasses, one in the 5 mol percent and one in the 10-mol-percent Ta_2O_5 series. The values were 8.3×10^{-6} and 9.5×10^{-6}/°C respectively. The deformation points for the two glasses were 800 and 853 °C, which are rather high compared to those of most silicate glasses.

The transmittances from the limit of transmittance in the ultraviolet to 0.500 μm, and from 2 μm to the limit of transmittance in the infrared for 2-mm thicknesses of glasses from the 2, 5, 7, and 10 mol percent series are given in figures 20, 21, 22, 23, and 24.

TABLE 4. *Ternary* $BaO\text{-}Ta_2O_5\text{-}SiO_2$ *compositions*

Melt No.	Composition			n_C	n_D	n_F	ν	Density ρ	Sag point °C	Expansion per °C $\times 10^6$	Deformation point °C	Liquidus temp. °C	Remarks
	BaO Mol %	Ta_2O_5 Mol %	SiO_2 Mol %										
F575	25	2	73									> 1414	Opal glass.
F522	28	2	70	1.60786	1.61119	1.61928	53.5	3.672	835			1337	Clear glass.
F531	30	2	68	1.61803	1.62145	1.62972	53.2	3.770	820			1340	Do.
F576	33	2	65	1.63352	1.63706	1.64571	52.3	3.929	820			1355	Do.
F577	35	2	63	1.63998	1.64360	1.65237	51.9	4.005	810			1376	Do.
F588	38	2	60	1.65926	1.66309	1.67244	50.3	4.151	825			1371	Do.
F589	40	2	58	1.65740	1.66117	1.67037	51.0	4.192	825			1403	Do.
F578	25	5	70						860			> 1414	Opal glass.
F579	27	5	68	1.63942	1.64325	1.65258	48.9	3.952	865			1390	Clear glass.
F532	30	5	65	1.65577	1.65974	1.66942	48.4	4.105	855	8.3	800	1237	Do.
F540	32	5	63	1.66787	1.67160	1.68066	52.5	4.140	855			1240	Do.
F534	35	5	60	1.67544	1.67959	1.68972	47.6	4.317	855			1285	Do.
F580	37	5	58	1.68377	1.68799	1.69834	47.2	4.418	860			1322	Do.
F535	40	5	55	1.69318	1.69750	1.70809	46.8	4.481	855			1317	Do.
F542	45	5	50	1.70802	1.71249	1.72349	46.0	4.676	868			1325	Do.
F581	47	5	48	1.70870	1.71306	1.72431	45.7	4.696	860			1336	Do.
F590	50	5	45									> 1434	Considerable devit.
F541	25	7	68									> 1425	Opal glass.
F533	30	7	63									> 1425	Some devitrification.
F584	33	7	60	1.69368	1.69814	1.70907	45.4	4.480	885			1405	Clear glass.
F582	35	7	58	1.69592	1.70039	1.71136	45.4	4.508	885			> 1408	Do.
F591	38	7	55	1.70816	1.71274	1.72403	44.9	4.646	865			1345	Do.
F583	40	7	53	1.71379	1.71844	1.72991	44.6	4.703	885			1350	Do.
F592	43	7	50	1.72379	1.72848	1.74023	44.3	4.816	867			1354	Do.
F604	45	7	48	1.72115	1.72595	1.73749	44.4	4.771	856			1293	Do.
F615	46	7	47	1.72156	1.72624	1.73778	44.8	4.787	870			1289	Do.
F605	48	7	45	1.73675	1.74166	1.75380	43.5	4.947	880			1326	Do.
F593	40	10	50	1.74254	1.74766	1.76153	39.4					> 1431	Slight devitrification.
F616	45	10	45	1.74781	1.75293	1.76564	42.2	5.015	880	9.5	853	> 1425	Clear glass.
F617	48	10	42	1.76542	1.77082	1.78424	41.0		880			> 1425	Do.

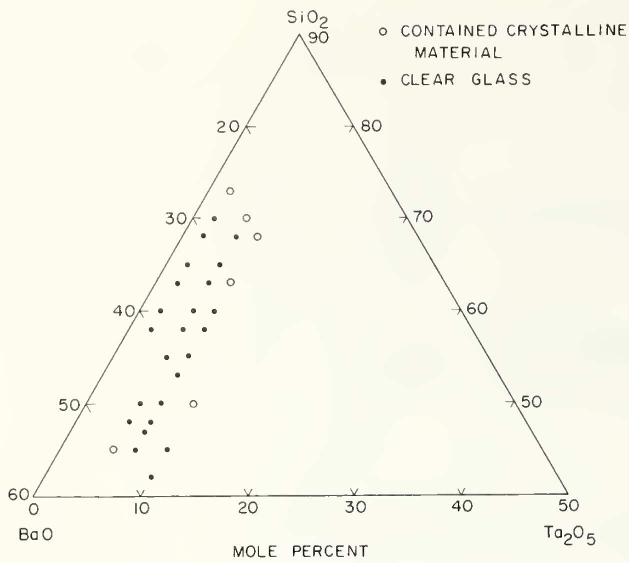


FIGURE 19. *Compositions studied in the system* $BaO-Ta_2O_5-SiO_2$.

3.4. The $BaO-ZnO-SiO_2$ System

ZnO may be used as a component of glass. It imparts intermediate values of refractive index and some glasses containing ZnO have relatively low values of thermal expansion. A survey of the glass-forming region of the $BaO-ZnO-SiO_2$ system was made. Data on the binary $BaO-SiO_2$ [8] and the $ZnO-SiO_2$ [15] systems are available.

The region of glass formation found in the system is shown in the triangular diagram in figure 25, and the compositions melted are listed in table 5. As may be seen from the figure clear glasses were obtained over a considerable area of the diagram.

The liquidus temperatures of the various compositions are also given in table 5. The glasses, over a relatively large composition area, have liquidus temperatures below 1300 °C. A smaller area has liquidus temperatures below 1200 °C and a still smaller area has temperatures below 1100 °C. The minimum liquidus temperature found was 1089 °C for a glass on the 26-mol-percent BaO isopleth.

The refractive index values for glasses in the system are also given in the table. The values range from 1.5878 to 1.6785 for n_D with ν from 48.4 to 56.8.

The transmittance curves for 2-mm thicknesses of glasses from the 36, 30, 26, 20, 14, and 10 mol percent BaO series are given in figures 26, 27, 28, 29, 30, and 31, respectively. For each series there is considerable spread in the transmittance values for the region between 2.75 to 4.0 μm as the SiO_2 content is varied. If one examines the transmittance values at 3.5 μm as the BaO content is decreased, it appears that the trend is for a decrease in transmittance from the 36 to the 30 mol percent series. Then the trend is for a gradual increase from the 30 to the 10 mol percent series. It would appear from the general shapes of the curves that some of the variations are due to the $(OH)^-$ content of the glasses.

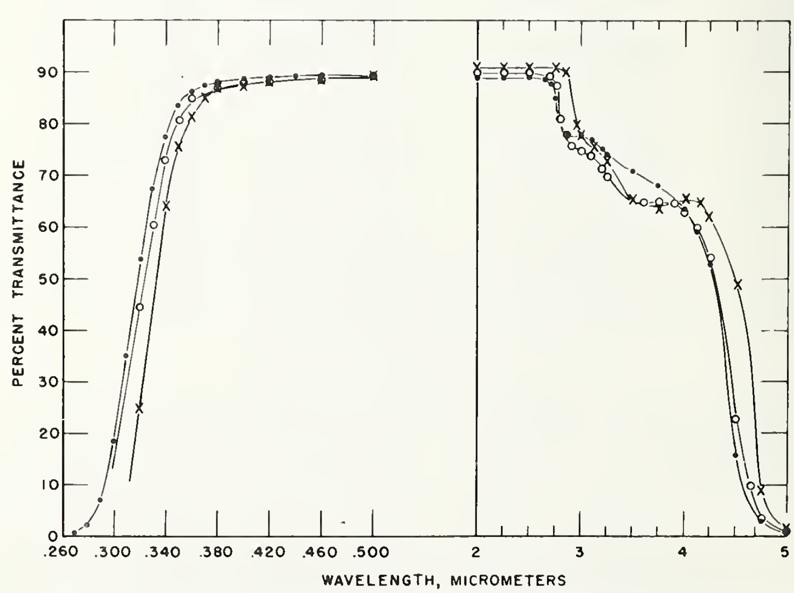


FIGURE 20. *Spectral transmittance of 2-mm thickness of glasses containing 2 mol percent of* Ta_2O_5. ● F522, × F588, ○ F576.

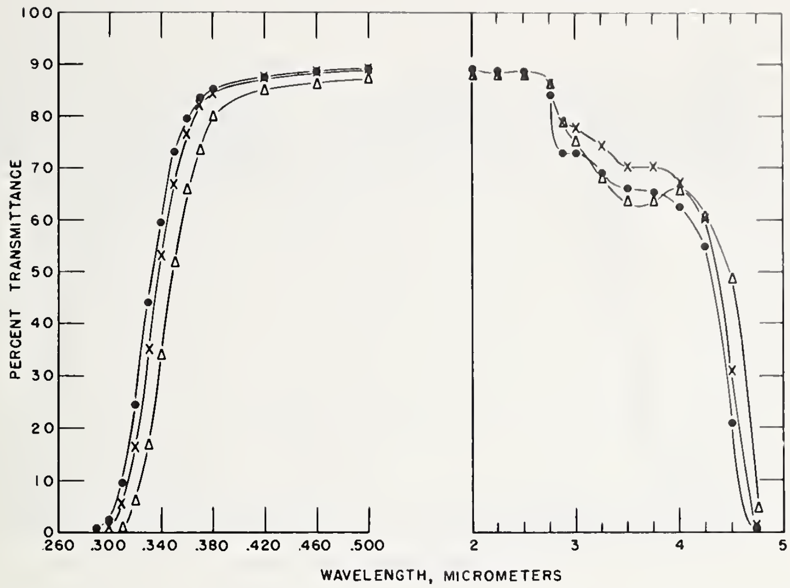


FIGURE 21. *Spectral transmittance of 2-mm thickness of glasses containing 5 mol percent of* Ta_2O_5. ● F532, × F534, Δ F542.

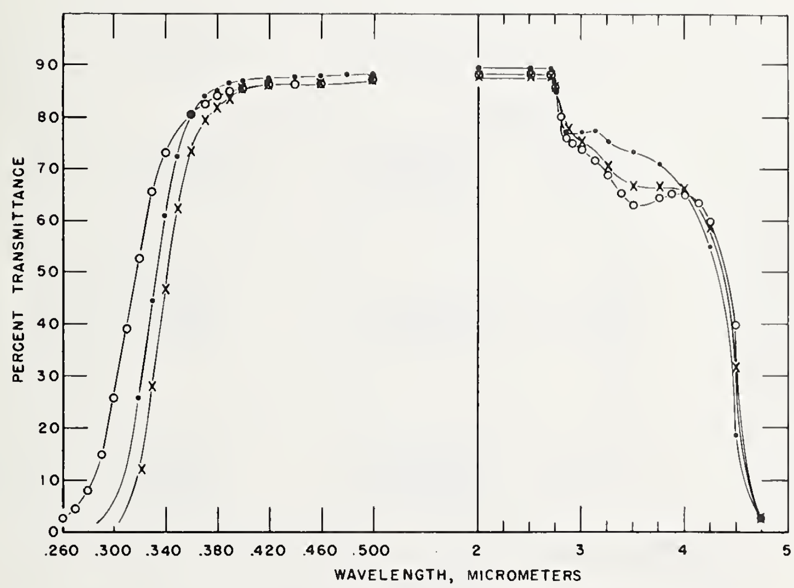


FIGURE 22. *Spectral transmittance of 2-mm thickness of glasses containing 5 mol percent of* Ta_2O_5. ● F579, × F580, ○ F540.

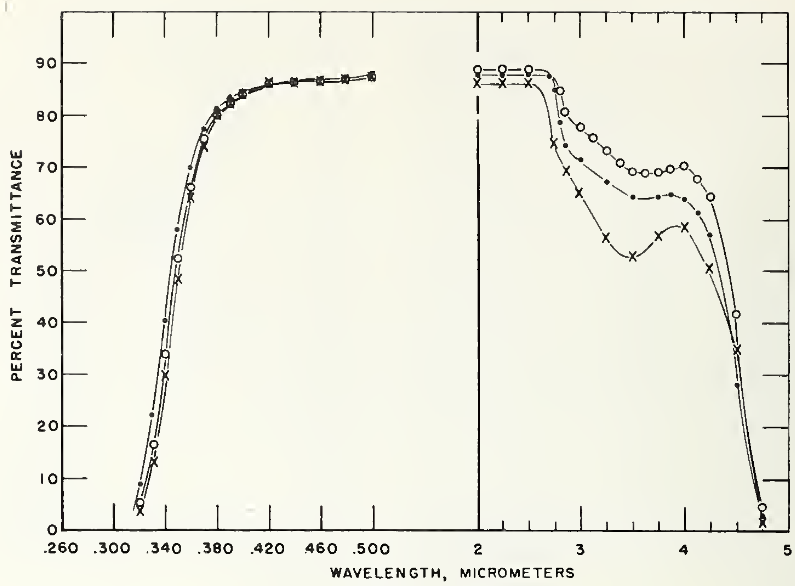


FIGURE 23. *Spectral transmittance of 2-mm thickness of glasses containing 7 mol percent of* Ta_2O_5. ● F584, × F615, ○ F591.

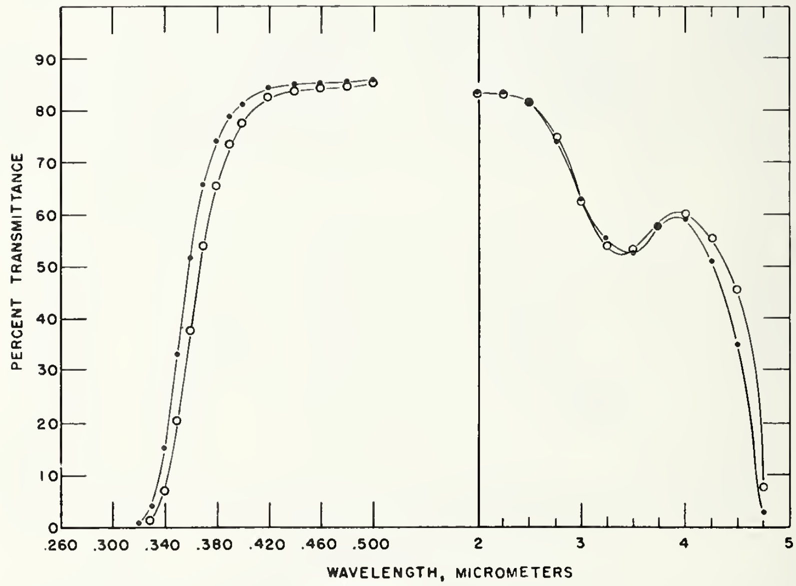


FIGURE 24. *Spectral transmittance of 2-mm thickness of glasses containing 10 mol percent of* Ta_2O_5. ● F616, ○ F617.

