THERMAL EXPANSION OF INSULATING MATERIALS

By Wilmer H. Souder and Peter Hidnert

CONTENTS

I. INTRODUCTION

The material here presented is selected from the mass of data accumulated during thermal expansivity tests, and is of importance where insulating materials are subjected to temperature variations. The range of expansion coefficients is rather large, extending from a value of 1.6×10^{-6} for certain porcelains to 109×10^{-6} for a specimen of celluloid.

In addition to the wide range in coefficients it has also been found that practically all of the molded materials, such as bakelite, condensite, hard rubber, and celluloid, take up a permanent length change when carried through a temperature cycle, especially if temperatures above 60° C are reached. This length change, always a shrinkage, may work to advantage in cases where a slight shrinkage tends to compress and retain metallic electrodes or inserts. On the other hand, these changes become very serious in precision apparatus depending upon accurate dimensions.

The following materials have been investigated and are included in this report: Porcelain, bakelite, condensite, formica, celluloid, hard rubber, marble, and limestone.

II. PREVIOUS WORK ON PORCELAIN

Some of the results of previous experimental determinations of the thermal expansion of porcelain are summarized in the following table. The values given for *a* and *b* are to be substituted in the general quadratic equation

$$L_t = L_o\ (1 + at + bt^2)$$

where L_o is the length of the material at 0° C and L_t the length at t° C within the proper temperature range.

TABLE 1

Kind of porcelain	Observer	Temperature range	Coefficients	
			a	*b*
		°C		
Bayeux	Tutton [a]	0–120	2.522×10^{-6}	7.43×10^{-9}
Do.	Bedford	0–600	3.425	1.07
Do.	Chappuis	0–83	2.824	6.17
Berlin	Holborn and Day [b]	250–625	2.954	1.125

[a] Proc. Phys. Soc. of Lond., **18**, p. 182; 1901–1903.
[b] Ann. der Phys. und Chem., **2**, p. 505; 1900.

Tutton agrees with Chappuis that the thermal expansion of Bayeux or Berlin porcelains can not be represented by a quadratic equation throughout a temperature range exceeding a very few hundred degrees.

Brundige[1] is of the opinion that expansion effects cause the major part of insulator deterioration. However, he points out that there are other investigators who believe that practically all insulator deterioration is attributed to porosity.

III. PREVIOUS WORK ON MARBLE

Roiti's Physics (vol. 1, sec. 399, Hungarian translation, p. 457), gives as the average coefficient of expansion for 1° C between 0° and 100° C, the following values:

White marble	0. 00000849 (Destigny)
Do.	. 00001072 (Dunn and Sang)

Fröhlich[2] found it necessary to know the coefficient of expansion of a large ring (standard of inductance) made from Carrara marble in order to determine the dimensions at a given temperature. From observations at room temperature and at 100° C (steam)

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[1] Trans. Amer. Inst. Elec. Eng., **36**, p. 535; 1917.

[2] Wiedemann Annalen der Physik und Chemie, **61**, p. 206; 1907.

on a 30 cm specimen cut from the same block of marble used for the ring, he obtained 0.000012 for the average coefficient of expansion between 15 and 100° C. However, he does not state whether the specimen returned to its original dimensions after cooling.

Kaye and Laby (Physical and Chemical Constants, etc., 1911) of the National Physical Laboratory give 1.4×10^{-6} to 3.5×10^{-6} for the coefficient of expansion of marble at 15° C.

Grüneisen[3] gives 4.3×10^{-6} as the coefficient between 14 and 24°, and 10.5×10^{-6} between 18 and 100° C. After keeping a specimen at a constant temperature of 100° C, he found the value 2.2×10^{-6} for the coefficient of expansion between 14 and 24° C.

Hallock[4] determined the expansion of several marbles by comparing them with brass, and gives the following values from room temperature to 100° C:

A marble from Rutland, Vt	0.00000659
	661
A marble from Knoxville, Tenn	0.00000495
	525
A marble, "Keowa," from Georgia	0.00000348
	309
A marble, "Creole," from Georgia	0.0000110
A marble, "Cherokee," from Georgia	0.00000740
	786
	855

The duplicate values are from different bars of the same marble.

He observed the phenomenon of permanent growth after heating, especially with the Vermont and Tennessee specimens. "Being heated for the first time to 100° C and allowed to cool, they did not contract to their original length, and the next two or three heatings resulted in continued but ever diminishing increments of length at ordinary temperatures; finally a permanent condition was reached." He also found that a Vermont marble when kept at constant temperature, contracted on drying and expanded on soaking in water.

In 1832, W. H. C. Bartlett[5] made determinations on the expansion of some stones at ordinary temperatures (range about 100° F). He gives for the coefficient of expansion of marble, $0.000005668 = \frac{1}{176\,429}$ per degree Fahrenheit. He reached the conclusion that the fractures of the stones at Fort Adams, Newport Harbor, were due to ordinary changes of temperature.

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[3] Recueil de Constantes Physiques, p. 188; 1913.

[4] U. S. Geol. Survey Bull., No. 77, p. 109; 1891.

[5] Amer. Jour. of Science, 1st series, 22, p. 136.

T. M. Reade[6] also determined the expansion of several rocks, and gives as the coefficient of expansion of marbles the value $\frac{1}{184\,797}$ per degree Fahrenheit. (Temperature range not indicated.)

N. E. Wheeler[7] investigated a specimen of white marble from Carrara, Italy. He obtained the following values for the coefficients of expansion per degree centigrade at intervals of 100° C:

Temperature	Coefficients of expansion	
	First heating	Fifth heating
100° C	82.3×10^{-7}	28.3×10^{-7}
200° C	181	92.3
300° C	239	127.3
400° C	276	179.2

Nisi[8] used an Abbe and Pulfrich interferometer over a range extending from 0° to 40° C. He found that the thermal expansion of white Carrara marble is different in different directions, and that the rate of expansion increases with temperature. He failed to obtain a marked permanent set, on account of his very limited temperature range. The coefficients of linear expansion for differently oriented specimens at temperatures between 0° and 40° C varied from -0.77×10^{-6} to $+11.24\times10^{-6}$.

Nisi states that marble is by no means an homogeneous mass, and that the anomalous behavior of marble as regards thermal expansion is closely connected with the cleavage planes.

IV. APPARATUS AND SPECIMENS

Each specimen was in the form of a straight rod or bar of uniform cross section. The length was about 30 cm and the cross section about 1 cm square. Both ends were cylindrical in shape.

Two kinds of apparatus[9] were used in making the thermal expansion tests—an oil bath[10] and air furnaces.

In the furnaces the specimen was supported horizontally and a 2-mil platinum wire, which was previously annealed, hung

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[6] The Origin of Mountain Ranges; 1886.

[7] Trans. Royal Soc. of Canada, 3d series, 4, p. 19; 1910–11.

[8] Tokyo Math.-Phys. Soc. Proc., 2d series, 7, p. 97; 1913–14.

[9] This consists essentially of the apparatus designed and installed by A. W. Gray and L. W. Schad, formerly of this Bureau.

[10] For short description, see Preliminary Determination of the Thermal Expansion of Molybdenum, Scientific Papers, No. 332, p. 31.

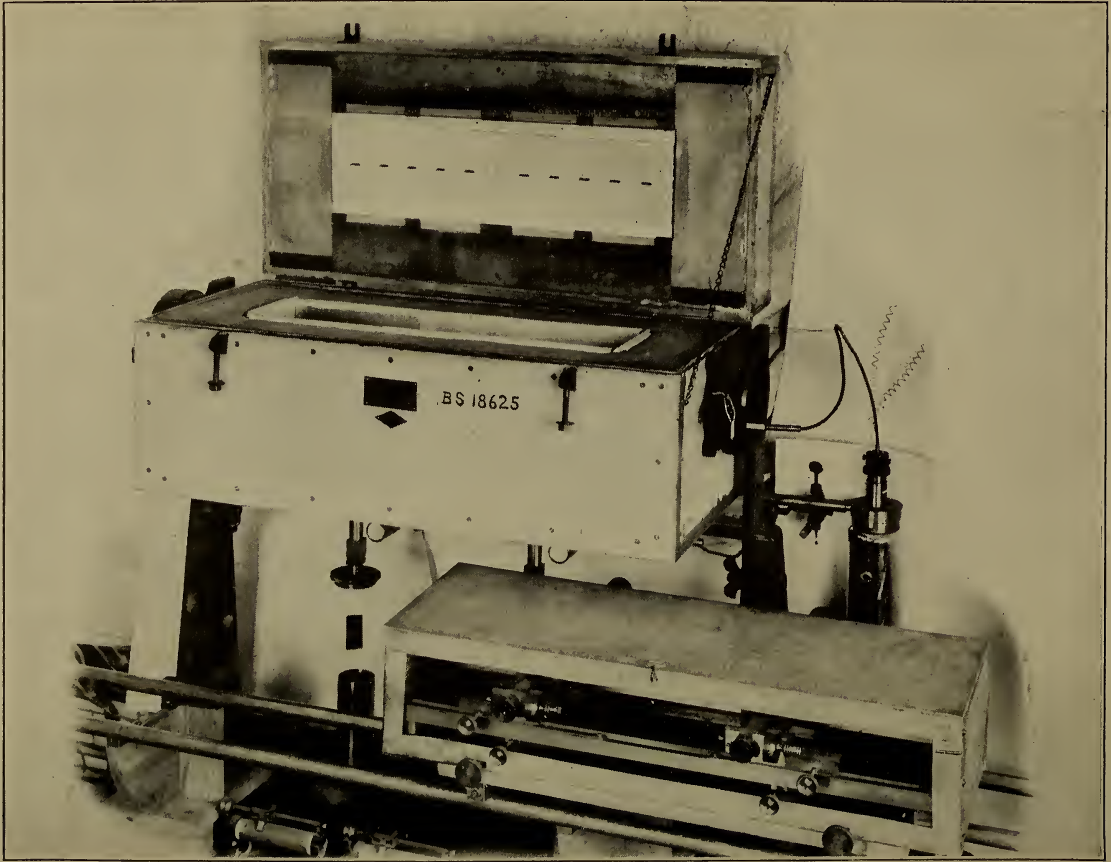

FIG. 1.—*Furnace and traveling microscopes*

over each end. Each wire, hanging through a hollow tube below the end of the specimen and extending downward through and below the furnace, had at its lower end a vane (or weight) immersed in oil in order to dampen the vibrations. Heating was effected by electric resistance coils (outside, inside, and end coils). With careful manipulation it was possible to adjust the circuits so that during an observation the specimen was at a uniform temperature within one-tenth degree centigrade, from end to end.

The length changes were determined with a comparator consisting of two microscopes rigidly clamped on an invar bar at a distance from each other equal to the length of the specimen (30 cm.). The microscopes were so arranged that they could first be sighted on a standard-length bar kept at constant temperature, and then on the vertically suspended wires which were in contact with the ends of the specimen.

