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THERMAL EXPANSION OF LEAD-ANTIMONY ALLOYS

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ABSTRACT

This paper gives the results of an investigation of the linear thermal expansion of cast lead-antimony alloys containing from 2.9 to 98.0 percent of antimony. Observations were made at various temperatures between −12 and +200° C and are shown in figures 3 to 5, inclusive.

A majority of the curves obtained on cooling lie below the expansion curves obtained on heating. The deviations between these curves are particularly noticeable for the alloys containing up to 15 percent of antimony which were cast in a preheated steel mold and cooled slowly. The deviations are less noticeable for the alloys of higher antimony content which were cast either in a sand mold or a chill mold. It is probable that the deviations indicate a lack of equilibrium in the samples on account of the effect of the casting conditions or of the chemical composition.

Table 3 gives the coefficients of expansion, the change in length after heating and cooling, and the densities of the alloys.

Equations 1 to 5 give linear relations between the coefficients of expansion and the atomic percentage of antimony of the lead-antimony alloys containing from 4.8 to 97.0 atomic percent of antimony (2.9 to 95.0 percent, by weight), and show that the coefficients of expansion decrease linearly with increase in the atomic percentage of antimony. The densities of the lead-antimony alloys also decrease linearly with increase in the atomic percentage of antimony. These linear relations are typical of relations for other properties of binary alloys having structures composed of solid solution + eutectic.

The coefficients of expansion of the lead-antimony alloys cover a wide range of values. It is possible to select lead-antimony alloys that have approximately the same coefficients of expansion as iron, nickel, gold, copper, silver, aluminum, magnesium, and many of their alloys.

CONTENTS

I. INTRODUCTION

In 1923 determinations were made by Hidnert and Sweeney [1][1] of the linear thermal expansion of lead and lead-antimony alloys containing from 0 to 15 percent of antimony. In 1930 and 1932 Hidnert and Sweeney [2, 3] published data on the thermal expansion

[1] The numbers in brackets here and elsewhere in the text refer to the references at the end of this paper.

of lead, and in 1935 Hidnert [4] published data on the thermal expansion of monocrystalline and polycrystalline antimony.

The results reported in the present paper represent an extension of the work started in 1923, which indicated that the coefficient of expansion of lead-antimony alloys (0 to 15 percent of antimony) decreases with increase of antimony. The work was extended in order to find, if possible, a relation between thermal expansion and chemical composition for alloys containing from 0 to 100 percent of antimony.

It has been pointed out by Goodrich [5] and others that the binary alloys of lead and antimony containing up to 25 percent of antimony are of considerable commercial importance. Goodrich [5] stated that alloys containing from 3 to 5 percent of antimony are used for rifle bullets and battery plates, alloys containing from 10 to 15 percent of antimony are used in much of the lead apparatus of chemical works, alloys containing from 12.5 to 20 percent of antimony are very useful as bearing metals for light loads, and that alloys containing from 10 to 25 percent of antimony are used for type metals.

II. PREVIOUS DETERMINATIONS

Previous observers on the thermal expansion of lead-antimony alloys include Daniell [6], Calvert, Johnson and Lowe [7], Vicentini and Omodei [8], Wüst [9], Hidnert and Sweeney [1], and Broniewski and Sliwowski [10]. None of these investigations, except the last, covered the whole range of composition. The most extensive previous report is that by Broniewski and Sliwowski [10], who not only covered the entire range in composition, but also covered a wider temperature range than was used by other observers. For these reasons the data by Broniewski and Sliwowski [10] are reproduced in table 1. It will be shown subsequently that Broniewski and Sliwowski's results are in good agreement with the results of the present investigation for the antimony-rich alloys, but their results are too high for pure lead and the lead-rich alloys.