TABLE 5. *Ternary* BaO-ZnO-SiO_2 *compositions*

Melt	Composition			n_C	n_D	n_F	ν	Liquidus Temp. °C	Sag Point °C	Coef. of Thermal exp. $\times 10^6$	Remarks
	BaO Mol %	ZnO Mol %	SiO_2 Mol %								
F829	40	6	54					1345	810		Some devit.
F830	40	10	50					1304	800		Some devit.
F831	40	14	46	1.67453	1.67848	1.68817	49.7	1288	800		Clear glass.
F832	40	18	42					1387			Devit in mold.
F850	39	3	58					1407	766		Some devit.
F847	37	3	60					1395	785		Some devit.
F828	36	6	58	1.63224	1.63568	1.64406	53.8	1341	800		Clear glass.
F786	36	10	54	1.65006	1.65371	1.66261	52.1	1268	765		Clear glass.
F787	36	14	50	1.66165	1.66544	1.67474	50.8	1212	765	10.5	Clear glass.
F788	36	18	46	1.67210	1.67605	1.68574	49.6	1281	748		Clear glass.
F833	36	22	42					>1414			Devit in mold.
F834	36	26	38								Did not melt.
F848	35	3	62					1400	786		Some devit.
F783	34	6	60					1329	728		Clear glass.
F760	34	10	56	1.64106	1.64461	1.65327	52.8	1277			Clear glass.
F761	34	14	52	1.64960	1.65327	1.66222	51.7	1193			Clear glass.
F764	34	16	50	1.65815	1.66192	1.67112	51.1	1167			Clear glass.
F762	34	18	48	1.66512	1.66898	1.67841	50.3	1229			Clear glass.
F765	34	20	46	1.66629	1.67017	1.67968	50.0	1221			Clear glass.
F785	34	22	44					1315			Some devit.
F849	33	3	64	1.60761	1.61084	1.61862	55.5	1374	795		Clear glass.
F784	32	16	52	1.65227	1.65598	1.66504	51.4	1172	728		Clear glass.
F766	32	18	50	1.65849	1.66228	1.67151	50.9	1152			Clear glass.
F835	32	26	42					1405			Devit in mold.
F690	30		70					1400	764		Slight devit.
F691	30	2	68					1385	764		Slight devit.
F692	30	4	66					1350	764		Clear glass.

TABLE 5. *Ternary* BaO-ZnO-SiO_2 *compositions*—Continued

Melt	Composition			n_C	n_D	n_F	ν	Liquidus Temp. °C	Sag Point °C	Coef. of Thermal exp. × 10^6	Remarks
	BaO Mol %	ZnO Mol %	SiO_2 Mol %								
F693	30	6	64	1.61047	1.61369	1.62156	55.3	1312	764		Clear glass.
F694	30	8	62	1.61841	1.62172	1.62980	54.6	1298	764		Clear glass.
F695	30	10	60	1.62461	1.62800	1.63625	54.0	1269	767	9.2	Clear glass.
F711	30	12	58	1.62890	1.63232	1.64071	53.5	1224	762		Clear glass.
F712	30	14	56	1.63785	1.64141	1.65002	52.7	1193	760		Clear glass.
F713	30	16	54	1.64489	1.64852	1.65735	52.0	1142	760		Clear glass.
F714	30	18	52	1.65060	1.65430	1.66330	51.5	1110	768		Clear glass.
F715	30	20	50	1.65650	1.66028	1.66949	50.8	1170	768		Clear glass.
F722	30	24	46	1.66957	1.67352	1.68316	49.6	1285	750		Clear glass.
F758	30	28	42					> 1425			Devit in mold.
F767	30	30	40					> 1406			Devit in mold.
F696	28	2	70	1.59088	1.59392	1.60134	56.8	1355	769	8.6	Clear glass.
F699	28	4	68					1335	760		Clear glass.
F700	28	6	66					1318	760		Striated.
F701	28	8	64	1.60711	1.61035	1.61816	55.2	1290	769		Clear glass.
F702	28	10	62	1.61549	1.61880	1.62682	54.6	1278	767		Clear glass.
F703	28	12	60	1.62199	1.62540	1.63360	53.9	1220	769	9.2	Clear glass.
F717	28	14	58	1.63151	1.63501	1.64354	52.8	1181	768		Clear glass.
F718	28	16	56	1.63674	1.64029	1.64892	52.6	1171	750		Clear glass.
F719	28	18	54					1141	750		Clear glass.
F720	28	20	52	1.64842	1.65212	1.66112	51.4	1165	750		Clear glass.
F723	28	24	48	1.66336	1.66725	1.67672	50.0	1261	750	9.5	Clear glass.
F775	28	26	46	1.67040	1.67438	1.68412	49.2	1306			Clear glass.
F776	28	28	44								Devit in mold.
F836	28	30	42					> 1407			Devit in mold.
F704	26	2	72					1333	802		Clear glass.
F705	26	4	70	1.58630	1.58933	1.59672	56.6	1315	780		Clear glass.
F706	26	6	68	1.59460	1.59772	1.60528	56.0	1300	775		Clear glass.
F707	26	8	66	1.60183	1.60495	1.61272	55.5	1285	762		Clear glass.
F708	26	10	64	1.60618	1.60941	1.61723	55.2	1255	767		Clear glass.
F709	26	12	62	1.61447	1.61779	1.62581	54.5	1235	762		Clear glass.
F710	26	14	60	1.62000	1.62336	1.63164	53.6	1199	762		Clear glass.
F716	26	16	58	1.63005	1.63354	1.64201	53.0	1148	768		Clear glass.
F731	26	18	56	1.63488	1.63842	1.64705	52.5	1089	763		Clear glass.
F721	26	20	54	1.64365	1.64729	1.65617	51.7	1177	760		Clear glass.

TABLE 5. *Ternary* BaO-ZnO-SiO_2 *compositions*—Continued

Melt	Composition			n_C	n_D	n_F	ν	Liquidus Temp. °C	Sag Point °C	Coef. of Thermal exp. × 10^6	Remarks
	BaO Mol %	ZnO Mol %	SiO_2 Mol %								
F724	26	24	50	1.65731	1.66112	1.67044	50.4	1250	760	9.3	Clear glass.
F757	26	28	46	1.66964	1.67361	1.68336	49.1	1325			Clear glass.
F789	26	30	44					1316	755		Considerable devit.
F725	24	2	74					> 1425	768		Opal glass.
F726	24	4	72					1408	763		Opal glass.
F698	24	6	70	1.58480	1.58785	1.59519	56.6	1327	769		Clear glass.
F727	24	10	66	1.59904	1.60228	1.60990	55.5	1228	763		Clear glass.
F728	24	14	62	1.61290	1.61622	1.62426	54.2	1140	763		Clear glass.
F730	24	18	58	1.62586	1.62932	1.63772	53.0	1102	760		Clear glass.
F745	24	20	56	1.63743	1.64102	1.64977	52.0	1158	763		Clear glass.
F746	24	22	54	1.64219	1.64584	1.65473	51.5	1201	750		Clear glass.
F753	24	24	52	1.64742	1.65114	1.66017	51.0	1228	750		Clear glass.
F754	24	26	50	1.65830	1.66216	1.67157	49.9	1274	750		Clear glass.
F756	24	28	48					1325	743		Slight devit.
F812	24	30	46					1327	727		Some devit.
F790	24	32	44								Devit in mold.
F732	20	10	70					1357	800		Opal glass.
F733	20	14	66	1.59986	1.60307	1.61084	54.9	1217	763		Clear glass.
F734	20	18	62					1153	763		Clear glass.
F763	20	20	60	1.62306	1.62651	1.63488	53.0	1125			Clear glass.
F735	20	22	58	1.61816	1.62158	1.62985	53.2	1126	763		Clear glass.
F744	20	26	54					1217	740		Clear glass.
F755	20	28	52	1.64567	1.64940	1.65849	50.7	1252	740		Clear glass.
F774	20	30	50	1.65172	1.65553	1.66482	50.0	1274		7.9	Clear glass.
F791	20	32	48					1283	733		Clear glass.
F811	20	34	46					1340	727		Some devit.
F803	18	30	52	1.64598	1.64976	1.65891	50.2	1298	755		Clear glass.
F806	18	34	48	1.66042	1.66436	1.67400	48.9	1276	755		Clear glass.
F792	16	16	68								Opal glass.
F793	16	20	64					1336	755		Slight opal.
F794	16	24	60	1.61432	1.61774	1.62604	52.7	1127	755	6.9	Clear glass.

TABLE 5. *Ternary* BaO-ZnO-SiO_2 *compositions*—Continued

Melt	Composition			n_C	n_D	n_F	ν	Liquidus Temp. °C	Sag Point °C	Coef. of Thermal exp. $\times 10^6$	Remarks
	BaO Mol %	ZnO Mol %	SiO_2 Mol %								
F795	16	28	56					1162	738		Clear glass.
F808	16	30	54	1.63462	1.63832	1.64727	50.5	1205	727		Clear glass.
F797	16	34	50	1.65131	1.65516	1.66454	49.5	1259	728		Clear glass.
F810	16	38	46					1333			Some devit.
F845	14	22	64					>1407	766		Opal glass.
F844	14	24	62	1.60812	1.61148	1.61966	53.0	1257	766		Slight devit.
F838	14	26	60					1254	765		Slight devit.
F837	14	28	58					1283	765		Slight devit.
F816	14	30	56	1.62566	1.62923	1.63789	51.4	1203	737		Clear glass.
F802	14	34	52	1.64298	1.64675	1.65593	49.9	1260	727		Clear glass.
F805	14	38	48	1.65546	1.65940	1.66906	48.5	1252	725		Clear glass.
F839	14	40	46	1.66423	1.66826	1.67816	48.0	1326			Clear glass.
F841	12	30	58	1.61789	1.62139	1.62989	51.8	1233			Slight devit.
F840	12	32	56	1.62320	1.62677	1.63543	51.3	1245	745		Clear glass.
F809	12	34	54	1.63434	1.63803	1.64699	50.4	1246	737		Clear glass.
F798	12	38	50	1.64908	1.65292	1.66235	49.2	1304	738	7.2	Clear glass.
F842	12	40	48	1.65487	1.65882	1.66847	48.4	1342	730		Clear glass.
F843	12	42	46	1.66526	1.66930	1.67923	47.9	1402	715		Slight devit.
F817	10	34	56					1293	735		Slight opal.
F813	10	36	54	1.63301	1.63671	1.64572	50.1	1307	727		Clear glass.
F801	10	38	52	1.64045	1.64424	1.65348	49.4	1340	727		Clear glass.
F804	10	42	48	1.65416	1.65810	1.66776	48.4	1390	735		Clear glass.
F799	8	42	50	1.64709	1.65098	1.66047	48.7	1371	738	5.7	Clear glass.
F818	6	38	56					>1412			Opal glass.
F814	6	40	54					>1408			Opal glass.
F807	6	42	52	1.63757	1.64134	1.65066	49.0	1403	735		Clear glass.
F815	6	46	48					1407	727		Considerable devit.
F800	4	46	50					>1425			Devit in mold.
F846	4	44	52					>1407			Devit in mold.

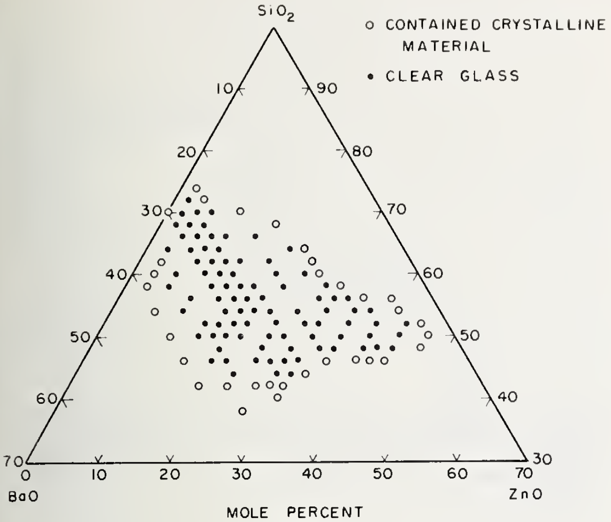


FIGURE 25. *Compositions studied in the system* BaO-ZnO-SiO_2.

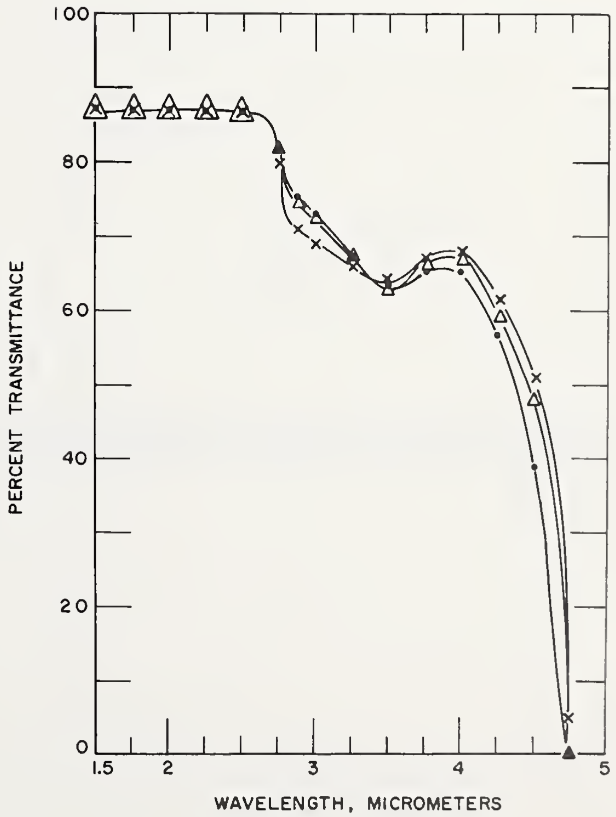


FIGURE 26. *Spectral transmittance of 2-mm thickness of glasses containing 36 mol percent of* BaO. ● F786, Δ F787, × F788.