The apparatus shown in Fig. 1 was used for part of this research and portrays the essential method of making observations on materials. The furnace is shown with the top lifted. The traveling microscopes, which are sighted (simultaneously) on the two vertical wires hung from the specimen, are displaced to the right in order to show the construction of the tube protecting the vertical or drop wires. The left oil pot is removed to show the weight attached to the wire.

The temperatures in the oil bath and furnaces were determined by means of a copper-constantan and a platinum-platinum rhodium thermocouple, respectively.

V. PORCELAIN

Data on the thermal expansion of 40 samples of various kinds of porcelain are presented in this paper.

The coefficients of expansion of these materials vary over a wide range, as may be seen from the accompanying curves and the following table. It is remarkable that the various kinds of porcelain, when heated to high temperatures and then cooled to room temperature, returned to their approximate initial lengths, as is evident from the last column in the table; that is, there is no marked set or permanent change in dimension due to the heat treatment.

The expansion curves of porcelain may be divided into three classes: Straight-line, concave, and convex curves. In the straight-line curve, the rate of expansion is constant. (See S494 in Table 2.) The concave expansion curve shows that the rate of expansion increases with temperature, but the convex curve indicates that the rate of expansion decreases with temperature. Examples of concave curves are shown by S472, S476, S496, and S500; and examples of convex curves by S436, S480, and S501.

TABLE 2

Bureau of Standards No.	Composition.							Average coefficients × 10^6				Change in length after test (per cent)
	Per cent clay	Per cent feldspar	Per cent flint	Per cent whiting	Per cent calcine No. 14[e]	Per cent sillimanite[e]	Per cent Al_2O_3	Room temperature to 200° C	200 to 400° C	400 to 540° C	400 to 600° C	
S391	......	......	......	......	......	......	......	4.4	5.4	......	5.8	0.00
S392	......	......	......	......	......	......	......	4.6	5.4	......	6.0	.00
S393	......	......	......	......	......	......	......	3.7	5.0	......	5.4	+ .01
S399	......	......	......	......	......	......	......	5.8	4.7	......	7.8	+ .01
S400	......	......	......	......	......	......	......	5.2	5.6	6.8	......	+ .02
S401	......	......	......	......	......	......	......	4.8	5.9	8.8	......	+ .04
S402	......	......	......	......	......	......	......	4.3	6.1	......	7.9	+ .01
S405	......	......	......	......	......	......	......	2.9	3.7	......	3.8	− .01
S416	......	......	......	......	......	......	......	5.2	4.4	......	4.9	.00
S417	......	......	......	......	......	......	......	5.3	4.4	......	4.8	+ .01
S436[a]	50	......	20	......	......	......	......	19.4	9.4	5.5	......	− .02
S437	50	......	30	......	20	......	......	19.6	11.1	8.1	......	+ .03
S438	50	......	20	......	30	......	......	10.4	5.4	4.5	......	− .01
S442[b]	50	......	30	......	......	......	......	7.3	6.1	4.7	......	.00
S443[c]	50	......	20	......	......	......	......	8.9	4.4	4.1	......	.00
S444	50	......	20	......	30	......	......	10.8	5.5	4.4	......	.00
S445	40	......	......	......	20	40	......	3.4	4.2	4.8	......	.00
S472[d]	50	......	15	......	......	......	......	1.6	3.0	3.6	......	− .01
S476	......	......	......	......	......	......	......	5.7	6.7	8.4	......	.00
S477	......	......	......	......	......	......	......	5.8	6.8	8.8	......	.00
S478	48	......	......	......	18	34	......	10.4	5.6	4.4	......	− .01
S479	40	......	......	......	16	44	......	10.9	6.6	7.8	......	+ .06
S480	45	......	......	......	15	40	......	8.9	5.0	5.1	......	− .01
S485	71.5	15.6	2.4	1.4	......	......	9.1	2.9	4.0	......	......	− .02
S486	50	16	32.5	1.5	......	......	......	6.2	4.6	......	......	.00
S487	77	12.5	......	1.45	......	......	9.05	3.4	3.9	......	......	− .01
S488	80.1	9.5	......	1.43	......	......	8.97	3.1	3.8	......	......	− .01
S489	85	13.5	......	1.5	......	......	......	3.2	3.5	......	......	− .01
S490	80	18.5	......	1.5	......	......	......	2.9	4.0	......	......	− .01
S491	80	13.5	5	1.5	......	......	......	3.3	3.2	......	......	− .01
S492	75	23.5	......	1.5	......	......	......	3.5	4.5	......	......	+ .01
S493	75	18.5	5	1.5	......	......	......	3.2	3.7	......	......	− .01
S494	75	10	13.5	1.5	......	......	......	4.1	4.1	......	......	− .01
S495	70	23.5	5	1.5	......	......	......	3.7	......	......	......	− .09
S496	70	19	9.5	1.5	......	......	......	3.3	4.0	......	......	.00
S497	70	15	13.5	1.5	......	......	......	3.4	3.6	......	......	.00
S499	80	10	8.5	1.5	......	......	......	4.7	4.6	......	......	.00
S500	75	13.5	10	1.5	......	......	......	3.7	4.3	......	......	− .01
S501	70	10	18.5	1.5	......	......	......	6.1	5.1	......	4.5	− .02
S502	50	16	34	......	......	......	......	4.7	4.6	......	......	.00

[a] Calcine No. 8A=30 per cent. (See Table 3.)

[b] Calcine No. 13=20 per cent. (See Table 3.)

[c] Calcine No. 13=30 per cent.

[d] Beryl=35 per cent.

[e] See Table 3.