TABLE 1.—*Coefficients of expansion of annealed lead-antimony alloys (Broniewski and Sliwowski [10])*

Atomic percentage of antimony	Coefficients of linear expansion		Remarks
	a	$2b$	
	$\times 10^{-6}$	$\times 10^{-6}$	
0 (Pb)	28.92	0.02478	Each value given for a represents a coefficient of expansion or rate of expansion at 0° C, and $2b$ represents the variation of the coefficient of expansion with temperature. The coefficient of expansion at any temperature may be computed from the following equation: $a_t = a + 2\,bt$, where a_t is the coefficient of expansion at any temperature t between −186 and +218° C.
1.7	28.82	.01467	
5	28.59	.00900	
10	27.58	.00816	
19.1	25.98	.00796	
20	25.65	.00814	
20.5	25.61	.00794	
21.9	24.94	.00510	
30	23.72	.00350	
40	21.73	.00718	
50	20.13	.00836	
60	18.47	.00830	
70	16.69	.00532	
80	14.80	.00396	
90	12.85	.00296	
95	11.48	.00248	
100 (Sb)	10.25	.00065	

III. MATERIALS INVESTIGATED

Twenty-four samples of lead-antimony alloys containing from 2.9 to 98.0 percent of antimony were cast at this Bureau from lead of high purity (99.99 percent) and antimony with a purity of 99.8 percent or higher. Each sample was about 300 mm in length and about 10 by 10 mm in cross section. After the thermal-expansion determinations had been completed, cross sections cut from the ends and the center of each sample were polished and examined microscopically in order to determine which samples showed evidence of segregation. Throughout this paper the term segregation is used to refer to nonuniformity in structure. Density determinations and chemical analyses were made on other pieces of the samples.

Table 2 gives the chemical compositions [2] and also indicates the samples which showed segregation. Samples *989* to *1000* were cast in a preheated steel mold and cooled slowly, samples *1062* to *1148* were cast in a sand mold, and samples *1452* to *1453A* were cast in a steel chill mold.

TABLE 2.—*Cast lead-antimony alloys investigated*

Sample	Batch formula		Chemical analysis		Segregation
	Lead	Antimony	Lead	Antimony	
	Percent	*Percent*	*Percent*	*Percent*	
989			90.0	9.8	No.
990			91.0	8.8	No.
991			92.7	7.1	No.
992			92.8	7.0	No.
993			94.1	5.7	No.
994			94.9	4.9	No.
995			95.9	4.0	No.
996			96.9	2.9	No.
997			89.1	10.7	No.
998			87.9	11.9	No.
999	87	13			Yes.
1000	85	15			Yes.
1062	75	25			Yes.
1063	60	40	60.4	39.6	No.
1064	45	55	45.2	54.7	No.
1065	30	70	32.3	67.6	No.
1066	15	85	17.4	82.5	No.
1145	83	17			Yes.
1146	75	25			Yes.
1147	5	95	5.0	95.0	No.
1148	2	98	2.0	98.0	No.
1452	87	13			Yes.
1453 [a]	73	27	75.2	24.8	No.
1453A	73	27	76.2	23.8	No.

[a] Contained arsenic, less than 0.02 percent.

The samples containing from 13 to 25 percent of antimony were found to be segregated. Figure 1 shows the differences in structure observed in two portions of sample *1452*. The distribution of the antimony-rich solid solution (white particles) varies considerably in different portions of this alloy.

Figure 2 illustrates the nonuniformity of structure in sample *1062* (25 percent of antimony). The background of this figure represents

[2] Weight percentages are used in this paper, except where noted otherwise.

the eutectic composition, and the light areas are the antimony-rich solid solution present in excess of the eutectic composition.

The segregation encountered in the cast lead-antimony alloys is attributed to the following factors:

(a) The large difference in the densities of lead (11.3) and antimony (6.7).

(b) The rate of cooling.

(c) The percentage of lead and antimony.

(d) The viscosity of the liquid mixture.

As antimony is lighter than lead, and as it solidifies first, antimony crystals tend to rise to the top of the liquid.

Segregation may be avoided by increasing the rate of cooling. Samples *1062* and *1146* containing about 25 percent of antimony, cast in a preheated steel mold and a sand mold, respectively, were segregated, but samples *1453* and *1453A* containing about the same percentage of antimony, cast in a chill mold, showed no evidence of segregation.

Segregation appears to be most common with lead-antimony alloys containing a little more than the eutectic proportion of antimony (12.5 percent). Casting sample *1452*, containing about 13 percent of antimony, in a chill mold, did not prevent segregation.