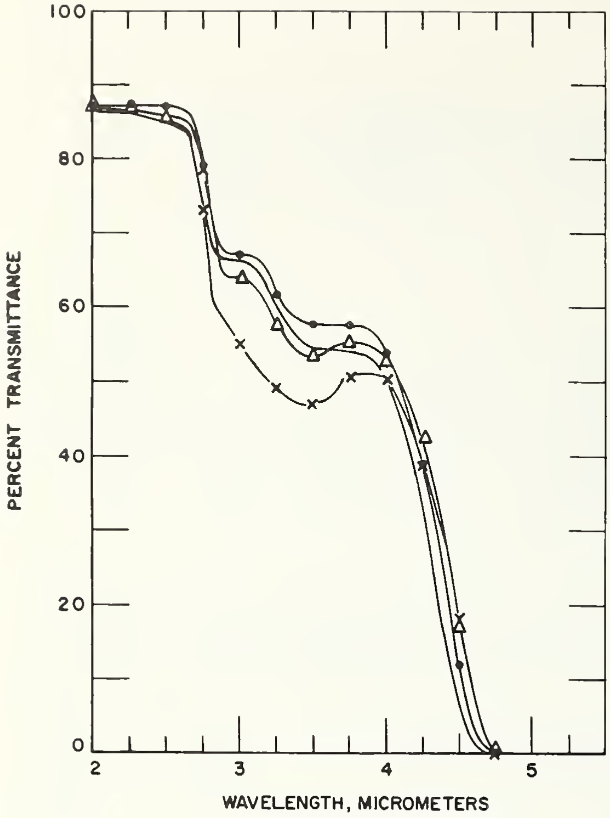


FIGURE 27. *Spectral transmittance of 2-mm thickness of glasses containing 30 mol percent of* BaO. – F690, ● F692, Δ F694, × F711.

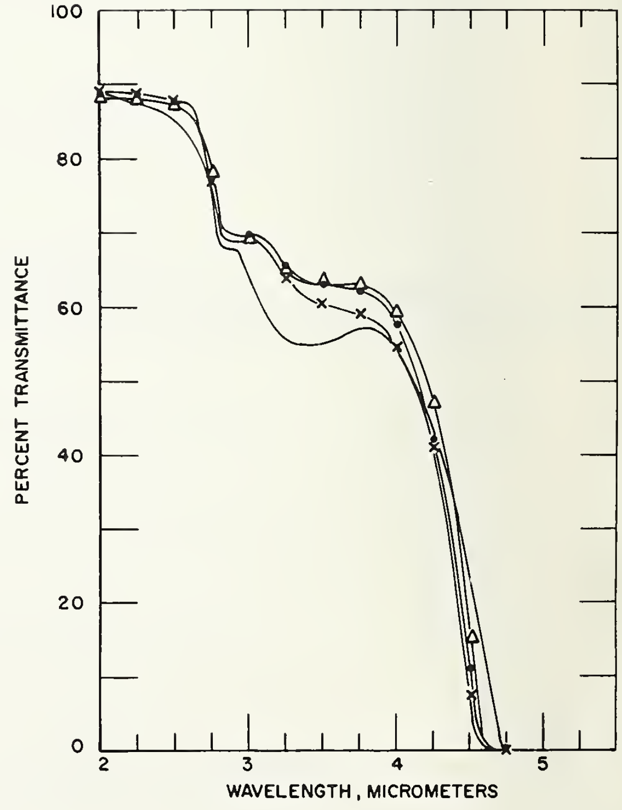


FIGURE 28. *Spectral transmittance of 2-mm thickness of glasses containing 26 mol percent of* BaO. × F705, ● F707, Δ F709, – F716.

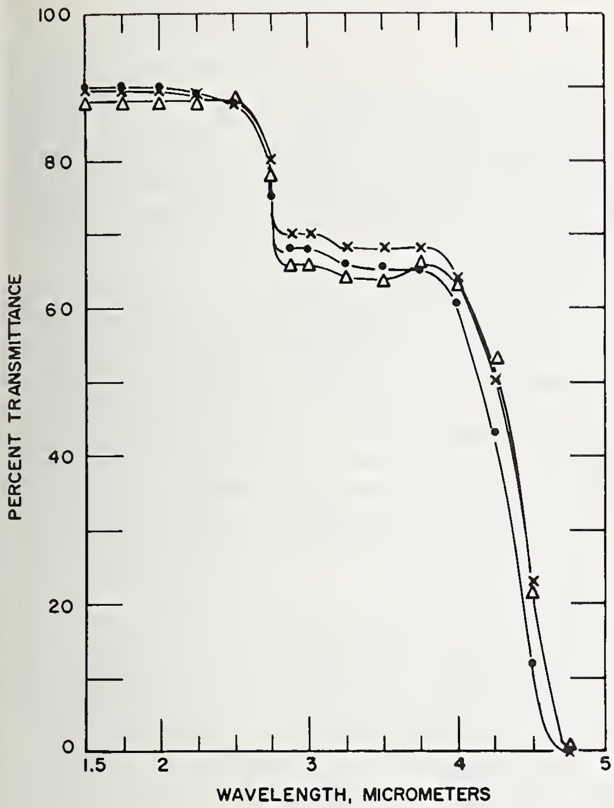
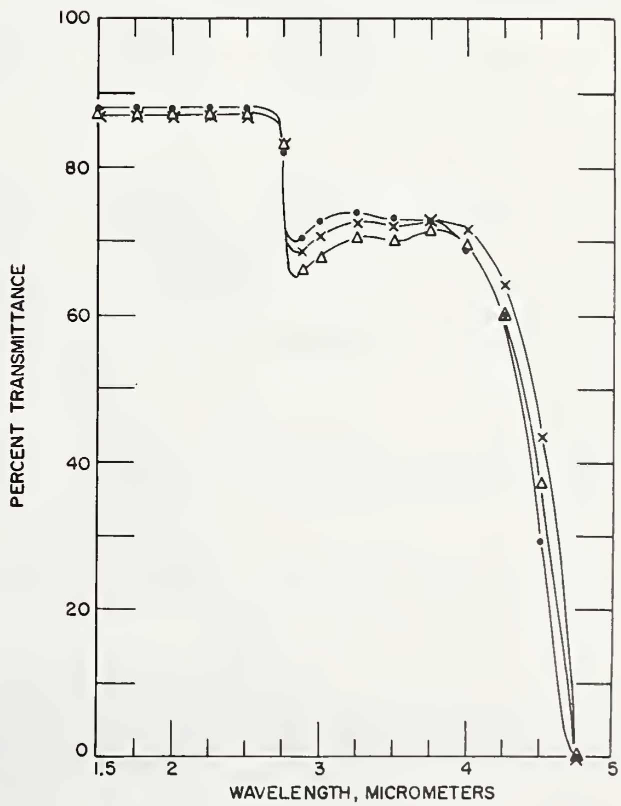


FIGURE 29. *Spectral transmittance of 2-mm thickness of glasses containing 20 mol percent of* BaO. ● F733, △ F763, × F735.

FIGURE 30. *Spectral transmittance of 2-mm thickness of glasses containing 14 mol percent of* BaO. ● F816, △ F802, × F805.



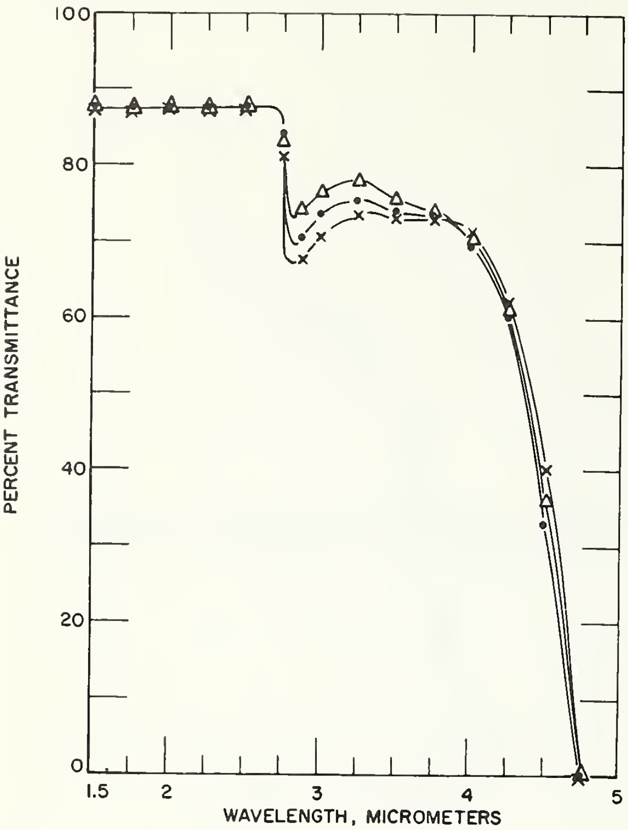


FIGURE 31. *Spectral transmittance of 2-mm thickness of glasses containing 10 mol percent of* BaO. ● F813, △ F801, × F804.

3.5. The $BaO-Nb_2O_5-SiO_2$ System

Nb_2O_5, when used as a component of glass, imparts relatively high values of refractive index along with high dispersion, or low ν. The glass-forming region of the $BaO-Nb_2O_5-SiO_2$ system was determined. Information on the binary sides, $BaO-SiO_2$ [8], $BaO-Nb_2O_5$ [16], and $Nb_2O_5-SiO_2$ [17], is available, but the ternary system has not been worked out.

The region of glass formation in the system is shown in the triangular diagram in figure 32, and the compositions melted and their measured properties are listed in table 6. Except for the 2 and 6 mol percent glasses, most of the melts had liquidus temperatures below 1300 °C. A minimum value of 1152 °C was found for one glass in the 14-mol-percent Nb_2O_5 series. Glasses were formed to remarkably low SiO_2 contents, as may be seen from the table and from figure 32. Glass F1466 contained 38-mol-percent SiO_2.

The refractive index, n_D, ranged from 1.615 to 1.902 with ν from 51.7 to 27.6.

The transmittance curves for 2 mm thicknesses of the glasses from the 2, 6, 10, 14, 18, and 22 mol percent Nb_2O_5 series are shown in figures 33 to 38, respectively. As the Nb_2O_5 content of the glasses increase the minimum in transmittance in the 2.75 to 4 μm region increases. This evidently is related to the $(OH)^-$ content of the glasses and to the manner in which $(OH)^-$ is bound, but no general explanation of this behavior is readily seen.

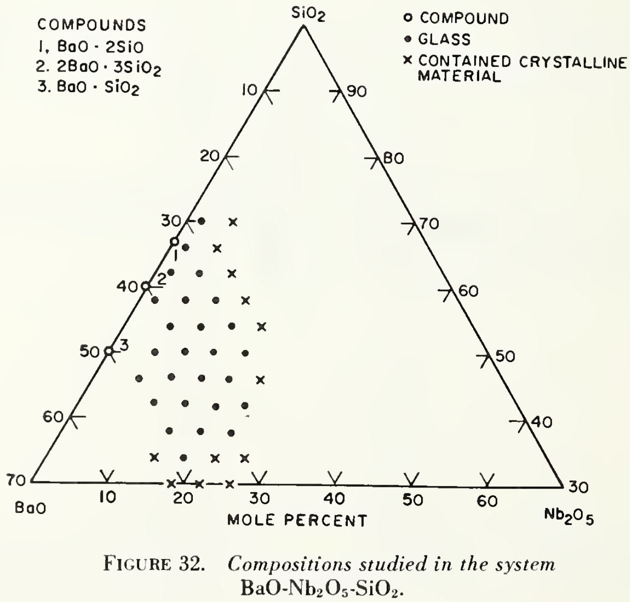


FIGURE 32. *Compositions studied in the system* $BaO-Nb_2O_5-SiO_2$.

TABLE 6. *Ternary* BaO-Nb_2O_5-SiO_2 *compositions*

Melt No.	Compositions			n_C	n_D	n_F	ν	Sag Point °C	Liquidus Temp. °C	Remarks
	SiO_2 Mol %	BaO Mol %	Nb_2O_5 Mol %							
F1431	70	28	2	1.61152	1.61497	1.62341	51.7	812	1348	Seedy glass.
F1432	66	32	2	1.63111	1.63471	1.64352	51.1	818	1343	Clear glass.
F1433	62	36	2	1.64421	1.64794	1.65704	50.5	809	1380	Do.
F1434	58	40	2	1.66006	1.66394	1.67345	49.6	822	1394	Do.
F1435	70	24	6							Devit in mold.
F1436	66	28	6							Do.
F1437	62	32	6	1.68287	1.68738	1.69856	43.8	819	1339	Clear glass.
F1438	58	36	6	1.69921	1.70391	1.71558	43.0	813	1331	Do.
F1439	54	40	6	1.71062	1.71543	1.72739	42.7	850	1336	Do.
F1445	50	44	6	1.72775	1.73290	1.74573	40.8	832	1274	Do.
F1486	46	48	6							Devit in mold.
F1441	62	28	10							Devit in mold.
F1442	58	32	10	1.73419	1.73977	1.75373	37.9	835	1212	Clear glass.
F1443	54	36	10	1.74802	1.75372	1.76803	37.7	827	1244	Do.
F1444	50	40	10	1.75390	1.75959	1.77385	38.1	819	1246	Do.
F1446	46	44	10	1.76825	1.77413	1.78884	37.6	868	1226	Do.
F1456	42	48	10					843	1234	Opal during anneal.
F1447	58	28	14							Devit in mold.
F1448	54	32	14	1.78176	1.78844	1.80532	33.5		1273	Clear glass.
F1449	50	36	14	1.79500	1.80176	1.81887	33.6	853	1250	Do.
F1450	46	40	14	1.80584	1.81269	1.83002	33.6	862	1191	Do.
F1451	42	44	14	1.81450	1.82140	1.83888	33.7			Do.
F1457	38	48	14	1.82084	1.82777	1.84529	33.8	837	1152	Do.
F1488	34	52	14					850	1242	Opal on cooling.
F1458	54	28	18							Devit in mold.
F1459	50	32	18	1.82988	1.83792	1.85805	29.8	862	1295	Clear glass.
F1460	46	36	18	1.84130	1.84922	1.86945	30.2	836	1240	Clear yellowish glass.
F1461	42	40	18	1.84890	1.85680	1.87702	30.5	833	1247	Do.
F1462	38	44	18	1.85714	1.86508	1.88533	30.7	856	1203	Do.
F1463	34	48	18	1.86176	1.86967	1.88983	31.0	866	1203	Do.
F1489	30	52	18						1269	Opal on cooling.
F1464	46	32	22							Devit in mold.
F1465	42	36	22	1.88213	1.89116	1.91444	27.6	872	1306	Clear yellowish glass.
F1466	38	40	22	1.89258	1.90166	1.92498	27.8	862	1274	Do.
F1490	34	44	22					887	1286	Devit streaks on cooling.
F1491	30	48	22						1262	Do.
F1492	34	40	26					887		Devit streak & seedy.
F1493	30	44	26							Devit streaks on cooling.