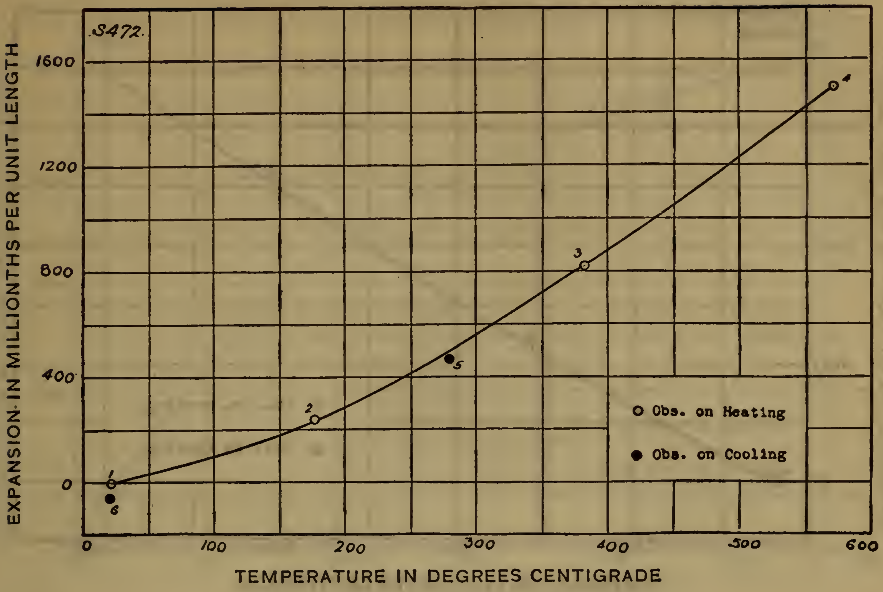

Fig. 2.—*Expansion of porcelain (S 472)*

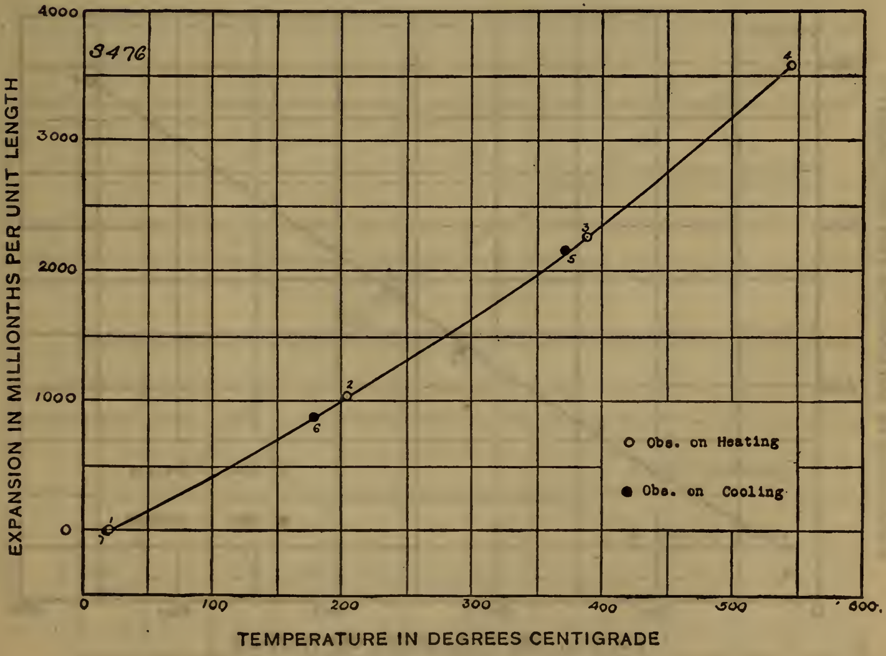

Fig. 3.—*Expansion of porcelain (S 476)*

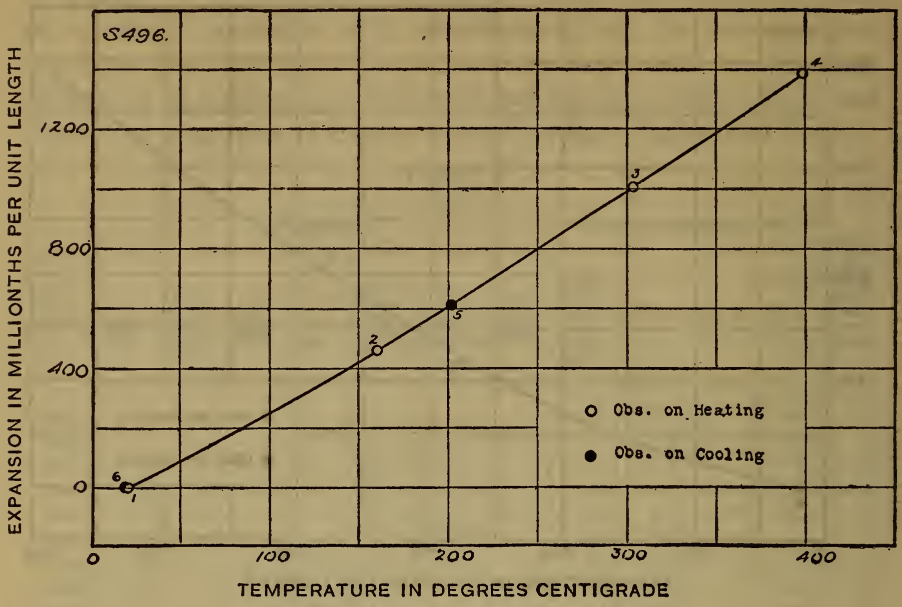

FIG. 4.—*Expansion of porcelain (S 496)*

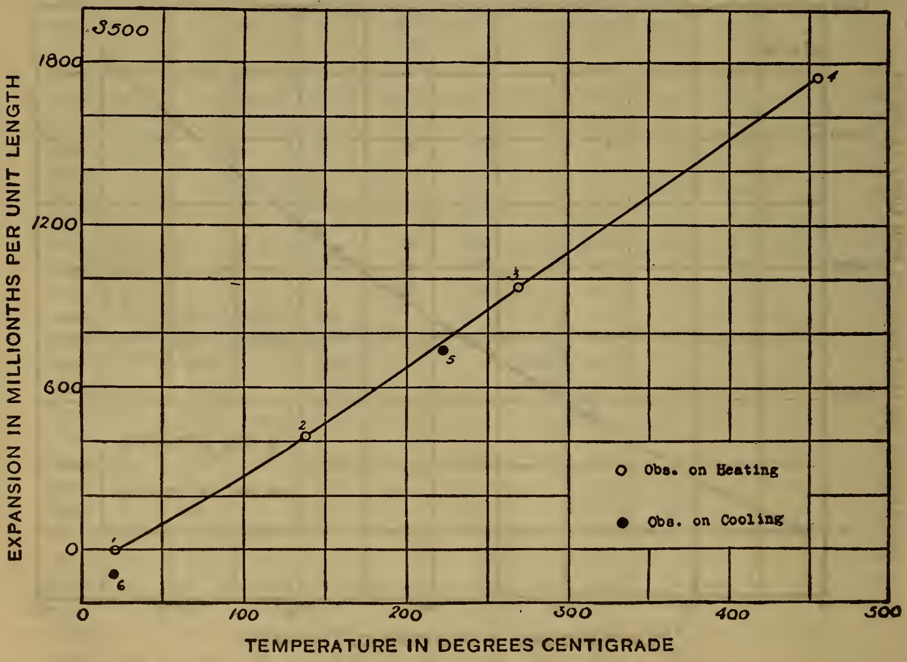

FIG. 5.—*Expansion of porcelain (S 500)*

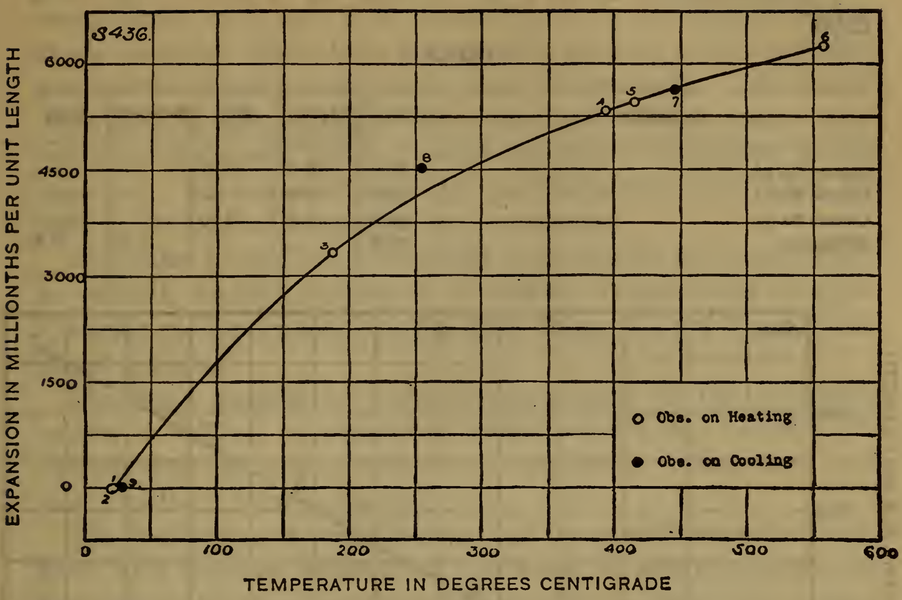

Fig. 6.—*Expansion of porcelain* (*S 436*)

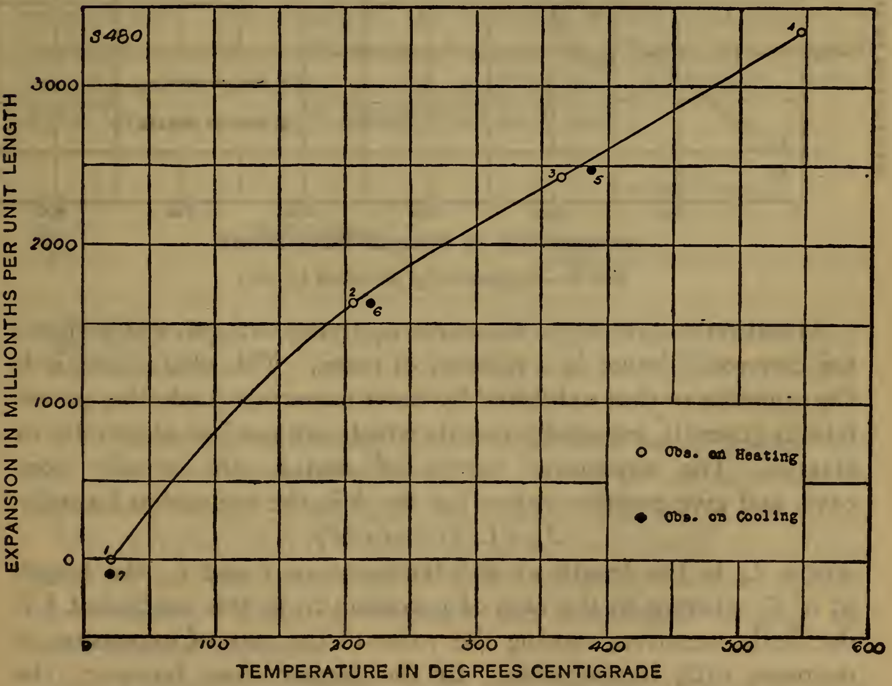

Fig. 7.—*Expansion of porcelain* (*S 480*)

The constituents of the calcines are given in the accompanying table.

TABLE 3

Composition	Clay	$MgCO_3$	Flint	Boric acid	Al_2O_3
Calcine No. 8A	44.30	14.40	41.30		
Calcine No. 13	76.15	23.85			
Calcine No. 14	56.00	18.20	25.80		
Sillimanite	70.20			2.00	27.80

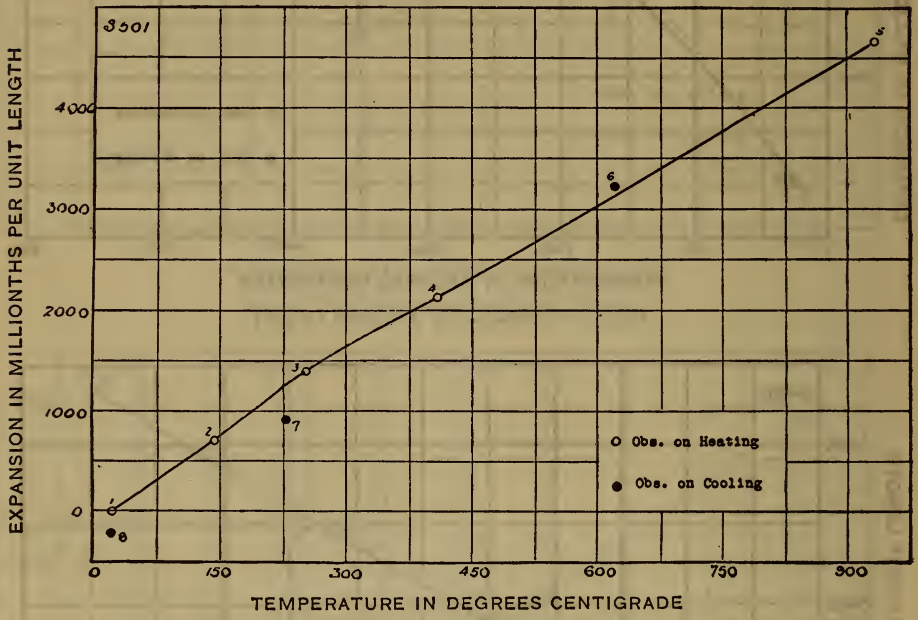

FIG. 8.—*Expansion of porcelain (S 501)*

Attention is directed to the curve applying to S436, which shows the convexity found in a number of cases. This characteristic is the opposite to that exhibited by most materials (including porcelain in general), especially metals which are used as electrodes or clamps. The expansion curves of metals are usually concave, and give positive values for the b in the expansion formula:

$$L_t = L_o\ (1 + at + bt^2)$$

where L_t is the length at any temperature t and L_o the length at 0° C, whereas in the case of porcelain S436 this coefficient b is decidedly negative, causing the value of the rate of expansion to decrease with temperature. In the former case, however, the instantaneous coefficient or rate of expansion increases with temperature.

The fact that the average coefficient of S436 between room temperature and 550° C is about the same as that of certain steels does not mean that these steels may be used as perfect matches for expansion (in spark plugs, for example). The rate of expansion of this porcelain decreases rapidly with temperature (see curve S436 and Table 2), while the rate of expansion of steel increases. Serious cracking of the porcelain may occur when the differential expansion approaches a maximum.

Porcelains having low coefficients of expansion have been found to exhibit marked resistance to sudden temperature changes. Plunging cold specimens into the blast flame did not cause checking or cracking.

The large number of varying constituents in the porcelains makes it difficult to obtain an exact relationship between the composition and the coefficients of expansion. However, some relations have been deduced.

The coefficients of porcelains having the same amounts of clay, flint, and calcines depend on the kind of calcines contained. Porcelains containing calcines No. 8A, No. 14, and No. 13 have relatively large, intermediate, and small coefficients of expansion, respectively. For example, the following comparison shows the variations in the coefficients of S436, S438, and S443, which contain 50 per cent clay, 20 per cent flint, and 30 per cent calcine. (The kind of calcine is different in each case.)

Bureau of Standards No.	Kind of calcine	Average coefficients		
		Room temperature to 200° C	200 to 400° C	400 to 540° C
S436	No. 8A	19.4×10^{-6}	9.4×10^{-6}	5.5×10^{-6}
S438	No. 14	10.4	5.4	4.5
S443	No. 13	8.9	4.4	4.1

All porcelains containing 50 per cent clay, 20 or 30 per cent flint, and the remainder calcine (No. 8A, 13, or 14) have convex expansion curves. (See S436, S437, S438, S442, S443, and S444.)