Segregation is more noticeable the lower the viscosity of the liquid mixture. Plüss [11] made viscosity measurements at 292° C on lead-antimony alloys containing from 7.6 to 17.0 percent of antimony. He found that the viscosity decreases from 7.6 percent of antimony to the eutectic at 13 percent of antimony and then increases rapidly above the latter percentage.

Ewen and Turner [12] obtained marked segregation in two bars of lead-antimony alloys containing 14.6 and 23.2 percent of antimony. They stated, "It would appear that in casting alloys of this range of composition, which includes bearing metals and type metals, the casting temperature should be as low as possible if segregation is to be avoided. With higher percentages of antimony the dendritic structure effectually prevents segregation." In order to obviate the tendency of lead to collect at the bottom of the melts of lead-rich lead-antimony alloys, Goodrich [5] sealed the constituent metals in a bulb, melted them in vacuo in a tilting furnace, and agitated the melt until the first signs of solidification appeared. The alloy was then cooled slowly in the furnace, remelted and again agitated.

The equilibrium diagram obtained from the results of a number of investigations [10, 13, 14, 15, 16, 17, 18] shows that lead-antimony alloys form a eutectiferous series with limited solid solubility of antimony in lead and of lead in antimony. The eutectic is at about 13 percent of antimony and at 247° C. The solid solubility of antimony in lead increases from about 0.2 percent of antimony at 25° C. to about 2.5 percent of antimony at the eutectic temperature. There is uncertainty in regard to the solid solubility of lead in antimony. Values ranging from less than 1 percent to about 11 percent have been reported [10, 13, 17] for the limiting solid solubility at the eutectic temperature. According to Endo [17], the solid solubility of lead in antimony increases from 1 percent of lead at 0° C to 5 percent of lead at the eutectic temperature, but the results of Broniewski and Sliwowski [10] indicate that the solid solubility is about 11 percent from about 150° C to the eutectic temperature.

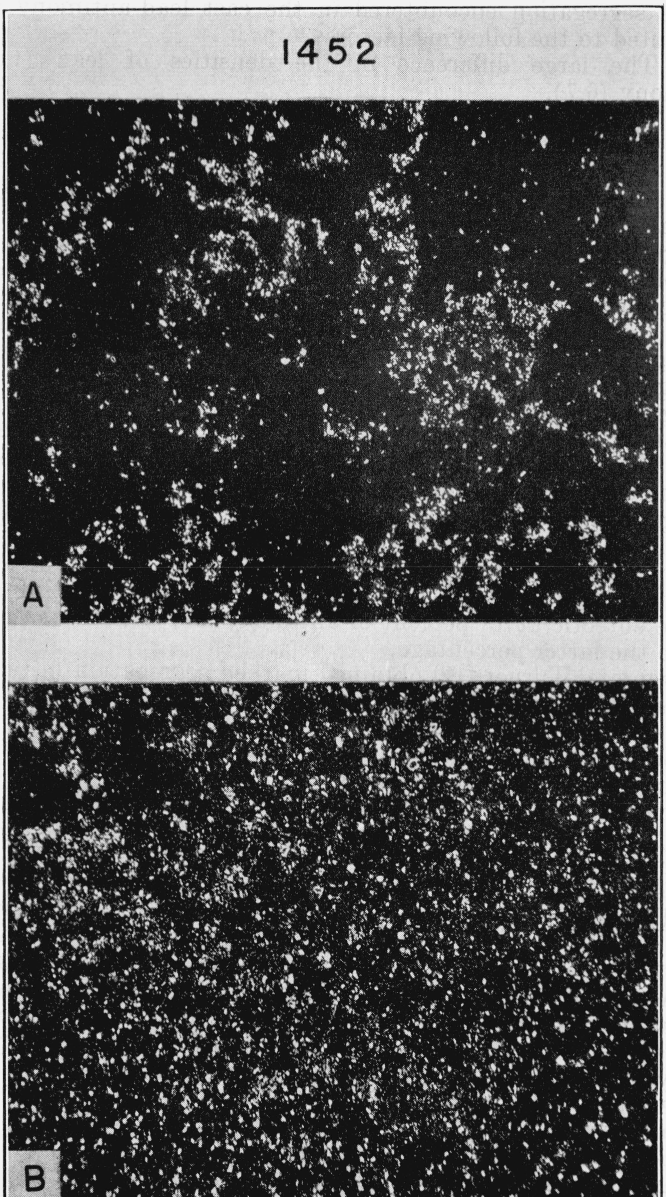

FIGURE 1.—*Typical structure of different parts of cast lead-antimony alloy showing segregation.* $\times 50$.