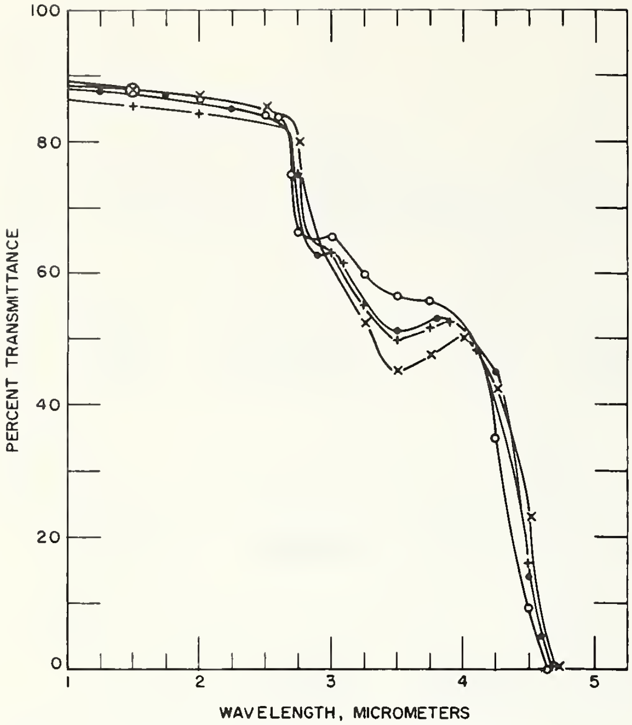


FIGURE 33. *Spectral transmittance of 2-mm thickness of glasses containing 2 mol percent of* Nb_2O_5. ○F1431, ●F1432, +F1433, ×F1434.

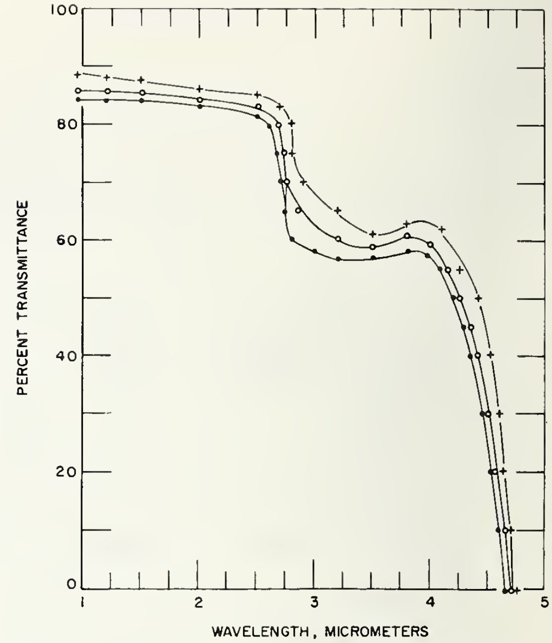


FIGURE 35. *Spectral transmittance of 2-mm thickness of glasses containing 10 mol percent of* Nb_2O_5. ●F1442, ○F1443, +F1444.

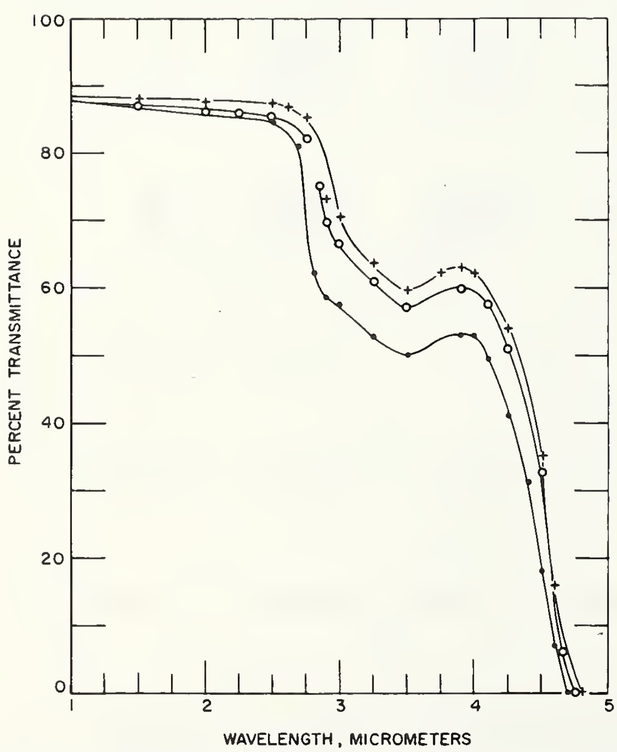


FIGURE 34. *Spectral transmittance of 2-mm thickness of glasses containing 6 mol percent of* Nb_2O_5. ●F1437, ○F1438, +F1439.

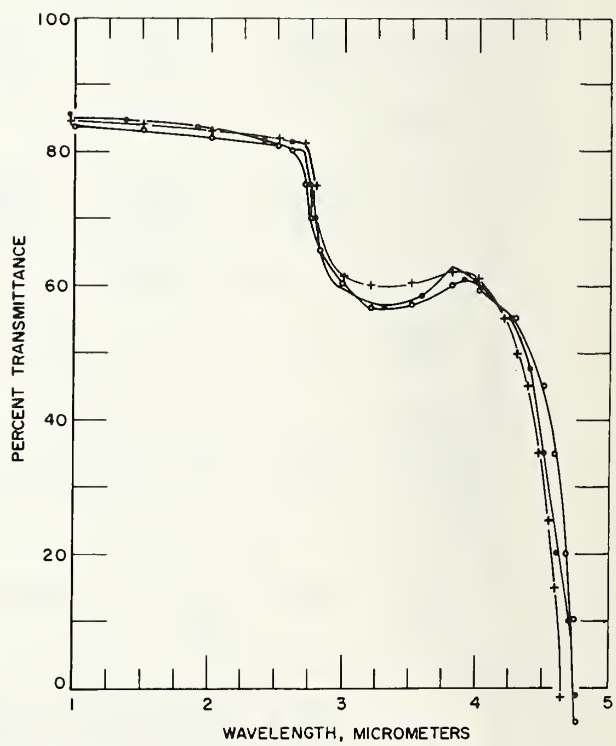


FIGURE 36. *Spectral transmittance of 2-mm thickness of glasses containing 14 mol percent of* Nb_2O_5. +F1448, ●F1449, ○F1451.

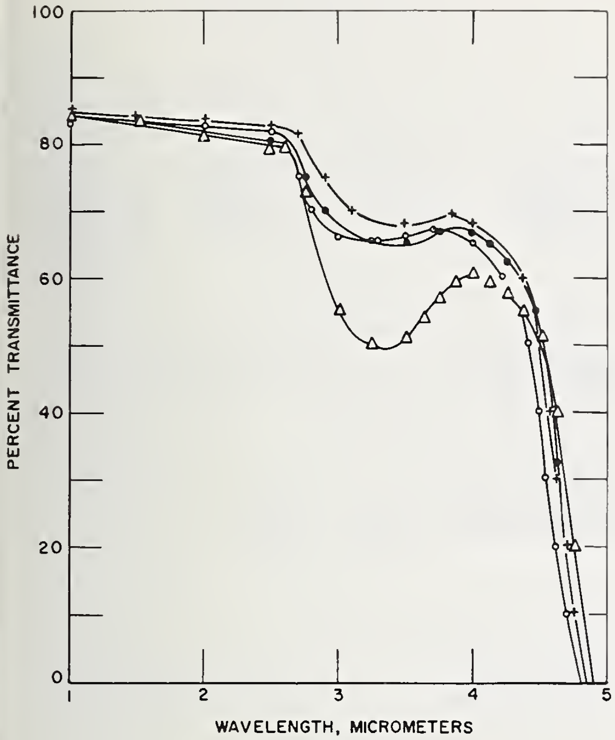


FIGURE 37. *Spectral transmittance of 2-mm thickness of glasses containing 18 mol percent of* Nb_2O_5. ○F1460, + F1461, ●F1462, △ F1463.

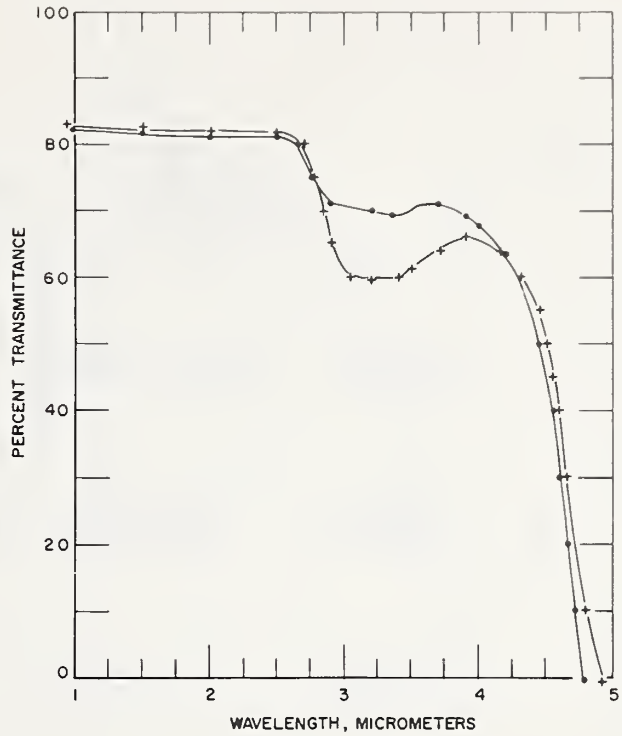


FIGURE 38. *Spectral transmittance of 2-mm thickness of glasses containing 22 mol percent of* Nb_2O_5. ●F1465, + F1466.

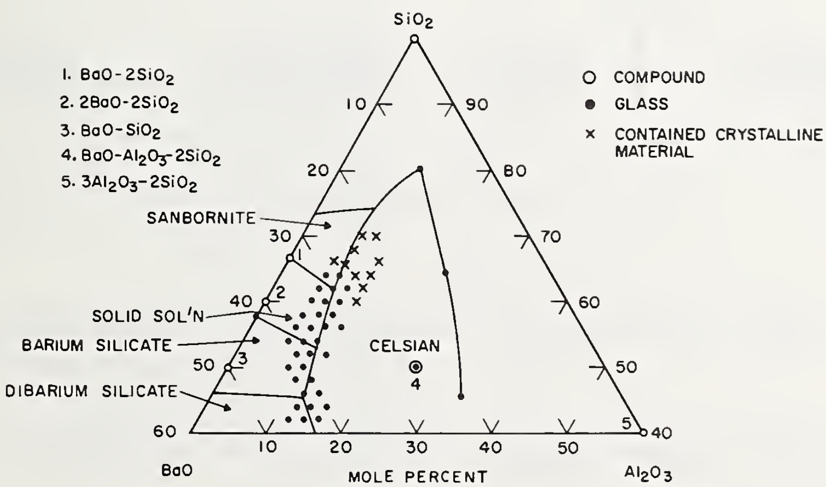


FIGURE 39. *Compositions studied in the system* BaO-Al_2O_3-SiO_2 *and approximate phase boundaries.*

Table 7. *Ternary* $BaO \cdot Al_2O_3 \cdot SiO_2$ *compositions*

Melt No.	Compositions: SiO_2 Mol %	Compositions: BaO Mol %	Compositions: Al_2O_3 Mol %	n_C	n_D	n_F	ν	Liquidus Temp. °C	Sag Point °C	Remarks
F1170	66	28	6						857	Seedy.
F1169	64	30	6	1.60438	1.60758	1.61537	55.3	1208	857	
F1168	62	32	6	1.60887	1.61207	1.61991	55.5	1268	840	
F1167	60	34	6	1.61158	1.61483	1.62264	55.6	1286	840	
F1166	58	36	6	1.62514	1.62862	1.63672	54.3	1277	832	
F1165	56	38	6	1.62831	1.63170	1.63993	54.3	1263	832	
F1164	54	40	6	1.63238	1.63586	1.64415	54.0	1290	825	
F1119	70	22	8							Seedy.
F1158	68	24	8						874	Do.
F1159	66	26	8						874	Do.
F1148	64	28	8	1.59445	1.59760	1.60501	56.6	1162	853	Striated.
F1145	62	30	9					1166	840	
F1124	60	32	8					1205	833	Impossible to measure index.
F1131	58	34	8	1.61694	1.62023	1.62827	54.8	1177		
F1132	56	36	8	1.62142	1.62473	1.63280	54.9	1232	838	
F1133	54	38	8	1.62491	1.62822	1,63626	55.4	1176	838	
F1146	52	40	8	1.63133	1.63475	1.64309	54.0	1247	838	Striated.
F1147	50	42	8	1.63861	1.64207	1.65063	53.4	1305	840	
									848	
F1121	70	20	10							Seedy.
F1153	64	26	10					1332		Do.
F1143	62	28	10	1.59091	1.59397	1.60132	57.0	1368	827	
F1123	60	30	10	1.59885	1.60200	1.60942	57.0	1377	830	Striated.
F1128	58	32	10	1.60452	1.60770	1.61535	56.1	1412	833	Seedy.
F1129	56	34	10	1.61284	1.61612	1.62396	55.4	1368	833	Striated.
F1130	54	36	10	1.61956	1.62289	1.63094	54.7	1355	830	Striated.
F1144	52	38	10	1.62786	1.63127	1.63952	54.2	1367	840	
F1154	50	40	10	1.62626	1.62964	1.63784	54.4	1347	850	
F1157	48	42	10	1.63339	1.63684	1.64523	53.8	1292	857	
F1161	66	22	12					>1404		Seedy.
F1162	64	24	12					>1411		Do.
F1163	62	26	12					>1411		Do.
F1122	60	28	12					>1425	833	Do.
F1195	56	32	12							
F1196	52	36	12	1.62024	1.62357	1.63163	54.7	1337		
F1197	48	40	12	1.63315	1.63660	1.64501	53.7	>1445	872	
F1198	46	42	12	1.64036	1.64390	1.65254	52.9	1379	879	Striated.
F1210	44	44	12	1.64614	1.64972	1.65852	52.5		898	Striated.
F1211	42	46	12	1.65313	1.65685	1.66591	51.4		899	Striated.
F1199	46	40	14	1.63264	1.63611	1.64452	53.6		885	
F1200	44	42	14	1.64402	1.64765	1.65635	52.5		892	
F1209	42	44	14	1.65000	1.65365	1.66263	51.7		898	Striated.
F1207	44	40	16	1.63727	1.64080	1.64937	53.0		895	Striated.
F1208	42	42	16	1.64329	1.64689	1.65565	52.4		895	Striated.

3.6. The $BaO-Al_2O_3-SiO_2$ System

Alumina is widely used as a component of glass. Morey [18] states that "alumina in small quantity is a frequent constituent of glass. It gives greater chemical durability, lower coefficient of expansion, and greater freedom from devitrification." It has long been known that small amounts of Al_2O_3 improved the flame working properties of thermometer glass [19].