The porcelain (S472) containing 35 per cent beryl, in addition to 50 per cent clay and 15 per cent flint, gave the lowest coefficient of expansion. Beryl is probably the constituent causing the small thermal expansion.

In a porcelain containing 40 per cent clay, an increase of 4 per cent in sillimanite and a corresponding decrease in calcine No. 14, caused a marked increase in the coefficients, as shown by the following values:

Bureau of Standards No.	Sillimanite, per cent	Calcine No. 14, per cent	Average coefficients		
			Room temperature to 200° C	200 to 400° C	400 to 540° C
S445	40	20	3.4×10^{-6}	4.2×10^{-6}	4.8×10^{-6}
S479	44	16	10.9	6.6	7.8

In a porcelain containing 40 per cent sillimanite, an increase of 5 per cent in clay and a corresponding decrease in calcine No. 14, caused an increase in the coefficients, as shown by the following values:

Bureau of Standards No.	Clay, per cent	Calcine No. 14, per cent	Average coefficients		
			Room temperature to 200° C	200 to 400° C	400 to 540° C
S445	40	20	3.4×10^{-6}	4.2×10^{-6}	4.8×10^{-6}
S480	45	15	8.9	5.0	5.1

Three specimens, S485, S487, and S488, containing from 71.5 to 80.1 per cent clay and about 9 per cent Al_2O_3 had low coefficients of expansion (2.9 to $3.4 \times 10-^6$ between room temperature and 200° C, and 3.8 to $4.0 \times 10-^6$ between 200 and 400° C).

The porcelains, S489 to S501, inclusive, containing from 70 to 85 per cent clay, in addition to feldspar (10 to 23.5 per cent), flint (0 to 18.5 per cent), and Whiting (1.5 per cent), have low coefficients of expansion, which vary from 2.9 to $6.1 \times 10-^6$ and from 3.2 to $5.1 \times 10-^6$ for the ranges extending from room temperature to 200° C and from 200° to 400° C, respectively.

Most of the porcelains described above are products of this Bureau's Pittsburgh laboratory, from which additional information[11] relating to composition, baking, etc., may be secured.

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[11] Bleininger and Riddle, J. Am. Ceram. Soc., 2, 564; 1919.

VI. PHENOL CONDENSATION PRODUCTS, ETC.

An extended study was made of these materials with a view to determining their applicability for use in instruments of high precision which may be subjected to temperature variations.

The accompanying representative figures are self-explanatory, and in general show the tendency of contraction at constant temperature (above 60° C). In most cases, after cooling to room temperature, these materials show a marked diminution in length. The numbers near the circles represent the order of the observations. The time elapsing between consecutive observations is indicated. When the time is less than one hour (except at critical temperatures) it is not indicated.