Made to contain lead 87 percent, antimony 13 percent. Etched with mixture composed of 75 parts of glacial acetic acid and 25 parts of hydrogen peroxide. *A*, One end of sample 1452; *B*, other end of sample 1452.

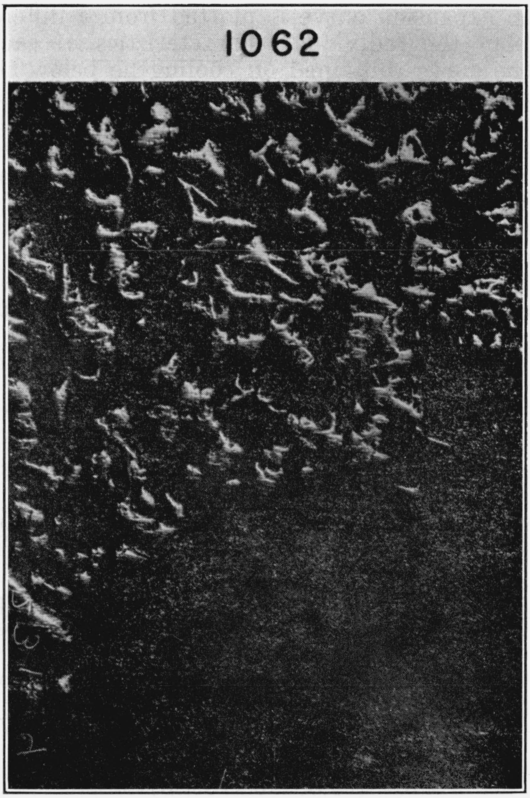

FIGURE 2.—*Micrograph showing the structure near the joining of the segregated and unsegregated areas of cast lead-antimony alloy.* × *50.*

Made to contain lead 75 percent, antimony 25 percent. Not etched.

IV. APPARATUS

Samples *989* to *1000* were investigated in the bath furnace described by Hidnert [19], and Souder and Hidnert [20]. Samples *1062* to *1148* were investigated in the black furnace and samples *1452* to *1453A* were investigated in the white furnace shown in figure 1 of the latter publication.

V. RESULTS

The observations obtained on heating and cooling at various temperatures between −12 and +200° C are shown in figures 3 to 5, inclusive. Each expansion curve is plotted from a different origin in order to display the individual characteristics of each curve. A majority of the curves obtained on cooling lie below the expansion curves obtained on heating. The deviations between these curves are particularly noticeable for the alloys containing up to 15 percent of antimony which were cast in a preheated steel mold and cooled slowly. The deviations are less noticeable for the alloys of higher antimony content which were cast either in a sand mold or a chill mold. It is probable that the deviations indicate a lack of equilibrium in the samples on account of the effect of the casting conditions or of the chemical composition.

Only one test was made on each sample except *1146* and *1065* (fig. 5) on which two tests were made. The results obtained on the first heating apply for cast alloys, but the data obtained on the second heating of samples *1146* and *1065* apply for alloys which had received the heat treatment incident to the first heating. As the observations on cooling nearly coincide with the expansion curves on heating in the second tests of samples *1146* and *1065*, it may be assumed that other alloys would show similar results in a second test.

Table 3 gives coefficients of linear expansion which were computed from the results indicated in figures 3 to 5, inclusive. The antimony contents are given in weight and atomic percentages. The table also shows the difference in length before and after each expansion test, and the densities of the samples after the expansion tests.