Aluminate glasses [20, 21] have been of interest because of their improved infrared transmittance as compared to most silicate glasses. An area of glass formation in the $CaO-Al_2O_3$ system is the basis for these glasses. Aluminosilicate glasses [22] containing 20 to 40 percent Al_2O_3, have high softening temperatures, relatively low thermal expansion coefficients, and high values of hardness. They have been used for lamp envelopes, chemical combustion tubes and "top-of-stove" ware.

The ternary diagram for the $BaO-Al_2O_3-SiO_2$ system [23] has been published along with isofracts for the ternary glasses [24]. More recently Forster et al. [25] have made further studies in this ternary system and have revised the earlier diagram.

The compositions melted in this work are listed in table 7 along with the properties measured on the resulting glasses. The 10 mol percent Al_2O_3 series fall near the phase boundary between the ternary compound $BaO \cdot Al_2O_3 \cdot 2SiO_2$ and the binary barium silicates. This is illustrated in the ternary diagram shown in figure 39, where the compositions melted and the approximate location of the phase boundaries as determined by Foster et al. [25], and by Thomas [24] are plotted. The refractive index, n_D varied from 1.5940 to 1.6536 with ν in the range from 51.4 to 57.0.

The transmittance curves for 2-mm thicknesses of representative glasses from 6, 8, and 10 mol percent Al_2O_3 series are plotted in figures 40, 41, and 42, respectively. Again, as the Al_2O_3 content of the glasses increase the minimum in transmittance in the 2.75 to 4.0 μm region moves to higher values. No general explanation of this behavior is readily evident other than that it is related to $(OH)^-$ content of the glasses and the manner in which the $(OH)^-$ is bound.

The thermal expansion of glass F1123 is shown in figure 43. The linear coefficient of thermal expansion over the temperature range from 100 to 600 °C is 8.1×10^{-6}/°C which is only slightly lower than ordinary window or plate glass. The deformation temperature is 797 °C which is considerably higher than most ordinary glasses.

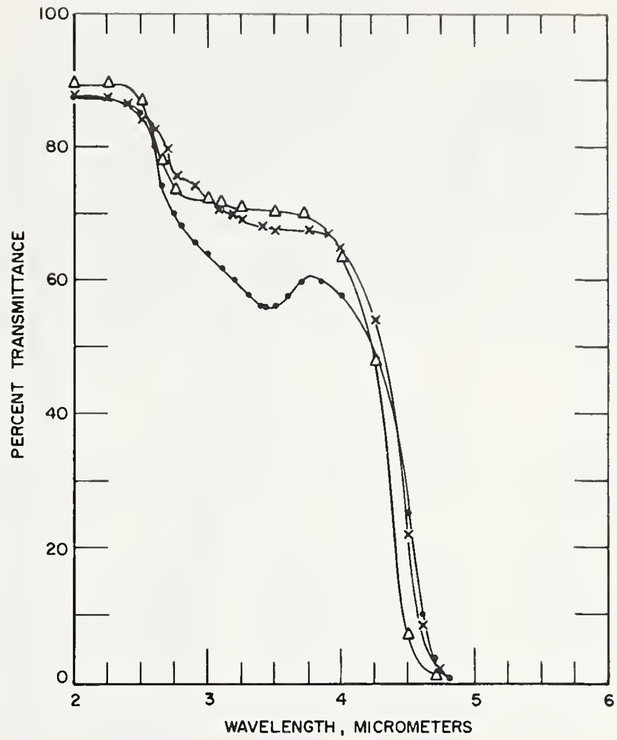


FIGURE 40. *Spectral transmittance of 2-mm thickness of glasses containing 6 mol percent of* Al_2O_3. ● F1164, × F1166, △ F1169.

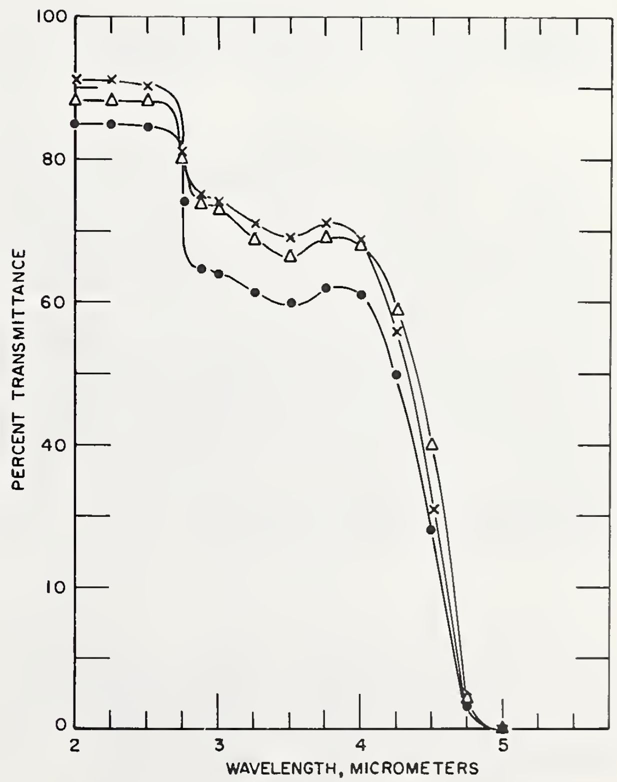


FIGURE 41. *Spectral transmittance of 2-mm thickness of glasses containing 8 mol percent of* Al_2O_3. ● F1124, × F1132, △ F1133.

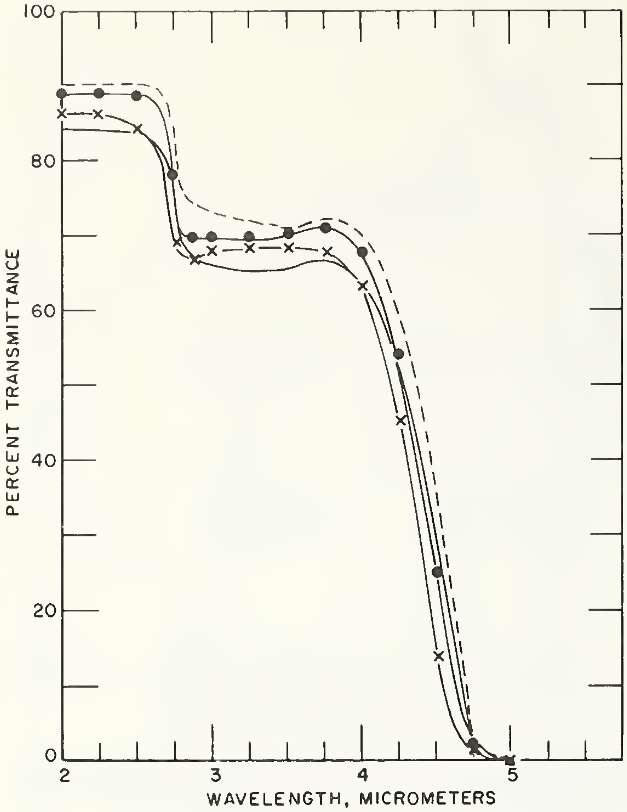


FIGURE 42. *Spectral transmittance of 2-mm thickness of glasses containing 10 mol percent of* Al_2O_3. ●F1123, — F1129, — — — F1130, × F1143.

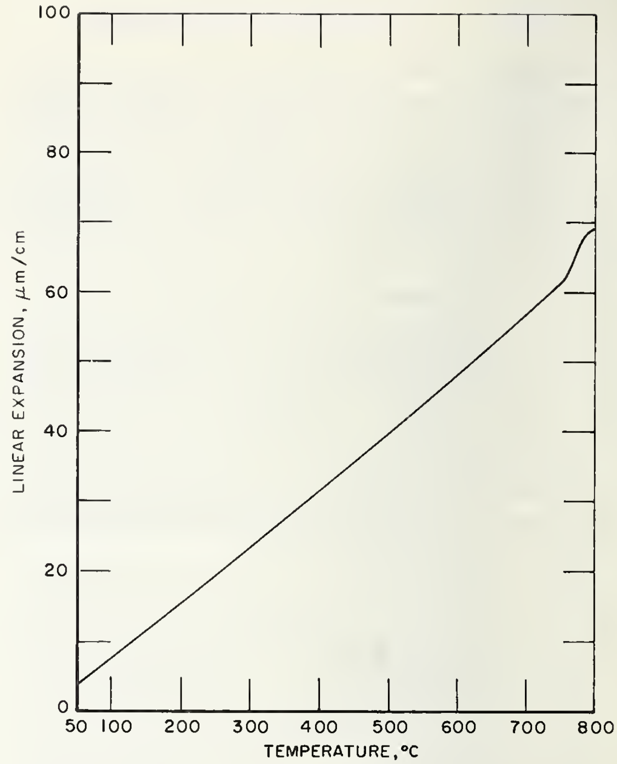


FIGURE 43. *Thermal expansion of Glass F 1123 as determined by an interferometric method.*

Linear coefficient of thermal expansion (100–600 °C) is 8.1×10^{-6}/°C and deformation temperature is 797 °C.

4. Analytical Representation of Data

Composition-property data in the six ternary barium silicate glass systems have been quantitatively evaluated following the method of Babcock [3]. Data on refractive index and specific volume, in a number of silicate glass systems, were segregated into groups according to the composition ranges and areas covered by the known primary crystallization phase fields involved. The separate groups of data, one group for each primary phase field, were then subjected to least-squares computer analysis. The program called for determining the role of each oxide in linear equations of the form

$$\text{Glass Property} = A\ SiO_2 + B\ CaO + C\ Na_2O + \ldots$$

A, B, and C are numerical constants characteristic of the respective oxides and amounts of oxides are expressed in mole fractions. The fidelity with which the equations represent the measured data is indicated by the computerized standard error

$$\sqrt{\frac{\sum (\Delta P)^2}{N-1}}$$

wherein ΔP is the difference between measured and calculated data and N equals the number of measurements.

This work [3] demonstrated that data on several hundred silicate glasses, measured by the National Bureau of Standards and the Geophysical Laboratory, Carnegie Institute of Washington, could be accurately represented to the fourth decimal place by such linear equations. This accuracy was good enough to permit calculation of phase boundaries and compositions of invariant points in binary and ternary silicate glass systems. Approximate phase diagrams were developed in this manner simply by using linear composition-property equations. It follows from this method that boundaries between primary phases are straight lines and that three such property planes may intersect in an invariant point for ternary systems. It must be emphasized that development of an approximate phase diagram in this manner is not meant to replace the well-established phase equilibrium methods of Gibbs [26], Morey [27], and others. This quantitative analytical method [3] has two important uses: (1) Formulation of glass compositions for specific property applications, (2) Furnishing first-approximation information on incomplete or nonexistent phase diagrams of silicate glass systems.

A modified procedure has been used for the ternary barium silicates since phase diagrams do not exist for most of these systems. The glasses have been segregated into groups within which the data can be quantitatively represented by linear equations. This procedure made it necessary to adopt an arbitrary criterion for the grouping of glasses. In terms of intended usage of the data and the precision of the measurements, it was decided that the standard error for refractive index for a given group be limited to 0.001. This criterion resulted in placing 71 percent of the glasses in groups which can be referred to here as "compatibility groups." The differences between measured and calculated values, of the other 29 percent, were 0.0020 or greater and were arbitrarily left out of the computerized groups. The interested reader will, of course, draw his own conclusions in this regard and use the measured data and computerized information to fit his own particular needs.

It is pointed out that refractive index, partial dispersions and specific volume are properties of the glasses, but that the ν-value, and its inverse, the dispersive power, are empirical ratios. These properties are linear functions of mole compositions, but the ν-values are not. Linear equations representing ν-values are only first approximations and are shown here for estimation purposes only.

It is also to be noted that the previous work [3] involved a larger number of glasses within groups than were available for the barium silicate glasses. The compositions were chemically analyzed while the barium silicate compositions are calculated from batch compositions. It is to be expected, therefore, that the placement of glasses in given groups and the boundaries between groups will be somewhat less definite in the case of the barium silicate glasses. However, the composition-property information on the barium silicates is quite good enough for the formulation of glasses. As a practical matter the refractive index of a glass depends on the composition, the homogeneity, and the annealing treatment. The determination of the refractive index is dependent upon the precision and accuracy of the measurement process and the environmental conditions of measurement. Unfortunately, annealing procedures cannot be specified quantitatively, and depending on the glass composition in question, may cause differences in the third decimal place in refractive index. To achieve greater precision, say in the fourth or fifth decimal places as in the case of commercial optical glasses, it is necessary to pay much closer attention to all the factors influencing refractive index.

Detailed information on analytical representation of data in the barium silicates is shown in the following sections. Tables 8 to 13 give property-composition equations. Figures 44 to 51 are graphical plots of the derived composition-property relations.

4.1. The BaO-TiO_2-SiO_2 System

Table 8 shows equations relating compositions and properties of glasses in the two compatibility groups in this system. Equations for the partial dispersions are obtained simply by taking differences between the respective refractive index equations. A given partial dispersion may be calculated either by using the partial dispersion oxide factors or by calculating each refractive index and taking differences between the two. The same value will be obtained in the two cases. Calculated values of ν are only first approximations.