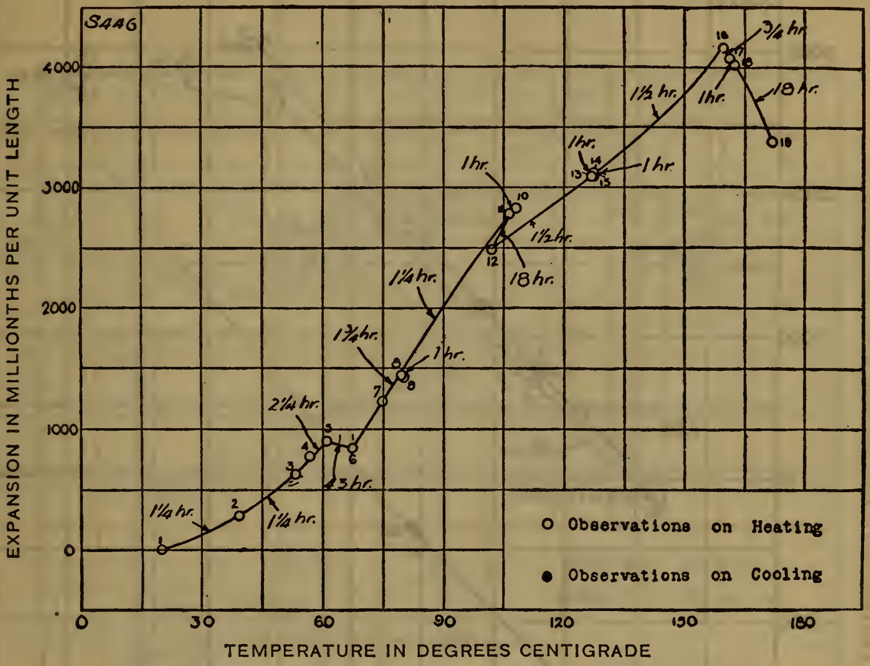

FIG. 9.—*Expansion of bakelite-dilecto (black) S 446*

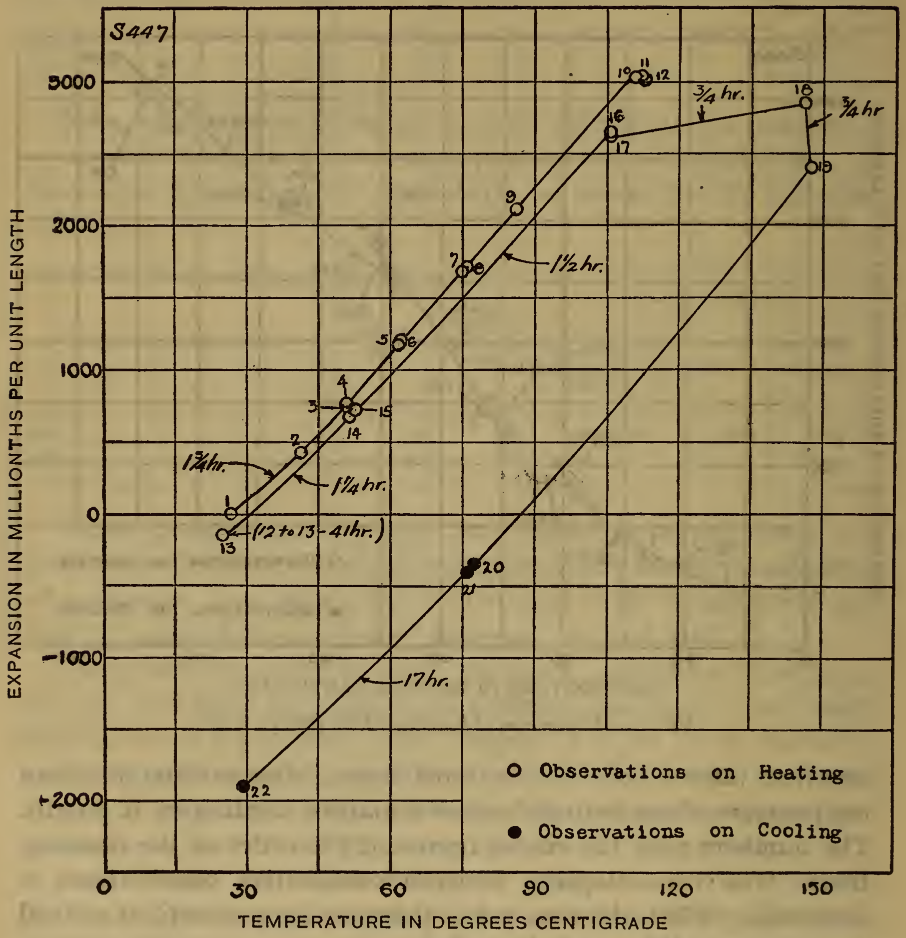

FIG. 10.—*Expansion of bakelite-dilecto (black) S 447*

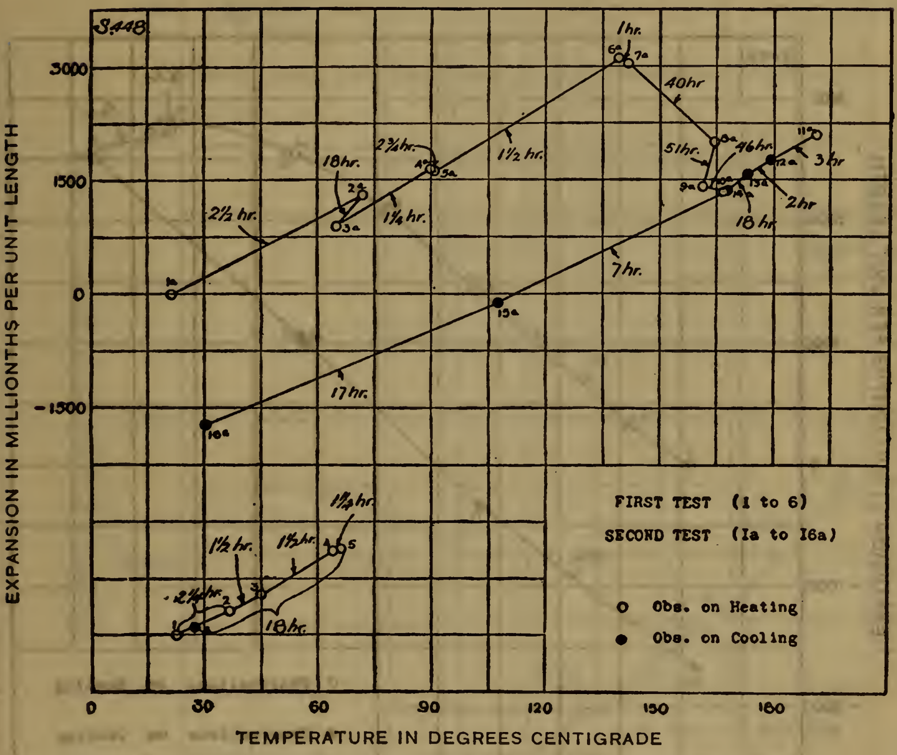

Fig. 11.—*Expansion of bakelite-dilecto (natural XX grade) S 448*

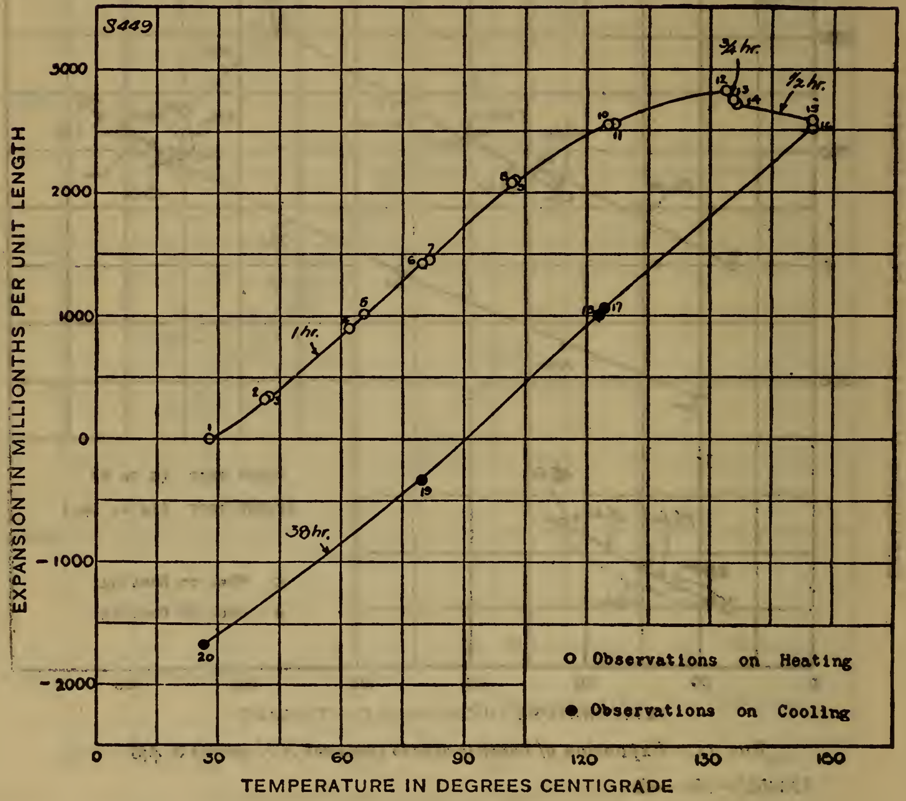

FIG. 12.—*Expansion of bakelite-dilecto (natural XX grade) S 449*

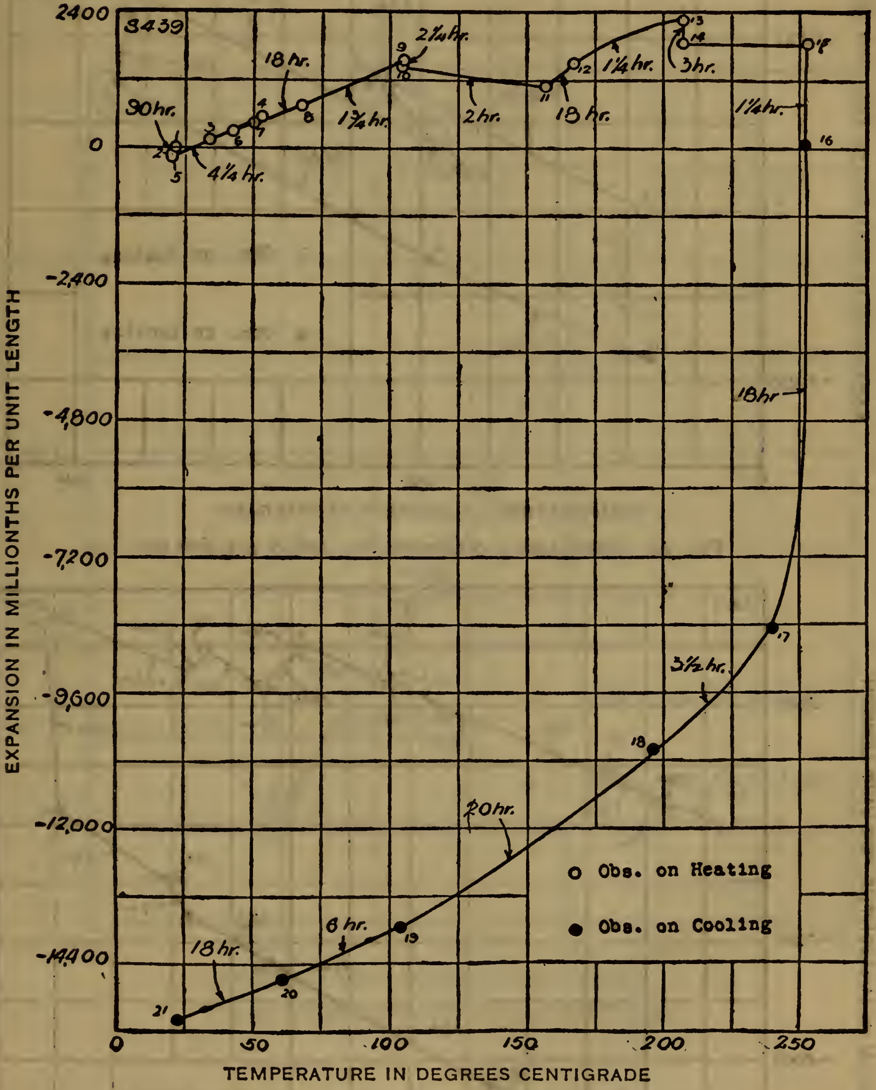

FIG. 13.—*Expansion of bakelite-dilecto (XX grade) S 439*

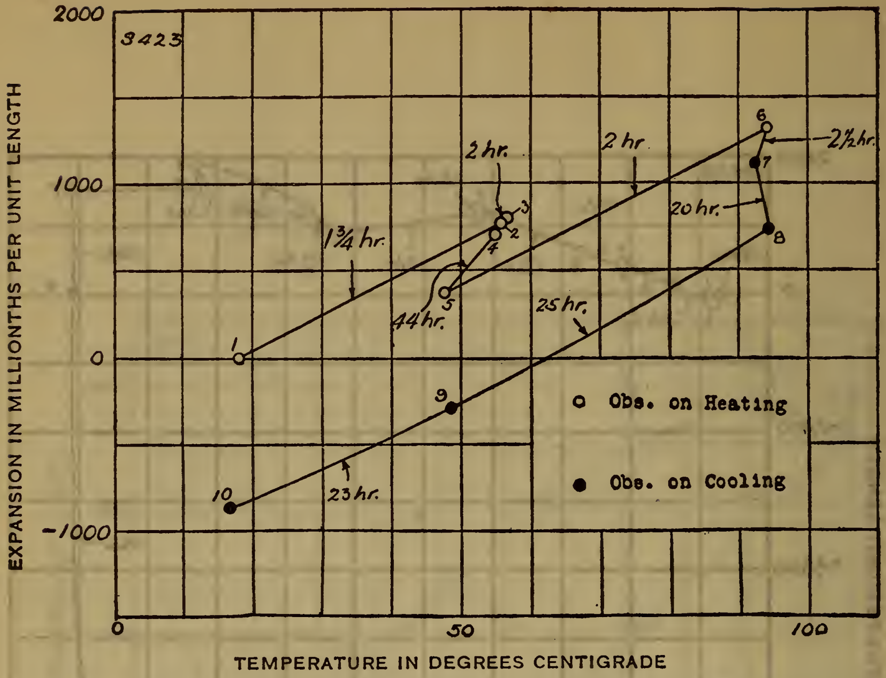

FIG. 14.—*Expansion of condensite (No. 128) S 423, first test*

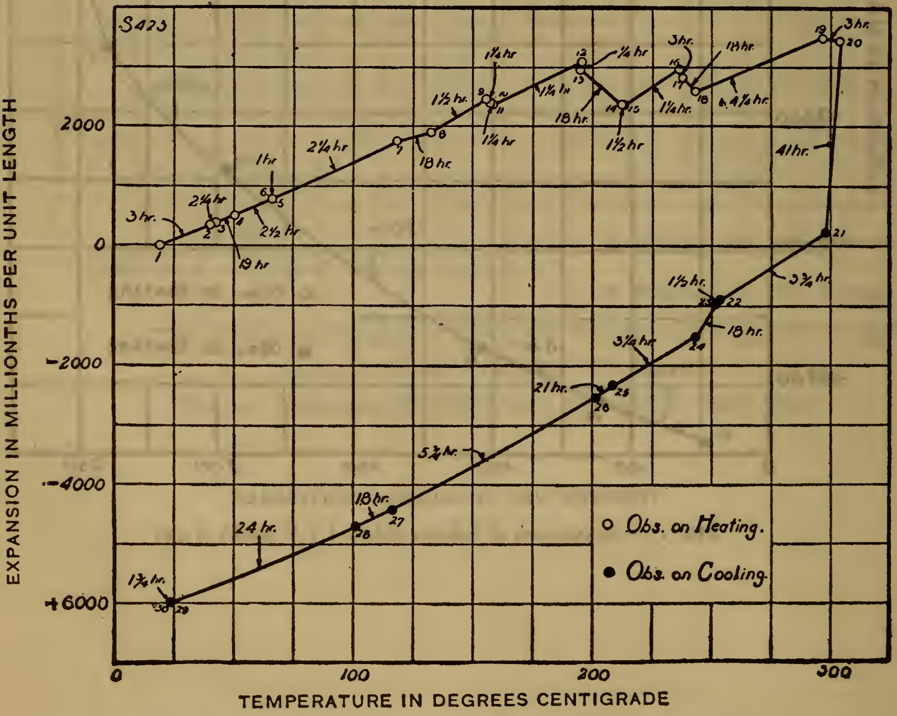

FIG. 15.—*Expansion of condensite (No. 128) S 423, second test*

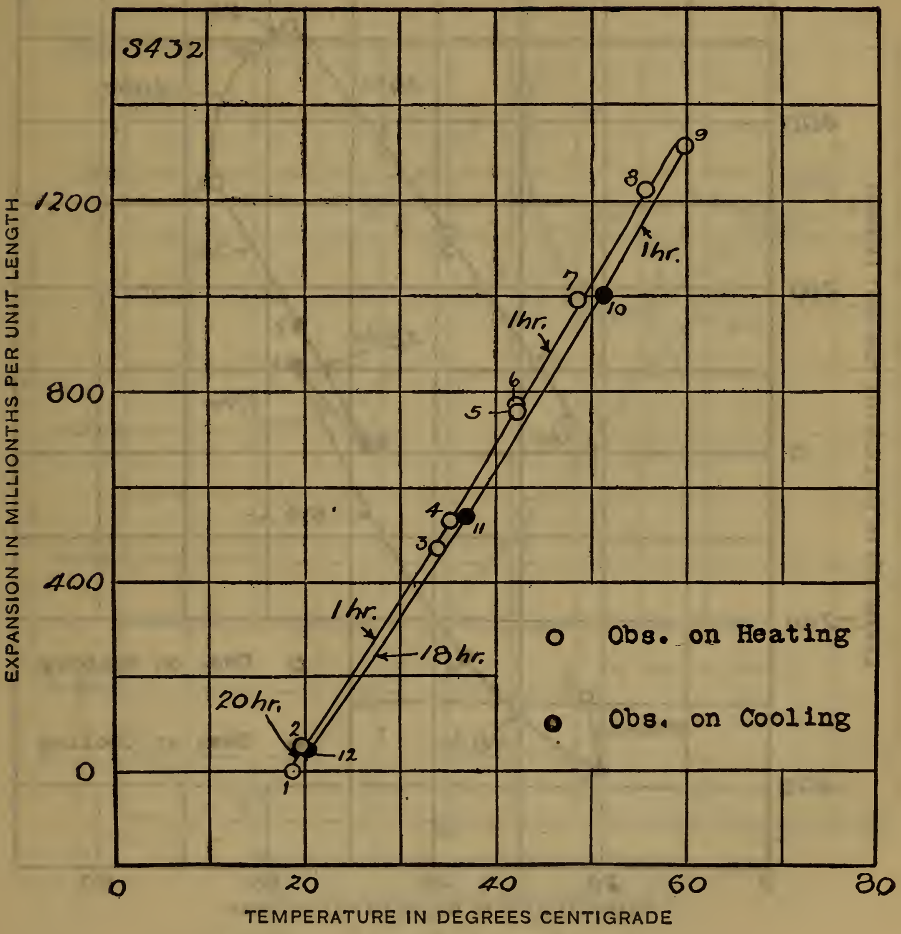

Fig. 16.—*Expansion of formica (grade M) S 432*

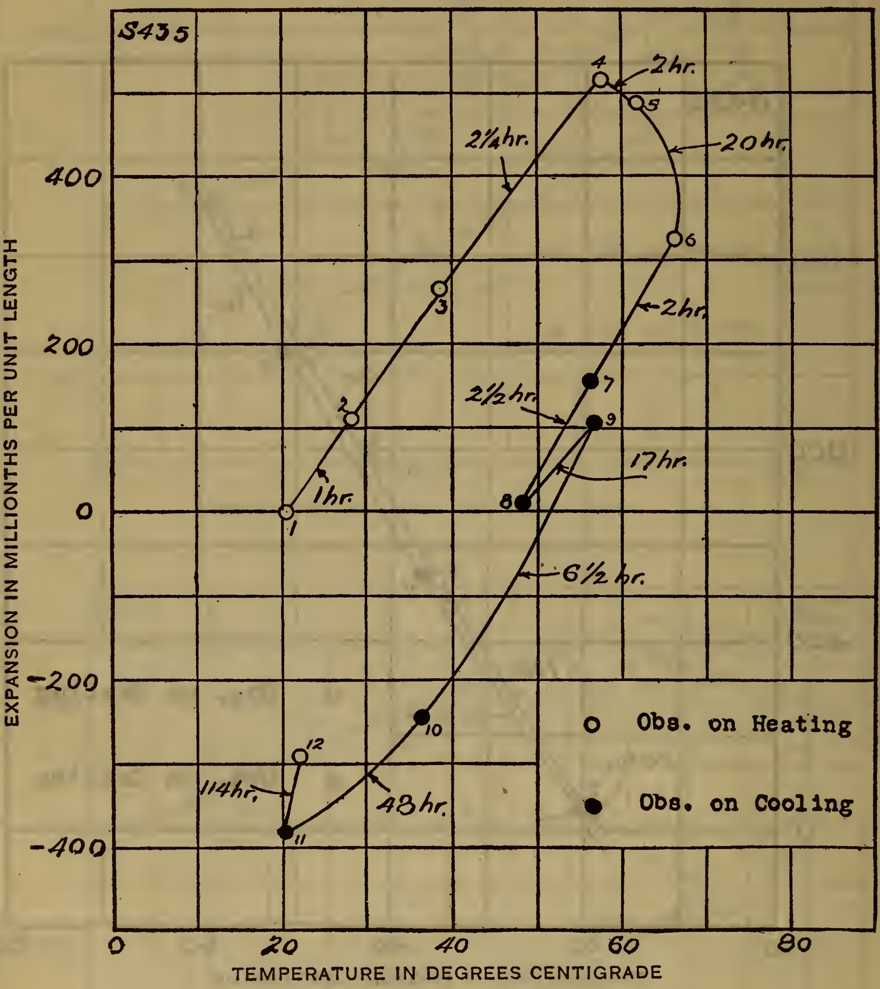

FIG. 17.—*Expansion of formica (grade M) S 435*

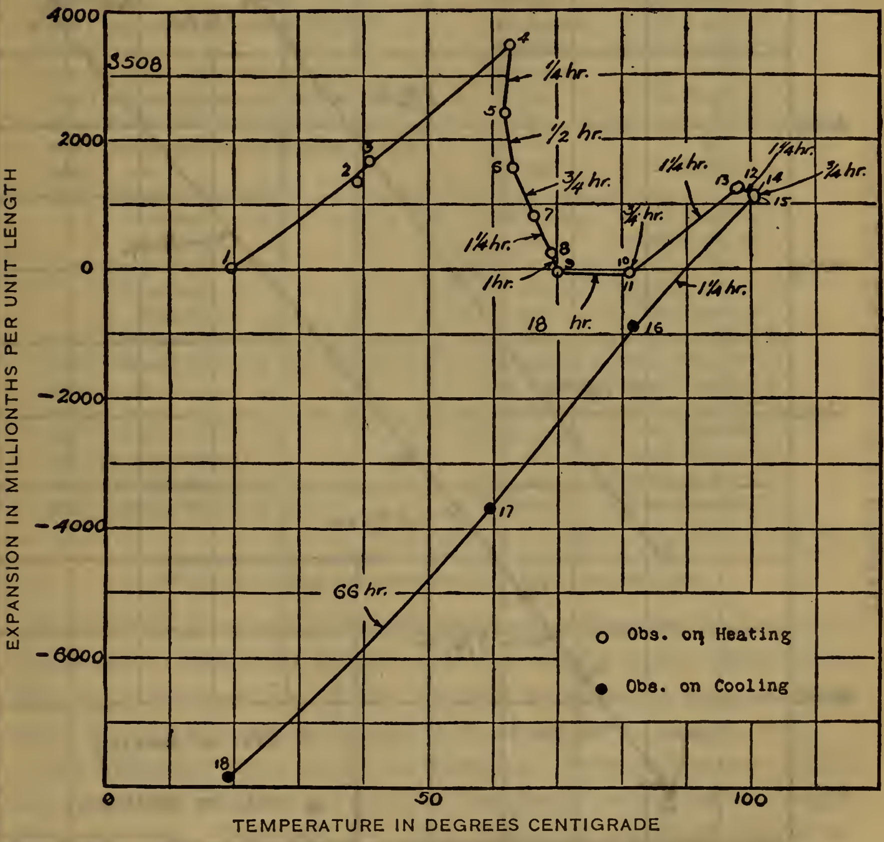

FIG. 18.—*Expansion of hard rubber (S 508)*

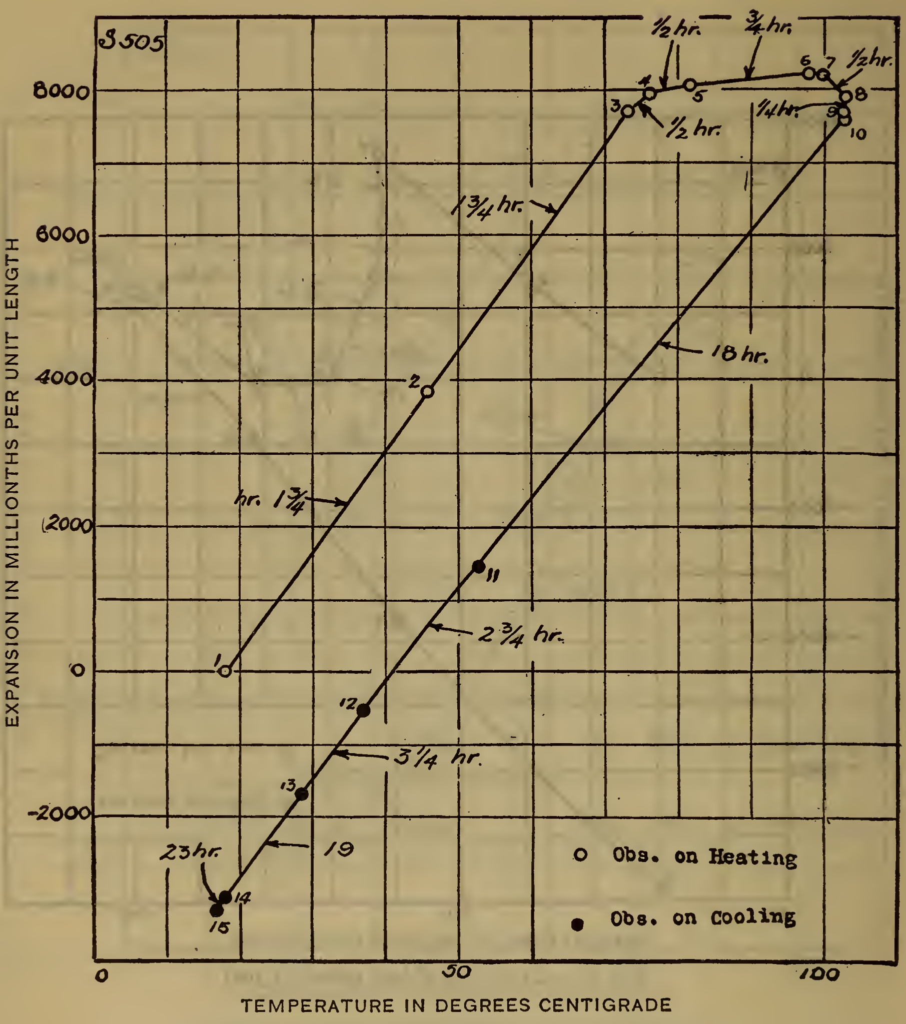

FIG. 19.—*Expansion of celluloid (S 505) second heating*

The coefficients of expansion obtained on various samples of these materials are summarized in the following table:

TABLE 4

Bureau of Standards No.	Material	Sample heated in—	Average coefficients $\times 10^6$
S446	Bakelite-dilecto (black)	Air furnace	22 bet. 20 and 60° C
S447	do	Oil bath	36 bet. 30 and 100° C
S448	Bakelite-dilecto (natural XX grade)	Air furnace	26 bet. 25 and 60° C
S449	do	Oil bath	28 bet. 30 and 100° C
S439	Bakelite-dilecto (XX grade)	Air furnace	21 bet. 25 and 50° C
S440	Bakelite Micarta (32X grade)	do	33 bet. 25 and 50° C
S441	Bakelite Micarta (323 grade)	do	29 bet. 25 and 50° C
S451	Continental bakelite (bakelized canvas)	do	(a)
S450	do	Oil bath	31 bet. 25 and 60° C
S422	Condensite (No. 100):		
	First test	Air furnace	44 bet. 16 and 79° C
	Second test	do	40 bet. 20 and 60° C
S423	Condensite (No. 128):		
	First test	do	20 bet. 18 and 56° C
	Second test	do	17 bet. 20 and 100°
S424	Condensite (No. 5053H)	do	27 bet. 20 and 80° C
S432	Formica (grade M) [b]	Oil bath	33 bet. 20 and 60° C
S433	do	Air furnace	30 bet. 20 and 60° C
S434	do	Oil bath	20 bet. 20 and 60° C
S435	do	Air furnace	14 bet. 20 and 60° C
S508	Hard rubber (rod)	do	80 bet. 20 and 60° C
S505	Celluloid (rod)	do	109 bet. 20 and 70° C
S481	Celluloid (slide rule)	do	74 bet. 20 and 40° C

[a] Expansion very irregular.