From the coefficients of expansion obtained for the temperature range from 20 to 60° C on the lead-antimony alloys containing 4.8 to 97.0 [3] atomic percent of antimony (2.9 to 95.0 percent, by weight), the following empirical equation was derived by the method of least squares:

$$_{20}a_{60} = (29.09 - 0.1789\text{Sb})10^{-6}, \qquad (1)$$

where $_{20}a_{60}$ represents the average coefficient of linear expansion between 20 and 60° C, and Sb represents the atomic percentage of antimony (between 4.8 and 97.0 atomic percent). The probable error of a single computed value is $\pm 0.3 \times 10^{-6}$. In deriving the equation, the coefficients of expansion of the segregated alloys and the coefficient of expansion obtained in the second test on sample *1065*, were ignored. Only alloys that were uniform and the compositions of which were known, were used in the derivation of the equation.

[3] The alloy containing 98.8 atomic percent of antimony (98.0 percent, by weight) was excluded, for there is doubt whether or not this alloy lies outside of the region of the solid solution of lead in antimony.

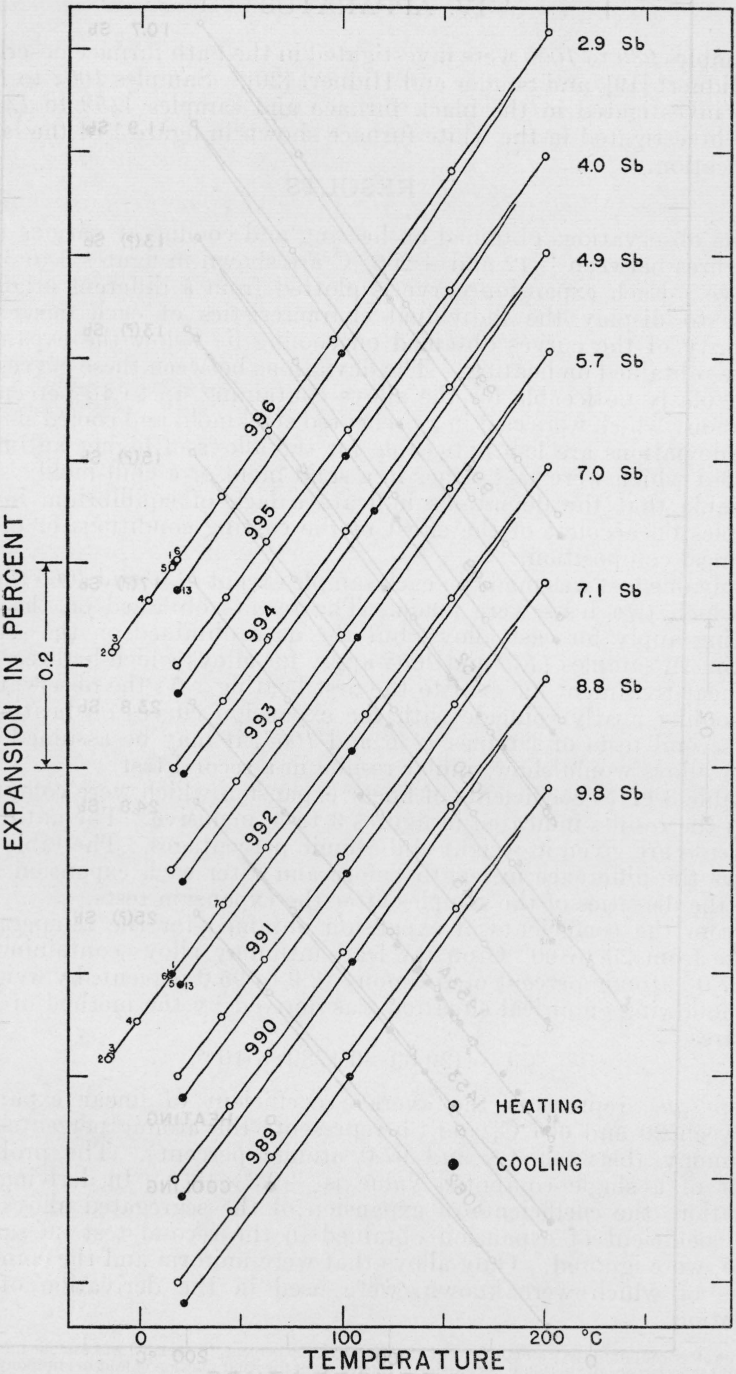

FIGURE 3.—*Linear thermal expansion of cast lead-antimony alloys containing from 2.9 to 9.8 percent of antimony.*

The numbers adjoining the observations at the lower end of the expansion curves of samples *996* and *992* indicate the sequence of the observations. The tagged symbol indicates more than one observation.