TABLE 8. BaO-TiO_2-SiO_2 *glasses*

Glass Property $= A\ SiO_2 + B\ TiO_2 + C\ BaO$

Property	A	B	C	Std. Error
		Group I Glasses		
n_C	1.47915	2.27530	1.84290	0.00066
n_D	1.48163	2.29497	1.84628	.00062
n_F	1.48594	2.34396	1.85834	.00070
n_F-n_D	0.00431	0.04899	0.01206	
n_D-n_C	.00248	.01967	.00338	
n_F-n_C	.00679	.06866	.01544	
ν	60.06	−43.03	41.56	.4418
Volume	0.36089	0.23177	0.08893	.00078
Average of differences between measured and calculated densities = 0.096				
		Group II Glasses		
n_C	1.48429	2.32814	1.79030	0.00116
n_D	1.48553	2.35228	1.79234	.00119
n_F	1.48783	2.41798	1.79543	.00127
n_F-n_D	0.00230	0.06570	0.00309	
n_D-n_C	.00124	.02414	.00204	
n_F-n_C	.00354	.08984	.00513	
ν	41.27	−10.73	49.93	0.1633
Volume	0.34946	0.25306	0.09806	.00027
Average of differences between measured and calculated densities = 0.003				

Figure 44 shows compositions of glasses used in the two computerized groups. The position of the boundary between the two groups, shown as a broken line, was obtained by solving the following equations simultaneously

$$\text{I}\quad n_D = 1.48163\ SiO_2 + 2.29497\ TiO_2 + 1.84628\ BaO$$
$$\text{II}\quad n_D = 1.48553\ SiO_2 + 2.35228\ TiO_2 + 1.79234\ BaO$$
$$SiO_2 + TiO_2 + BaO = 1$$

Solutions and calculation checks are as follows

SiO_2	0.35	SiO_2	0.55
TiO_2	.30	TiO_2	.20
BaO	.35	BaO	.25
n_D (I)	1.8533		1.7354
n_D (II)	1.8529		1.7356

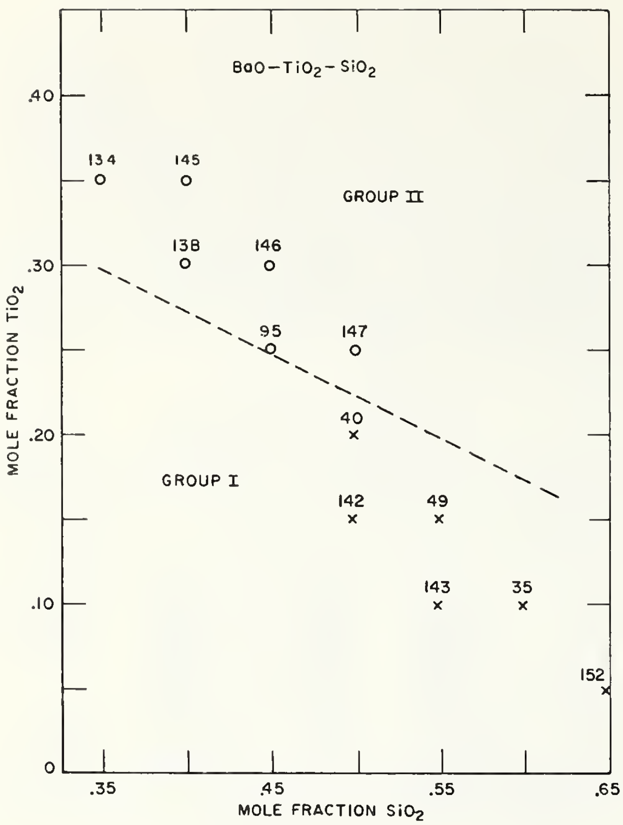


FIGURE 44. *Compositional plot showing the groups into which glasses in the* $BaO\text{-}TiO_2\text{-}SiO_2$ *system were divided by computer evaluation of property data.*

Numbers of glasses in each group are those from earlier composition tables with F omitted.

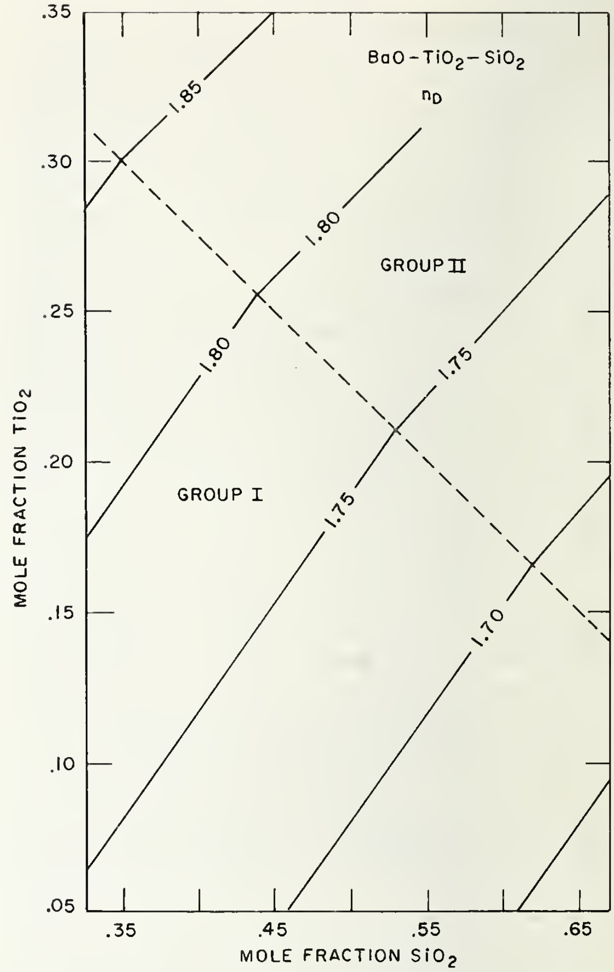


FIGURE 45. *Isofracts in the* $BaO\text{-}TiO_2\text{-}SiO_2$ *system.*

The averages of differences between measured and calculated densities (reciprocals of the specific volumes) are shown in the tables.

Representation of the data in terms of linear equations permits arranging the information in a number of ways. Figure 45, for example, shows lines of equal n_D in a $SiO_2\text{-}TiO_2$ plot. It will be noted that the equal property lines are continuous across the boundary between the two groups. Similar plots can be made of equal values of partial dispersions and specific volume. Plots showing lines of equal density can be made, but they will not be quite linear. Figure 46 shows lines of equal ν in a $SiO_2\text{-}TiO_2$ plot. As previously mentioned, ν is an empirical ratio and the lines of equal value are not continuous across the boundary.

Reference to partial phase diagram information by Rase and Roy [6] and by Cleek and Hamilton [4] suggests that glasses in Group I may lie in the $BaO \cdot 2SiO_2$ phase field and those in Group II may lie in the $BaO \cdot TiO_2 \cdot SiO_2$ phase field.

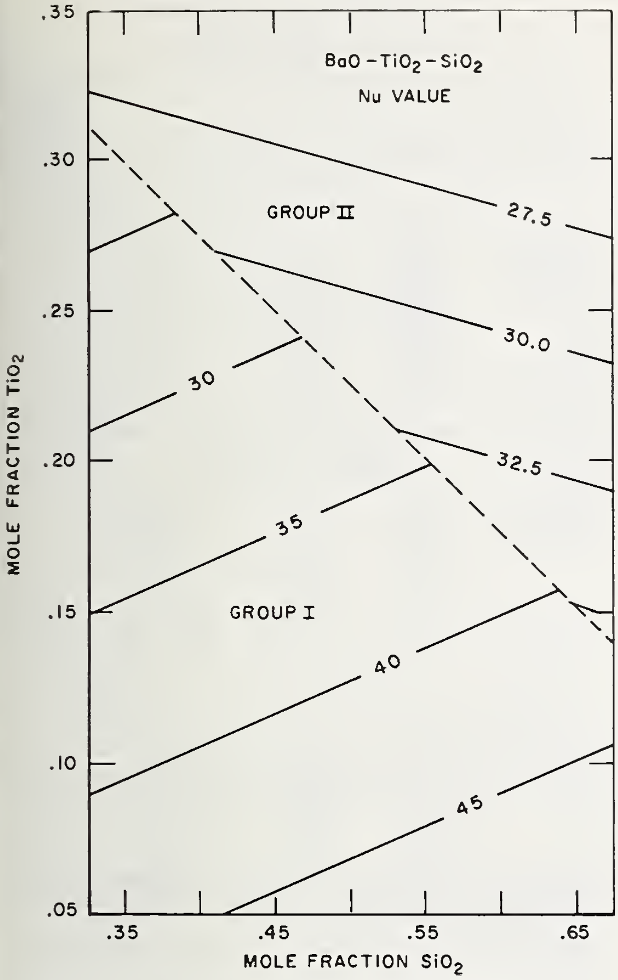


FIGURE 46. *Lines of constant* ν in the BaO-TiO_2-SiO_2 *system.*

4.2. The BaO-La_2O_3-SiO_2 System

Table 9 shows equations representing data in the two groups of glasses in this system. It will be noted that La_2O_3 has negative volume factors in both groups. The volume equations represent the density data quite closely.

Figure 47 shows compositions of glasses used in the computerized groups. Information on this system does not permit calculating the exact location of the broken line separating the two groups It is drawn roughly to denote the separation. That glass F549 is in Group I and glass F530 in Group II is verified by the following differences between measured and calculated n_D when equations for the two groups are used

	Group I	Group II
*F*530	0.0023	0.0002
*F*549	.0004	.0039

TABLE 9. BaO-La_2O_3-SiO_2 *glasses*

Glass property = A SiO_2 + B La_2O_3 + C BaO

Property	*A*	*B*	*C*	Std. Error
		Group I Glasses		
n_C	1.48825	2.51281	1.83983	0.00068
n_D	1.49036	2.52380	1.84518	.00068
n_F	1.49538	2.55158	1.85810	.00070
n_F-n_D	0.00502	0.02778	0.01292	
n_D-n_C	.00211	.01099	.00535	
n_F-n_C	.00713	.03877	.01827	
ν	63.00	6.90	41.88	0.0913
Volume	0.35428	−0.17875	0.10807	.00076
Average of differences between measured and calculated densities = 0.009				
		Group II Glasses		
n_C	1.51660	2.46619	1.79980	0.00037
n_D	1.51872	2.47735	1.80510	.00039
n_F	1.52372	2.50559	1.81819	.00039
n_F-n_D	0.00500	0.02824	0.01309	
n_D-n_C	.00212	.01116	.00530	
n_F-n_C	.00712	.03940	.01839	
ν	63.54	5.35	40.78	0.0965
Volume	0.32645	−0.10865	0.14791	.00030
Average of differences between measured and calculated densities = 0.005				

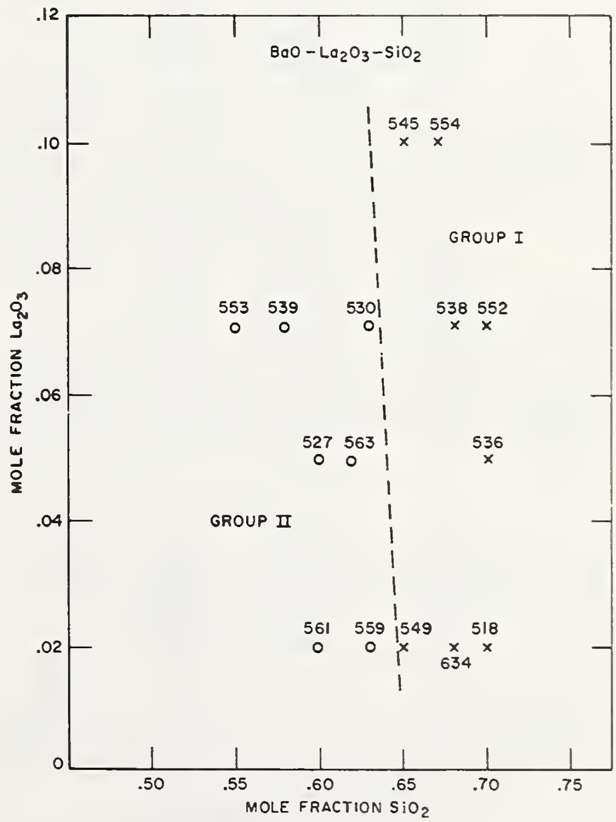


FIGURE 47. *Compositional plot showing the groups into which glasses in the* BaO-La_2O_3-SiO_2 *system were divided by computer evaluation of property data.*

Numbers of glasses in each group are those from earlier composition tables with F omitted.

4.3. The $BaO-Ta_2O_5-SiO_2$ System

Table 10 shows equations representing data in the three groups in this system. It will be noted that Ta_2O_5 has negative ν in all groups and negative volume factors in groups I and II.

Figure 48 shows compositions of glasses used in the computerized groups. The data are not sufficient to allow calculation of the boundaries between the three groups. The broken lines roughly indicate the separations. Calculation of n_D for the four glasses near boundaries, F588, F534, F592, and F542 indicates that the glasses have been correctly grouped. The following indicates differences between measured and calculated n_D using the indicated equations:

Table 10. $BaO-Ta_2O_5-SiO_2$ *glasses*

Glass property $= A\ SiO_2 + B\ Ta_2O_5 + C\ BaO$

Glass Property	A	B	C	Std. Error
Group I Glasses				
n_C	1.43819	2.68156	1.95482	0.00028
n_D	1.43974	2.70166	1.96134	.00028
n_F	1.44331	2.75161	1.97761	.00028
$n_F - n_D$	0.00357	0.04995	0.01627	
$n_D - n_C$	.00155	.02010	.00652	
$n_F - n_C$	.00512	.07005	.02279	
ν	65.77	−96.27	34.13	0.2208
Volume	0.37394	−0.34930	0.06008	.00077
Average of differences between measured and calculated densities = 0.007				
Group II Glasses				
n_C	1.50395	2.48739	1.85520	0.00048
n_D	1.50627	2.50586	1.86048	.00048
n_F	1.51030	2.57296	1.87262	.00045
$n_F - n_D$	0.00463	0.06710	0.01214	
$n_D - n_C$	.00172	.01847	.00528	
$n_F - n_C$	.00635	.08557	.01742	
ν	59.09	−85.41	47.28	0.4249
Volume	0.31595	−0.16059	0.14165	.00071
Average of differences between measured and calculated densities = 0.010				
Group III Glasses				
n_C	1.65915	2.31775	1.69455	0.00003
n_D	1.66596	2.33911	1.69456	.00000
n_F	1.67132	2.36772	1.70992	.00004
$n_F - n_D$	0.00536	0.02861	0.01536	
$n_D - n_C$	.00681	.02136	.00001	
$n_F - n_C$	.01217	.04997	.01537	
ν	50.87	−12.64	46.87	0.2008
Volume	0.24761	0.02726	0.19721	.00009
Average of differences between measured and calculated densities = 0.002				

	Group I	Group II	Group III
F588	0.0001	0.0026	
F534	.0026	.0006	
F592		.0001	0.0014
F542		.0028	.0000

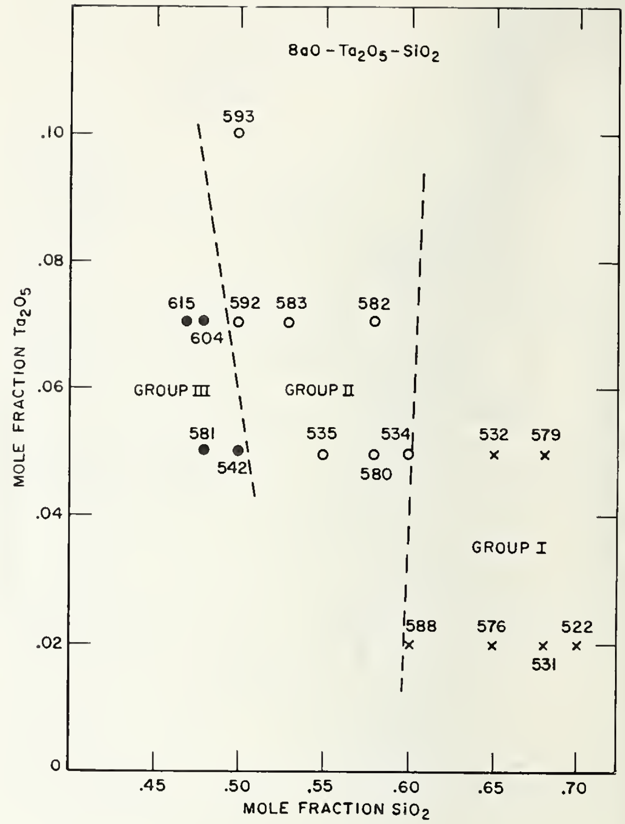


Figure 48. *Compositional plot showing the groups into which glasses in the* $BaO-Ta_2O_5-SiO_2$ *system were divided by computer evaluation of property data.*

Numbers of glasses in each group are those from earlier composition tables with F omitted.