[b] Nos. S432 and S433 were cut perpendicular to Nos. S434 and S435.

Most of these materials when kept at some constant temperature above 60° C shrink in length and lose weight (give off vapors). When the temperature of the material increases it expands, but when kept at a constant temperature above 60° C it contracts.

The following table gives the maximum temperatures to which the specimens were heated and the changes in weight and in length after the test. The plus (+) sign indicates a gain in weight or length and the minus (−) sign a diminution in weight or length

TABLE 5

Bureau of Standards No.	Material	Sample heated in—	Maximum temperature	Change in weight after test	Change in length after test
			° C	Per cent	Per cent
S446	Bakelite-dilecto (black)	Air furnace	172	− 6.3	−0.4
S447	do	Oil bath	147	− .1	− .2
S448	Bakelite-dilecto (natural XX grade)	Air furnace	191	− 2.8	− .2
S449	do	Oil bath	175	− .3	− .2
S439	Bakelite-dilecto (XX grade)[a]	Air furnace	253	−20.4	−1.5
S440	Bakelite Micarta (32X grade)	do	195	− 2.7	− .4
S441	Bakelite Micarta (323 grade)[a]	do	246	−27.6	−4.0
S451	Continental bakelite (bakelized canvas)	do	170	− 2.0	− .1
S450	do	Oil bath	160	+ .1	− .2
S422	Condensite (No. 100):				
	First test	Air furnace	79	....	− .2
	Second test[b]	do	288	....	−4.3
S423	Condensite (No. 128):				
	First test[c]	do	94	− .5	− .1
	Second test	do	304	− 4.0	− .6
S424	Condensite (No. 5053H)	do	124	− 2.3	− .3
S432	Formica (grade M)	Oil bath	60	+ .2	− .01
S433	do	Air furnace	79	− .6	− .14
S434	do	Oil bath	61	+ .2	.00
S435	do	Air furnace	66	− .3	− .03
S508	Hard rubber	do	100	− .1	− .8
S505	Celluloid (2 heatings)	do	103	− 1.1	−1.4

[a] After test, specimen was found warped, cracked on sides, and blistered on upper and lower surfaces.

[b] At 288°, specimen was contracting so rapidly that one end left support of the apparatus.

[c] After test 1, specimen kept in oven at 100° C. for several days. It showed a change in weight and in length of −0.6 per cent and −0.1 per cent, respectively.

From a study of the work on these materials it is evident that the length is a function of the temperature, medium in which the material is heated (air or oil), time, rapidity of heating or cooling, etc

From these experiments the conclusion may be drawn that delicate apparatus made from these materials or containing these materials as essential parts should not be heated above 60° C (140° F), if loss in weight and shrinkage or warpage are to be avoided.

The Bureau takes this opportunity of thanking the manufacturers of the above products for their cooperation in this research. Practically all of the above samples were given the Bureau by the respective manufacturers.

VII. MARBLE AND LIMESTONE

This research[12] includes 10 grades of marble[13] selected from the quarries of Vermont, Tennessee, and Georgia, and one specimen of Indiana limestone. After heating, it was found that each showed an increase in length. This growth is roughly proportional to the maximum temperature, as is shown by S209 (Florentine blue), which was heated to 100° C, cooled to room temperature, then heated to 150°, and cooled to room temperature, and so on. Each cycle of increased temperature caused an additional increase in length. The dotted line represents how the material would have behaved if it had been heated directly to 300° C. (See S207.) Then after being cooled, it would have returned approximately to point 11, which represents a growth of more than 0.3 per cent. In other words, the growth is approximately the same, whether the specimen is heated by cycles or heated directly to the maximum temperature.

S198 (Pittsford Italian) and S285 (Appalachian gray) show the changes in length on two heatings and two coolings. It will be noticed that the growth after the second heating is less than that after the first heating. Repeated heatings tend to bring the marble to a constant or permanent state. The Vermont marble shows a larger growth than the Tennessee.

S296 (Silver gray) shows the changes in length at low temperatures. On cooling below room temperature, it is seen that the specimen expands, contrary to the usual behavior of most materials. The coefficient of expansion of this specimen on the first cooling was numerically (but opposite in sign) about the same as that of steel at room temperature. For the other marbles tested, however, the coefficients of expansion on cooling are quite small, as may be seen from Table 7. The peculiar phenomenon of minimum length is common to all the specimens tested. This point of minimum length is not constant for the different kinds of marble, and usually occurs below room temperature, in some instances as low as −20° C. Attention is directed to the slight permanent lengthening of specimens when passed through the cooling cycle.

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[12] Parts of these data on marble were taken under the direction of L. W. Schad, formerly of this Bureau.

[13] Selected by D. W. Kessler, of this Bureau. For additional physical and chemical properties see Bureau of Standards Technologic Paper No. 123.

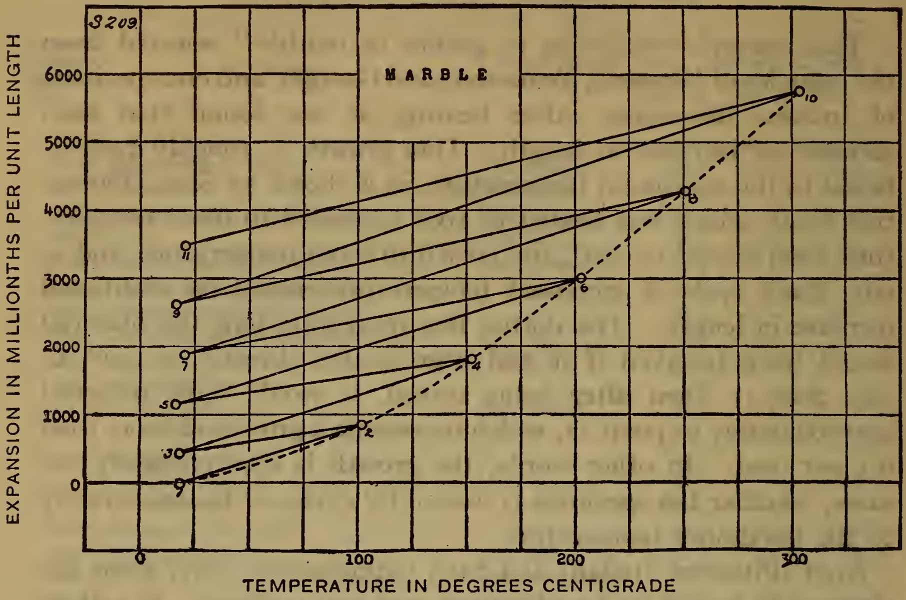

FIG. 20.—*Expansion and growth of marble (S 209)*

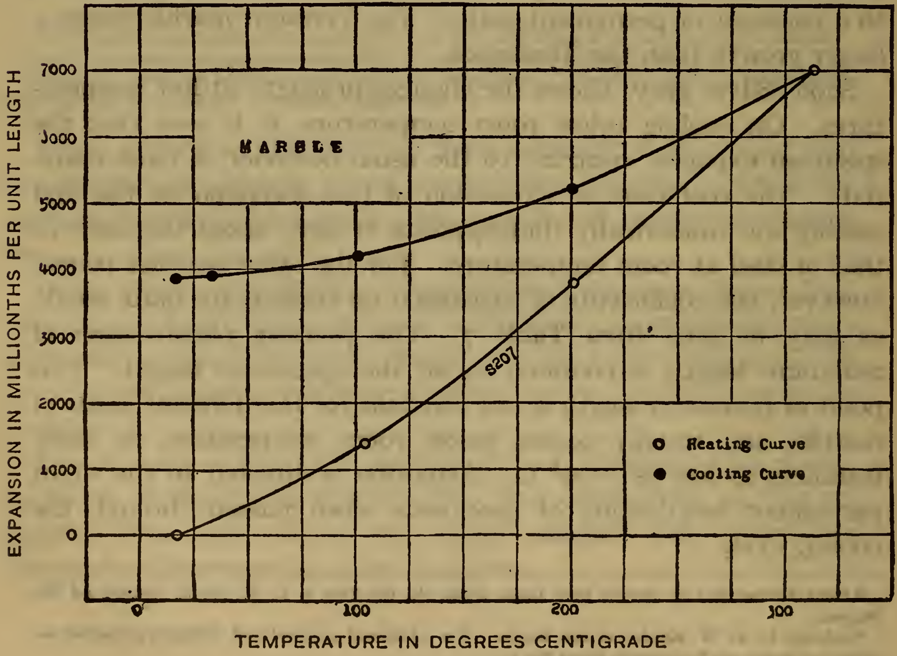

FIG. 21.—*Expansion of marble. (S 207)*

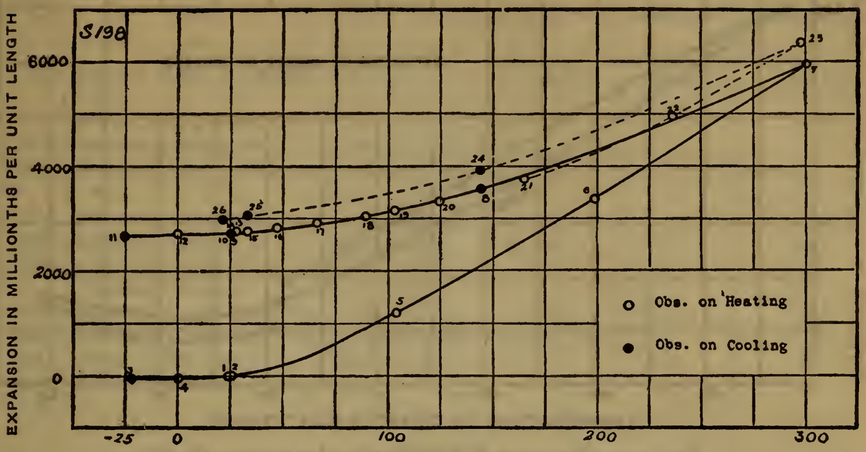

FIG. 22.—*Expansion of marble* (*S 198*)