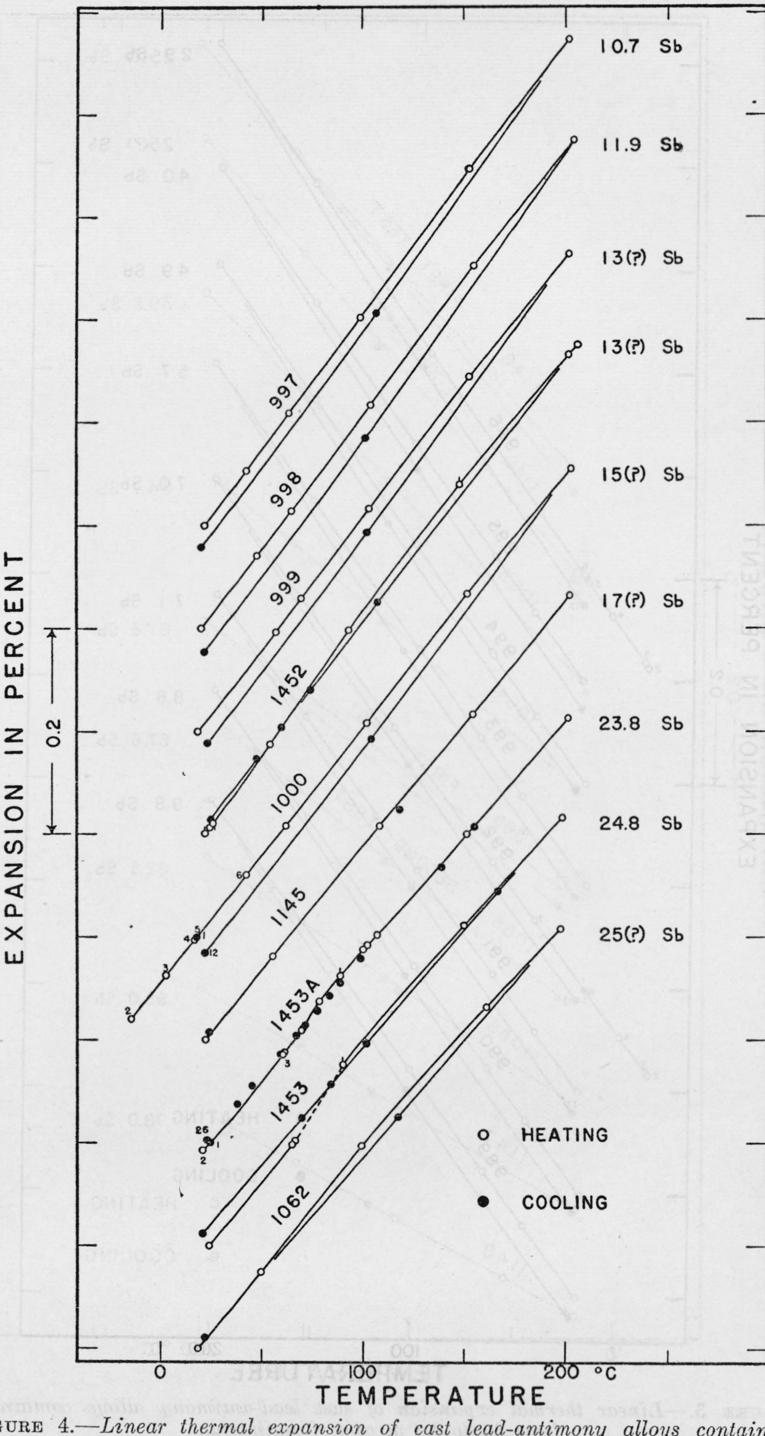

FIGURE 4.—*Linear thermal expansion of cast lead-antimony alloys containing from 10.7 to 25 percent of antimony.*

Samples *999, 1452, 1000, 1145,* and *1062* are segregated. The numbers adjoining the observations at the lower end of the expansion curves of samples *1000* and *1453A* indicate the sequence of the observations. A tagged symbol indicates more than one observation.