4.4. The $BaO-ZnO-SiO_2$ System

Table 11 shows composition-property equations for glasses in the five groups in this system. This table identified glasses placed in the different groups. Figure 49 gives compositions of the 57 glasses used in the evaluations. The broken lines serve to separate the five groups. Exact composition locations of the boundaries could not be calculated. The equations indicate that the property contributions of ZnO and BaO, in terms of their factors, are similar quantitatively. In this connection, all 57 glasses were run as one group on the computer. The resulting n_D equation in this case was $n_D = 1.47000\ SiO_2 + 1.81955\ ZnO + 1.87614\ BaO$ with a standard error of 0.00205. Differences between measured and calculated n_D ranged from −0.0073 to 0.0038. However, the range of standard errors for n_D for the five separate groups from 0.00048 to 0.00064 indicates proper placement of the glasses. The interested reader can determine by calculation that n_D values, for example, of glasses not used in groups, have measured minus calculated differences greater than 0.001.

TABLE 11. BaO-ZnO-SiO_2 *glasses*

Glass property $= A\ SiO_2 + B\ ZnO + C\ BaO$

Glass property	A	B	C	Std. Error
Group I Glasses:[a] 705, 698, 706, 707, 727, 693, 694, 702, 709, 728, 695 703, 710, 730, 712, 718, 731, 784, 714, 766, 713				
n_C	1.46539	1.80155	1.88253	0.00065
n_D	1.46731	1.80723	1.88812	.00064
n_F	1.47172	1.82073	1.90237	.00064
n_F-n_D	0.00441	0.01350	0.01425	
n_D-n_C	.00192	.00568	.00559	
n_F-n_C	.00633	.01918	.01984	
ν	64.55	33.86	39.39	0.1057
Group II Glasses: 809, 813, 803, 802, 801, 797, 798, 806, 842 804, 839, 807, 799, 755				
n_C	1.46248	1.81986	1.88284	0.00056
n_D	1.46422	1.82590	1.88864	.00057
n_F	1.46800	1.84130	1.90279	.00058
n_F-n_D	0.00378	0.01540	0.01415	
n_D-n_C	.00174	.00604	.00580	
n_F-n_C	.00552	.02144	.01995	
ν	63.73	32.00	42.13	0.1076
Group III Glasses: 733, 734, 794, 735, 841, 795, 840				
n_C	1.52488	1.74916	1.74302	0.00047
n_D	1.52747	1.75428	1.74696	.00048
n_F	1.53373	1.76683	1.75636	.00050
n_F-n_D	.00626	.01255	0.00940	
n_D-n_C	.00259	.00512	.00394	
n_F-n_C	.00885	.01767	.01334	
ν	58.21	37.56	55.81	0.0833
Group IV Glasses: 745, 721, 724, 754, 723, 722, 775, 720, 715				
n_C	1.49409	1.84200	1.80081	0.00051
n_D	1.49602	1.84844	1.80587	.00051
n_F	1.50064	1.86444	1.81811	.00053
n_F-n_D	0.00462	0.01600	0.01224	
n_D-n_C	.00193	.00644	.00506	
n_F-n_C	.00655	.02244	.01730	
ν	63.29	28.97	45.02	0.0827
Group V Glasses: 760, 786, 787, 764, 762, 788				
n_C	1.46984	1.75656	1.89008	0.00056
n_D	1.47139	1.76190	1.89640	.00056
n_F	1.47458	1.77476	1.91280	.00056
n_F-n_D	0.00319	0.01286	0.01640	
n_D-n_C	.00155	.00534	.00632	
n_F-n_C	.00474	.01820	.02272	
ν	69.07	38.17	30.43	0.0652

[a] Numbers of Glasses in each group are those from earlier composition tables with F omitted.

4.5. The BaO-Nb_2O_5-SiO_2 System

Table 12 gives equations for glasses in the two groups in this system. It will be noted that ν values for Nb_2O_5 are negative.

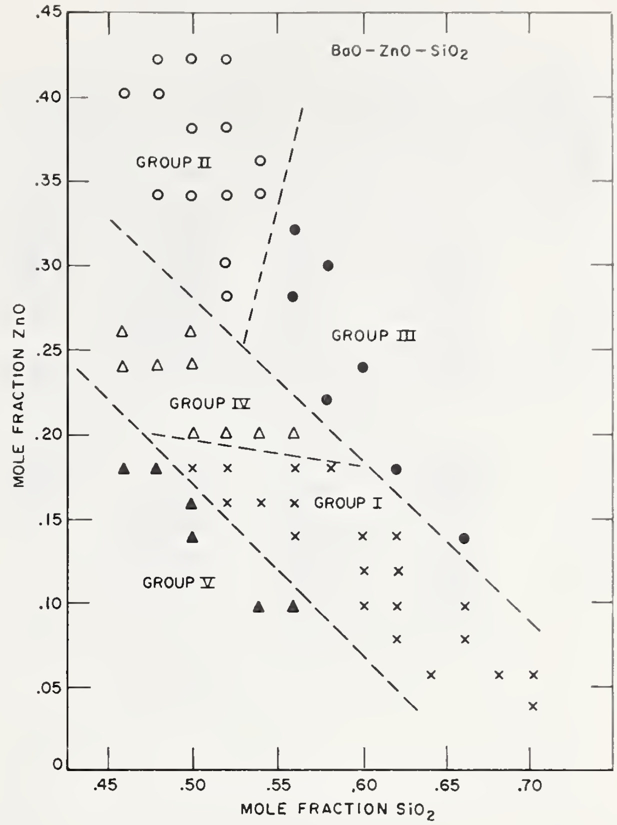


FIGURE 49. *Compositional plot showing the groups into which glasses in the* BaO-ZnO-SiO_2 *system were divided by computer evaluation of property data.*

Figure 50 shows compositions of glasses used in the two computer groups. The position of the boundary between the groups, indicated by a broken line, was determined by solving the following equations simultaneously

$$\text{I}\quad n_D = 1.49408\ SiO_2 + 2.80691\ Nb_2O_5 + 1.85111\ BaO$$
$$\text{II}\quad n_D = 1.56558\ SiO_2 + 2.69145\ Nb_2O_5 + 1.78584\ BaO$$
$$SiO_2 + Nb_2O_5 + BaO = 1$$

Solutions and calculation checks are as follows

SiO_2	0.477	0.516
Nb_2O_5	-------	.100
BaO	.523	.384
n_D (I)	1.6808	1.7624
n_D (II)	1.6808	1.7627

TABLE 12. BaO—Nb_2O_5—SiO_2 *glasses*

Glass property = *A* SiO_2 + *B* Nb_2O_5 + *C* BaO

Glass property	*A*	*B*	*C*	Std. Error
		Group I Glasses		
n_C	1.49209	2.78035	1.84569	0.00053
n_D	1.49408	2.80691	1.85111	.00053
n_F	1.49870	2.87595	1.86462	.00055
n_F-n_D	0.00462	0.06904	0.01351	
n_D-n_C	.00199	.02656	.00542	
n_F-n_C	.00661	.09560	.01893	
ν	59.38	−103.22	43.03	0.3705
		Group II Glasses		
n_C	1.56263	2.66145	1.78253	0.00112
n_D	1.56558	2.69145	1.78584	.00110
n_F	1.57170	2.77114	1.79431	.00109
n_F-n_D	0.00612	0.07969	0.00847	
n_D-n_C	.00295	.03000	.00331	
n_F-n_C	.00907	.10969	.01178	
ν	42.36	−35.25	47.86	0.3004

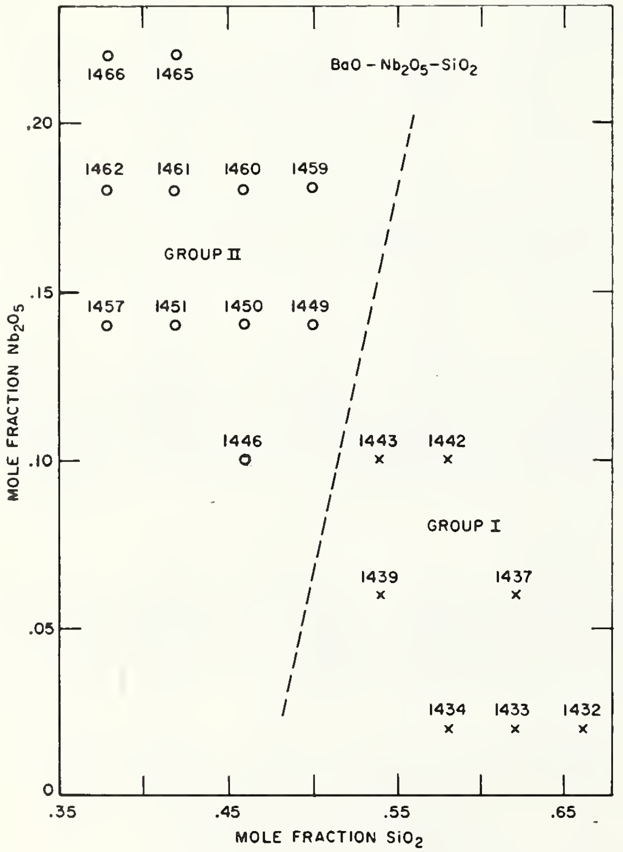


FIGURE 50. *Compositional plot showing the groups into which glasses in the* Ba-Nb_2O_5-SiO_2 *system were divided by computer evaluation of property data.*

Numbers of glasses in each group are those from earlier composition tables with F omitted.

4.6. The BaO-Al_2O_3-SiO_2 System

Table 13 gives composition-property equations for the two groups of glasses in this system. Phase diagrams for this ternary system and the three binary systems have been published [23, 24, 25]. Figure 51 is a mol fraction plot converted from published diagrams 210 and 556 [23]. This figure shows the compositions of glasses used in computerized groups. Glasses situated in the solid solution area of BaO · $2SiO_2$ and 2BaO · $3SiO_2$ were placed in Group I. Those in the BaO · Al_2O_3 · $2SiO_2$ primary phase field were placed in Group II. In each case the criterion, previously mentioned, for "compatibility groups" was adhered to. Location of the boundary between the two groups cannot be calculated exactly as was the case in some of the other systems.

TABLE 13. BaO-Al_2O_3-SiO_2 *glasses*

Glass Property = *A* SiO_2 + *B* Al_2O_3 + *C* BaO

Property	*A*	*B*	*C*	Std. Error
Group I Glasses: [a] 1131, 1132, 1133, 1164, 1165, 1166				
Solid Solution of BaO · $2SiO_2$ and 2BaO · $3SiO_2$				
n_C	1.56751	1.38164	1.75764	0.00029
n_D	1.57129	1.37834	1.76167	.00032
n_F	1.57893	1.38051	1.77168	.00032
n_F-n_D	0.00764	0.00217	0.01001	
n_D-n_C	.00378	−0.00330	.00403	
n_F-n_C	.01142	−0.00113	.01404	
ν	50.05	95.47	53.80	0.2210
Group II Glasses: 1143, 1123, 1128, 1129, 1130, 1196, 1197, 1198, 1210, 1207, 1211, 1209, 1208				
BaO · Al_2O_3 · $2SiO_2$ Primary Phase				
n_C	1.48964	1.57531	1.82391	0.00074
n_D	1.49166	1.57848	1.82924	.00075
n_F	1.49601	1.58578	1.84299	.00076
n_F-n_D	0.00435	0.00730	0.01375	
n_D-n_C	.00202	.00317	.00533	
n_F-n_C	.00637	.01047	.01908	
ν	66.90	55.62	36.61	0.2063

[a] Numbers of Glasses in each group are those from earlier composition tables with F omitted.

Previous work [3] has indicated that oxide factors for refractive index are characteristic of the primary phase field involved. For example, the n_D factors for SiO_2 in SiO_2 fields (particularly cristobalite and tridymite) is reasonably close to 1.458, the refractive index n_D for fused silica. Likewise the specific volume factor for such glasses corresponds to a density of 2.20 approximating the density of fused silica. The n_D factor of 1.57848 for glasses in Group II is reasonably close to those found for Al_2O_3 in other glass systems [3]. However, the 1.37834 n_D factor for Al_2O_3 for glasses in Group I is low and suggests the need for more data in this area.

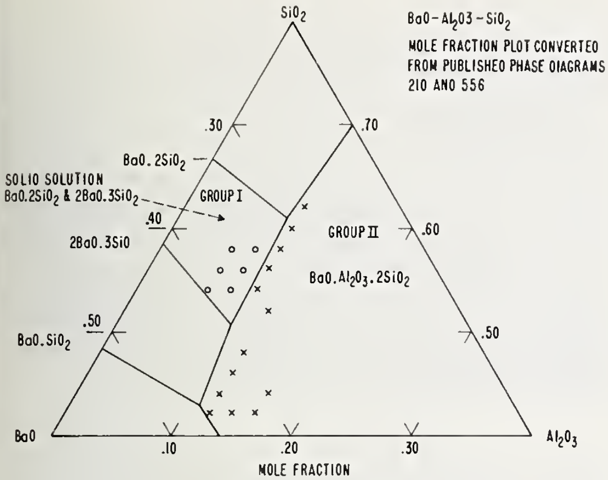


FIGURE 51. *Triangular plot showing the phase fields and groups into which glasses in the* $BaO\text{-}Al_2O_3\text{-}SiO_2$ *system were divided by computer evaluation of property data.*

5. Formulation of Glasses for Specific Optical Applications

The glass technologist and optical designer can use the foregoing quantitative relations between glass compositions and properties to calculate compositions having desired optical properties. The use of this method [3] must be based on reliable experimental data. The data shown in this report are considered to meet this criterion. The method can best be understood by outlining examples of its use.

5.1. Example One

Values of n_D in Group I TiO_2 glasses can be determined using the equation: $n_D = 1.48163\ SiO_2 + 2.29497\ TiO_2 + 1.84628\ BaO$. Consider glass F35 having a calculated $n_D = 1.67236$. It is desired to increase the index by 0.0050. This can be done in three ways: (1) substitution of TiO_2 for SiO_2, (2) substitution of BaO for SiO_2, or (3) substitution of TiO_2 for BaO. Differences between factors for these substitutions are respectively 0.81334, 0.36465, and 0.44869. The composition change for the first substitution is $0.0050/0.81334 = 0.0061$ TiO_2 for SiO_2. The others are determined in the same manner. The following table shows compositions and calculated values for n_D, mean dispersion $n_F - n_C$, ν, and densities for the four glasses.