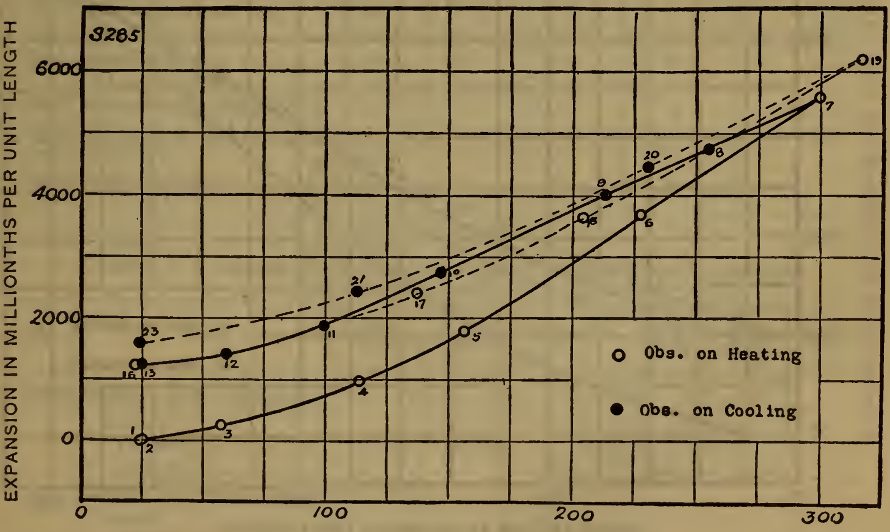

FIG. 23.—*Expansion of marble* (*S 285*)

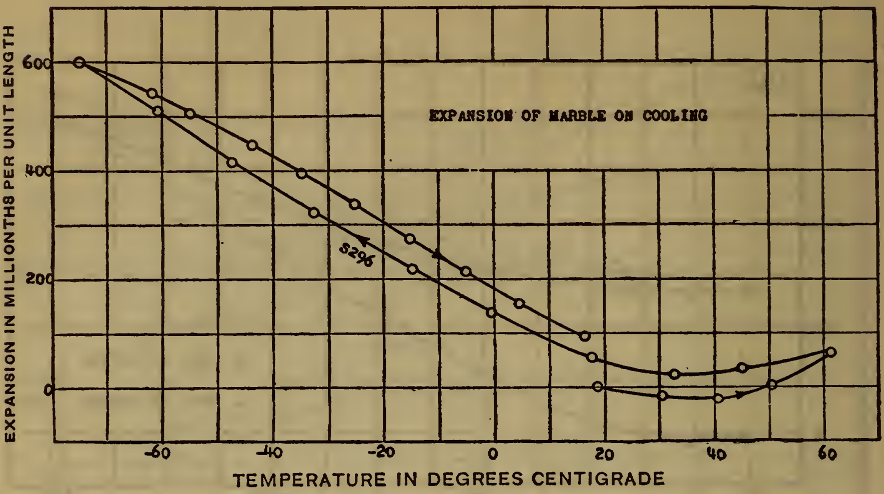

FIG. 24.—*Expansion of marble at low temperature (S 296)*

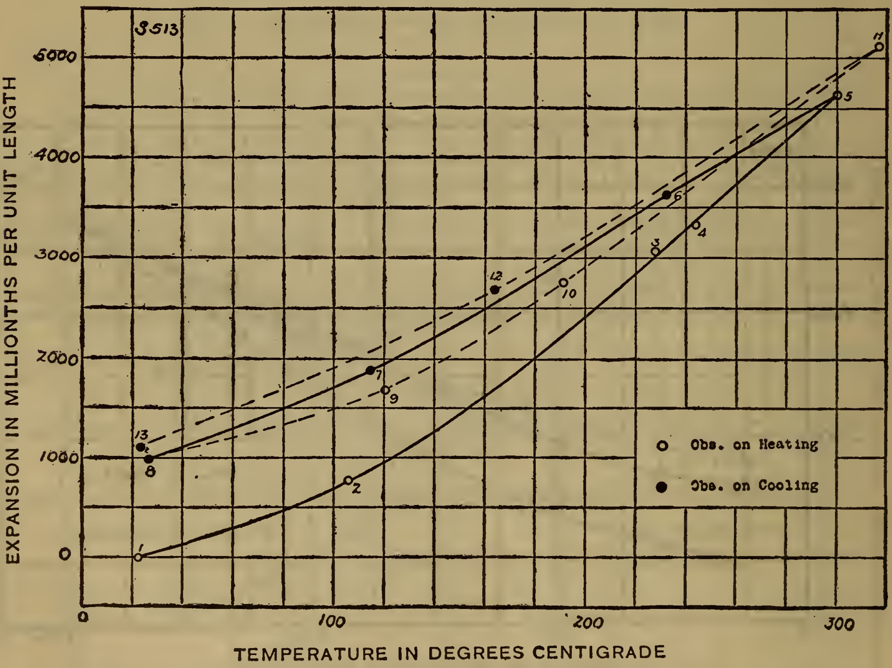

FIG. 25.—*Expansion of limestone (S513)*

TABLE 6.—Average Coefficients Above Room Temperature

HEATING

Number	Name	Heated in—	20 to 65° C	25 to 100° C	100 to 200° C	200 to 300° C
S198	Pittsford Italian, ⊥ (Pittsford, Vt.)	Oil	....	14×10^{-6}	23×10^{-6}	25×10^{-6}
S207	Rutland blue, ⊥ (Rutland, Vt.)	do	....	16	25	29
S208	Dorset gray (Dorset, Vt.)	do	10×10^{-6}	....	....	....
S209	Florentine blue, ⊥ (Florence, Vt.).	do	....	10	....	....
S210	Riverside, ⊥ (Proctor, Vt.)	do	....	13	....	....
S285	Appalachian gray, ⊥	Air	....	10	22	27
S286	Appalachian gray, ‖ (Asbury, Tenn.).	do	....	10	20	27
S310	Rutland blue, ⊥ (Rutland, Vt.)	do	....	15	23	28
S296	Silver gray, ‖ (Tate, Ga.)	....	[a]1	....	....	....
S514	Hollister ‖ (Florence, Vt.)	Air	....	5	13	15
S513	Indiana limestone	do	....	9	17	22

COOLING

Number.	Name	Heated in—	300 to 200° C	200 to 100° C	100 to 25° C	65 to 20° C
S198	Pittsford Italian, ⊥ (Pittsford, Vt.).	Oil	17×10^{-6}	11×10^{-6}	6×10^{-6}	....
S207	Rutland blue, ⊥ (Rutland, Vt.)	do	16	10	4	....
S208	Dorset gray (Dorset, Vt.)	do	....	....	....	7×10^{-6}
S285	Appalachian gray, ⊥	Air	19	18	9	....
S286	Appalachian gray, ‖ (Asbury, Tenn.)	do	18	17	10	....
S310	Rutland blue, ⊥ (Rutland, Vt.)	do	15	9	4	....
S296	Silver gray, ‖ (Tate, Ga.)	....	....	....	....	[a]0.5
S514	Vermont, ‖	Air	7	3	0	....
S513	Indiana limestone	do	15	14	10	....

[a] After cooling test.

TABLE 7.—Average Coefficients on Cooling Below Room Temperature

No.	Name	25 to 0° C	0 to −20° C	−20 to −40° C	−40 to −60° C	−60 to −80° C	−80 to −95° C
S283	Victoria pink ⊥ (Knoxville, Tenn.):						
	First test	4×10^{-6}	1×10^{-6}	....	....	....	....
	Second test	3	1	-4×10^{-6}	-4×10^{-6}	-2×10^{-6}	....
S287	Cumberland pink ⊥ (Meadow, Tenn.):						
	First test	4	1	−3	−3	−2	-1×10^{-6}
	Second test	2	0	−2	−2	....	....
S296	Silver gray, ‖ (Tate, Ga.):						
	First test	−13	−10	−10	−10	−12	....
	Second test	−4	−6	−6	−7	....	....

Tables 6 and 7 give the coefficients of expansion of the various samples. The former table gives the values on the first heating; and the latter, on cooling below room temperature. The coefficients are higher on the first heating than on any subsequent heating. The symbols ⊥ and || are used in the table to indicate the direction of the grain, the former representing specimens cut perpendicular to the bed and the latter parallel to the bed. Little, if any, difference in expansion can be detected; e. g., S285 and S286 are from the same block of marble, but cut in opposite directions to the grain.

The following table gives the principal constituents of the marbles investigated:

TABLE 8.—Chemical Analysis

Number[a]	CaO	CO_2	MgO	Al_2O_3	Fe_2O_3	Loss on ignition	Insoluble in HCl
S198	54.49	43.65	1.33	0.20	0.05	43.81	0.44
S207	55.90	43.80	.27	.06	.02	43.90	.34
S208	55.40	43.46	.35	.06	.04	43.78	.70
S209	55.60	43.94	.44	.07	.01	43.86	.30
S210[b]	55.40	43.76	.35	.10	.01	43.70	.24
S285	55.60	43.58	.07	.26	.06	43.89	.15
S286	55.60	43.58	.07	.26	.06	43.89	.15
S310	55.90	43.80	.27	.06	.02	43.90	.34
S296	55.00	43.18	.41	.09	.04	43.37	1.10
S514	55.54	43.75	.46	.09	.03	43.81	.24
S283	55.38	43.52	Trace	.14	.06	43.95	.08
S287	55.80	42.65	.06	.45	.16	43.68	.54

[a] Trace of SiO_3 in all samples except S514.

[b] $SiO_2=0.26$.

The difference in the coefficients of the various marbles when compared with each other or the difference of some marbles when compared with certain metals, raises a question of the advisability of assembling these in structures, subject to large temperature variations, where close or accurate relative dimensions are to be maintained unless proper compensating facilities are provided.

Length measurements made two years after these tests indicate that the growth of marble after heating is permanent.

VIII. SUMMARY

The present paper gives data on the thermal expansion of some of the more important insulating materials.

A short description of the method employed in making the observations is given. A photograph of one of the furnaces and the microscopes is shown in Fig. 1.

The dimensional changes incident to temperature variations have been measured. In most cases the expansions are too irregular to justify the use of the general quadratic equations.

The coefficients of 40 samples of various kinds of porcelain were found to vary over a wide range, from 1.6 to 19.6 millionths per unit length per degree centigrade. The coefficients of expansion are given in Table 2. The expansion curves of most materials are concave; but with porcelain three kinds of curves were found, namely, straight-line, concave, and convex curves. No marked set or permanent change in dimension due to the heat treatment was observed. Porcelains having low coefficients exhibited marked resistance to sudden temperature changes.

To understand the work done on the phenol condensation products (bakelite, condensite, formica, etc.), it is necessary to refer to the representative figures. (See p. 399.) The most striking peculiarity is the shrinkage and the loss in weight of most of these materials when subjected to temperatures above 60° C. A summary of the values obtained is given in Tables 4 and 5.

Marble and limestone showed a permanent growth when subjected to heat treatment. On cooling below room temperature, it was found that marble has a negative coefficient of expansion. The coefficients of expansion are given in Tables 6 and 7.

A knowledge of the thermal behavior of these materials is essential before assembling them in certain types of apparatus subjected to wide temperature variations.

We are indebted to John O. Eisinger for assistance in computing, etc.

WASHINGTON, June 30, 1919.

⁂