	F35	(1)	(2)	(3)
SiO_2	0.6000	0.5939	0.5863	0.6000
TiO_2	.1000	.1061	.1000	.1111
BaO	.3000	.3000	.3137	.2889
n_D	1.67236	1.67732	1.67736	1.67734
$n_F - n_C$	0.01558	0.01594	0.01569	0.01616
ν	44.20	43.57	43.95	43.27
Density	3.754	3.765	3.807	3.732

5.2. Example Two

Consider glass F1432 in Group I Nb_2O_5 glasses which has a measured n_D of 1.63471. It is desired to calculate the exact composition having this index value. Since it contains three oxides one must be fixed arbitrarily. Assume that $SiO_2 = 0.66$. The solution is obtained by solving these equations simultaneously:

$$n_D = 1.49408\ SiO_2 + 2.80691\ Nb_2O_5 + 1.85111\ BaO$$
$$SiO_2 + Nb_2O_5 + BaO = 1$$

Then; $1.63471 = 1.49408\ (.66) + 2.80691\ Nb_2O_5 + 1.85111\ (0.34 - Nb_2O_5)$

	Glass F1432	Calculated
SiO_2	0.6600	0.6600
Nb_2O_5	.0200	.0201
BaO	.3200	.3199
n_D	1.63471	1.63468
$n_F - n_C$	0.01241	0.01234
ν	51.10	50.87

(Measured values for F1432 are from table 6)

5.3. Example Three

Glass F583 in Group II Ta_2O_5 glasses has a measured mean dispersion of 0.01612. Calculate the exact composition assuming $SiO_2 = 0.53$. The answer is obtained from the equation:

$$0.01612 = 0.00635\ (0.53) + 0.08557\ (0.47 - BaO) + 0.01742\ BaO$$

	F583 (Table 4)	Calculated
SiO_2	0.5300	0.5300
Ta_2O_5	.0700	.0670
BaO	.4000	.4030
n_D	1.71844	1.71598
$n_F - n_C$	0.01612	0.01612
ν	44.60	44.65
Density	4.703	4.678

5.4. Example Four

Glass F553 in Group II La_2O_3 glasses has a measured density of 4.387 (volume = 0.22795). Assume $SiO_2 = 0.55$ and calculate exact composition. The solution is given by: $0.22795 = 0.32645\ (0.55) - 0.10865\ La_2O_3 + 0.14791\ (0.45 - La_2O_3)$

	F553 (Table 3)	Calculated
SiO_2	0.5500	0.5500
La_2O_3	.0700	.0708
BaO	.3800	.3792
Density	4.387	4.387
n_D	1.69496	1.69519
$n_F - n_C$	0.01369	0.01368
ν	50.80	50.79

5.5. Example Five

Figure 45 shows lines of equal n_D in the TiO_2 glasses and figure 46 shows lines of constant ν in this system. Superposition of these two figures indicates that the 1.75 n_D line crosses the 35 ν line in Group I. However, the 1.75 n_D line crosses the 30 ν line in Group II glasses. Calculate the two compositions.

(a) Composition of the glass having an n_D of 1.75 and a ν of 35 is obtained by solving the following equations simultaneously:

$$1.75 = 1.48163\ SiO_2 + 2.29497\ (1 - SiO_2 - BaO) + 1.84628\ BaO$$

$$35 = 60.06\ SiO_2 - 43.03\ (1 - SiO_2 - BaO) + 41.56\ BaO$$

The composition is found to be:

SiO_2	0.4918
TiO_2	.1851
BaO	.3231

A check calculation shows the values as 1.75000 and 35.01.

(b) Composition of the glass having an n_D of 1.75 and a ν of 30 is obtained by solving the equations:

$$1.75 = 1.48553\ SiO_2 + 2.35228\ (1 - SiO_2 - BaO) + 1.79234\ BaO$$

$$30 = 41.27\ SiO_2 - 10.73\ (1 - SiO_2 - BaO) + 49.93\ BaO$$

The composition is:

SiO_2	0.5852
TiO_2	.2450
BaO	.1698

A check calculation gives the values as 1.74998 and 30.00.

6. Summary

The areas of glass formation in the following ternary oxide systems have been determined:

$BaO\text{-}TiO_2\text{-}SiO_2$
$BaO\text{-}La_2O_3\text{-}SiO_2$
$BaO\text{-}Ta_2O_5\text{-}SiO_2$
$BaO\text{-}ZnO\text{-}SiO_2$
$BaO\text{-}Nb_2O_5\text{-}SiO_2$
$BaO\text{-}Al_2O_3\text{-}SiO_2$

Property measurements, including sag point, refractive index and dispersion, liquidus temperature, and infrared transmittance, were made on the resulting glasses. In addition, composition-property data were evaluated to develop quantitative relations for use by glass technologists in formulating glasses having specific property values.

The writers wish to thank John A. Moore, who melted the experimental glasses; Thomas G. Scuderi, who helped in making the property measurements; and I. H. Malitson, who made the refractive index measurements.

7. References

[1] Spinner, Sam, Cleek, Given W., and Hamilton, Edgar H., Determination and use of the sag point as a reference point in the heating of glasses, J. Res. Nat. Bur. Stand. (U.S.), **59**, No. 3, 227–231 (Sept. 1957) RP2791.

[2] Grauer, Oscar H., and Hamilton, Edgar H., An improved apparatus for the determination of liquidus temperatures and rates of crystal growth in glasses. J. Res. Nat. Bur. Stand. (U.S.), **44**, 495–502 (May 1950) RP2096.

[3] (a) Babcock, C. L., Substructures in silicate glasses, J. Amer. Ceram. Soc. **51**, 163 (1968);
(b) Babcock, C. L., Substructure classification of silicate glasses, Ibid. **52**, 151 (1969).

[4] Cleek, Given W., and Hamilton, Edgar H., Properties of barium titanium silicate glasses. J. Res. Nat. Bur. Stand. (U.S.), **57**, No. 6, 317–323 (Dec. 1956) RP2720.

[5] Phillips, C. J., Glass the miracle maker, p. 120 (Pittman Publishing Corp., 1948).

[6] Rase, D. E., and Roy, Rustum, Phase equilibria in the system $BaO\text{-}TiO_2$, J. Am. Ceram. Soc. **38**, 102 (1955).

[7] (a) Bunting, E. N., Phase equilibria in the systems TiO_2, $TiO_2\text{-}SiO_2$ and $TiO_2\text{-}Al_2O_3$, J. Res. Nat. Bur. Stand. (U.S.), 11, 719 (1933) RP619;
(b) Ricker, T. W., and Hummel, F. A., Reactions in the system $TiO_2\text{-}SiO_2$; revision of the phase diagram, J. Am. Ceram. Soc. **34**, 271 (1951);
(c) DeVries, R. C., Roy, Rustum, and Osborn, E. F., The system $TiO_2\text{-}SiO_2$, Trans. Brit. Ceram. Soc. **53**, 525 (1954).

[8] (a) Eskola, P., The silicates of strontium and barium, Am. J. Sci. 5th series, **4**, 331 (1922);
(b) Grieg, J. W., Immiscibility of silicate melts, Am. J. Sci., 5th series, **13**, 1 (1927).

[9] Rase, D. E., and Roy, Rustum, Phase equilibria in the system $BaTiO_3\text{-}SiO_2$, J. Am. Ceram. Soc. **38**, 389 (1955). Correction: Ibid. **39**, 120 (1956).

[10] Hamilton, Edgar H., and Cleek, Given W., Shape of the liquidus surface as a criterion of stable glass formation. J. Res. Nat. Bur. Stand. (U.S.), **60**, No. 6, 593–596 (June 1958) RP2872.

[11] Hubbard, Donald, and Hamilton, Edgar H., Studies of the chemical durability of glass by an interferometric method, J. Research J. Res. Nat. Bur. Stand. (U.S.), **27**, 143–157 (Aug. 1941) RP1409.

[12] Hubbard, Donald, Hygroscopicity of optical glasses as an indicator of serviceability, J. Res. Nat. Bur. Stand. (U.S.), **36**, 365–375 (April 1946) RP1706.

[13] Saunders, James B., An apparatus for photographing interference phenomena, J. Res. Nat. Bur. Stand. (U.S.), **35**, 157–186 (Sept. 1945) RP1668.

[14] Levin, Ernest M., Robbins, Carl R., and McMurdie, Howard F., Phase diagrams for ceramists, Figure 209, American Ceramic Society (1964).

[15] Bunting, E. N., Phase equilibria in the system SiO_2-ZnO, J. Res. Nat. Bur. Stand. (U.S.), **4**, 131–136 (1930) RP136.

[16] Roth, R. S., and Waring, J. L., Phase relations in the binary system barium oxide-niobium pentoxide. J. Res. Nat. Bur. Stand. (U.S.), **65A** (Phys. and Chem.), No. 4, 337–344 (July—Aug. 1961).

[17] Ibrahim, M., and Bright, N.F.H., The binary system Nb_2O_5-SiO_2, J. Amer. Ceram. Soc. **45** [5], 221 (1962).

[18] Morey, G. W., Properties of glass, 2nd Edition (Reinhold Publishing Corp., New York, N.Y., 1954), p. 75.

[19] Scholes, S. R., Modern Glass Practice (Industrial Publications, Inc., Chicago, Ill. 1941), p. 48.

[20] Morey, G. W., Properties of glass, 2nd Edition (Reinhold Publishing Corp., New York, N.Y., 1954), p. 85.

[21] Rawson, H., Inorganic glass-forming systems (Academic Press, London, 1967), p. 199.

[22] Stanworth, J. E., Physical properties of glass (Oxford at the Clarendon Press, Oxford, 1950), p. 5.

[23] Levin, Ernest M., Robbins, Carl R., and McMurdie, Howard F., Phase diagrams for ceramists, Figures 556 and 557, American Ceramic Society (1964).

[24] Thomas, Robert H., Phase equilibrium in a portion of the ternary system BaO-Al_2O_3-SiO_2, J. Amer. Ceram. Soc. **33**, 35 (1950).

[25] (a) Lin, H. C., and Foster, W. R., System BaO-Al_2O_3-SiO_2: I Amer. Mineral. **53** [1–2], 134 (1968);

(b) Foster, W. R., and Lin, H. C., System BaO-Al_2O_3-SiO_2: II Amer. J. Sci. **267A**, 134 (1969);

(c) Lin, H. C., and Foster, W. R., System BaO-Al_2O_3-SiO_2: III Mineral, Mag. **37** [288], 459 (1969);

(d) Semler, C. E., and Foster, W. R., System BaO-Al_2O_3-SiO_2: IV J. Amer. Ceram. Soc. **52** [12], 679 (1969);

(e) Lin, H.C., and Foster, W. R., System BaO-Al_2O_3-SiO_2: VJ. Amer. Ceram. Soc. **53** [10], 549 (1970);

(f) Semler, C. E., and Foster, W. R., System BaO-Al_2O_3-SiO_2: VI J. Amer. Ceram. Soc. **53** [11], 595 (1970).

[26] Gibbs, J. W., The Scientific Papers of J. Willard Gibbs, (Longmans Green, New York, 1906).

[27] (a) Morey, G. W., Section G in Commentary on the Scientific Writings of J. Willard Gibbs (Yale University Press, 1936);

(b) Morey, G. W., The Properties of Glass (Reinhold, New York, 1954).

FORM NBS-114A (1-71)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS-MN-135	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE PROPERTIES OF IN SOME TERNARY SYSTEMS CONTAINING BaO AND SiO_2			5. Publication Date September 1973
			6. Performing Organization Code
7. AUTHOR(S) G.W. Cleek and C.L. Babcock			8. Performing Organization
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No.
			11. Contract/Grant No.
12. Sponsoring Organization Name and Address Same as 9.			13. Type of Report & Period Covered Final
			14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The glass forming regions in six ternary oxide systems containing BaO, SiO_2 and a third oxide have been determined. The properties of the resulting glasses were measured and the results are reported. The data on refractive indices, dispersions and specific volumes were evaluated by computer methods in an attempt to identify "substructures" containing the cations present in the glasses.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Barium glasses; barium silicates; glass property factors; oxide glasses; silicate substructures; ternary glasses.

18. AVAILABILITY STATEMENT	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
[X] UNLIMITED.	UNCLASSIFIED	42
[ ] FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NTIS.	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price 70 cents

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, and chemistry. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts. Includes listings of other NBS papers as issued.

Published in two sections, available separately:

- **Physics and Chemistry (Section A)**

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $17.00; Foreign, $21.25.

- **Mathematical Sciences (Section B)**

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $9.00; Foreign, $11.25.

TECHNICAL NEWS BULLETIN

The best single source of information concerning the Bureau's measurement, research, developmental, cooperative, and publication activities, this monthly publication is designed for the industry-oriented individual whose daily work involves intimate contact with science and technology—*for engineers, chemists, physicists, research managers, product-development managers, and company executives.* Includes listing of all NBS papers as issued. Annual subscription: Domestic, $6.50; Foreign, $8.25.

NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.

Building Science Series. Research results, test methods, and performance criteria of building materials, components, systems, and structures.

Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality, and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other-agency and NBS-sponsored work) of limited or transitory interest.

Federal Information Processing Standards Publications. This series is the official publication within the Federal Government for information on standards adopted and promulgated under the Public Law 89–306, and Bureau of the Budget Circular A–86 entitled, Standardization of Data Elements and Codes in Data Systems.

Consumer Information Series. Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

BIBLIOGRAPHIC SUBSCRIPTION SERVICES

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:

Cryogenic Data Center Current Awareness Service (Publications and Reports of Interest in Cryogenics). A literature survey issued weekly. Annual subscription : Domestic, $20.00; foreign, $25.00.

Liquefied Natural Gas. A literature survey issued quarterly. Annual subscription: $20.00.

Superconducting Devices and Materials. A literature survey issued quarterly. Annual subscription: $20.00. Send subscription orders and remittances for the preceding bibliographic services to the U.S. Department of Commerce, National Technical Information Service, Springfield, Va. 22151.

Electromagnetic Metrology Current Awareness Service (Abstracts of Selected Articles on Measurement Techniques and Standards of Electromagnetic Quantities from D-C to Millimeter-Wave Frequencies). Issued monthly. Annual subscription: $100.00 (Special rates for multi-subscriptions). Send subscription order and remittance to the Electromagnetic Metrology Information Center, Electromagnetics Division, National Bureau of Standards, Boulder, Colo. 80302.

Order NBS publications (except Bibliographic Subscription Services) from: Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-215

U.S.MAIL