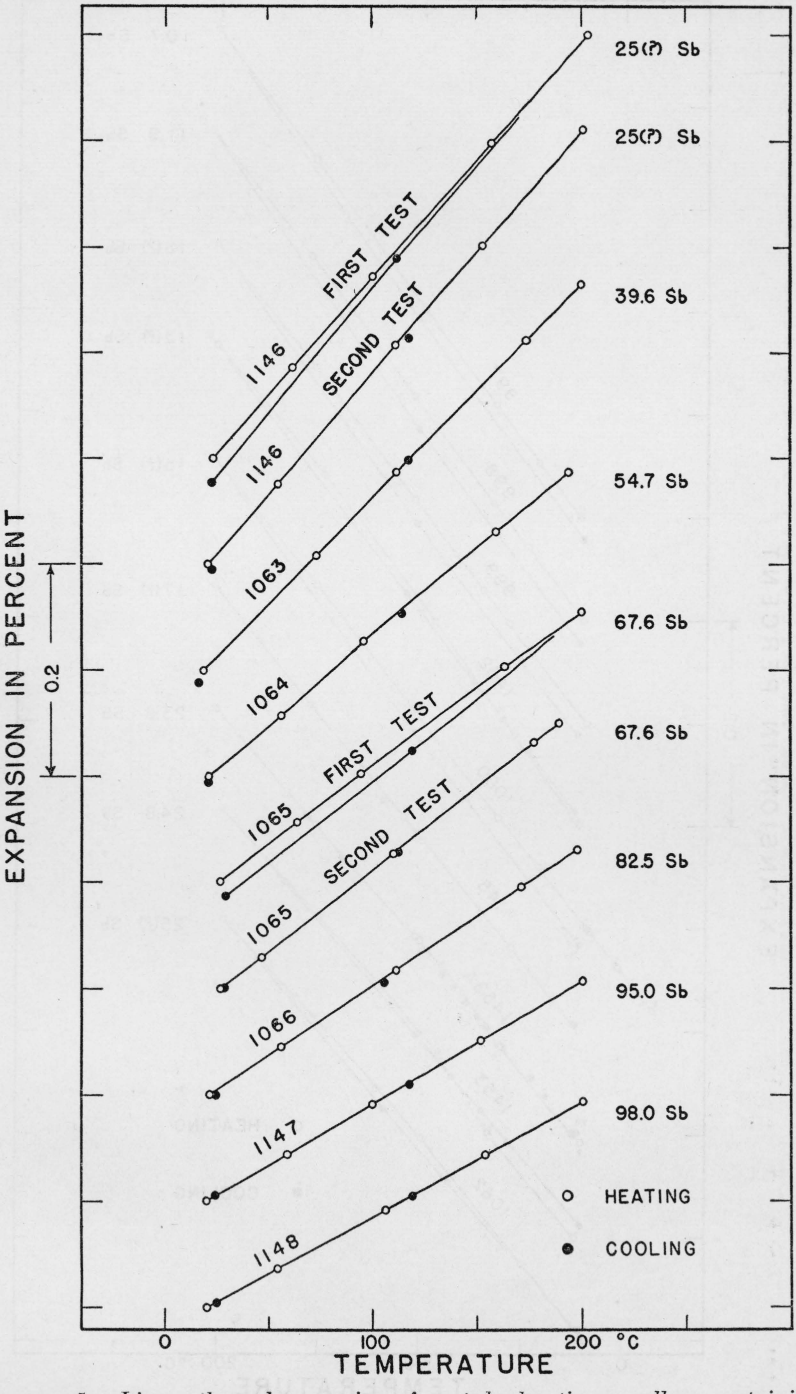

FIGURE 5.—*Linear thermal expansion of cast lead-antimony alloys containing from 25 to 98.0 percent of antimony.*

Sample *1146* is segregated.

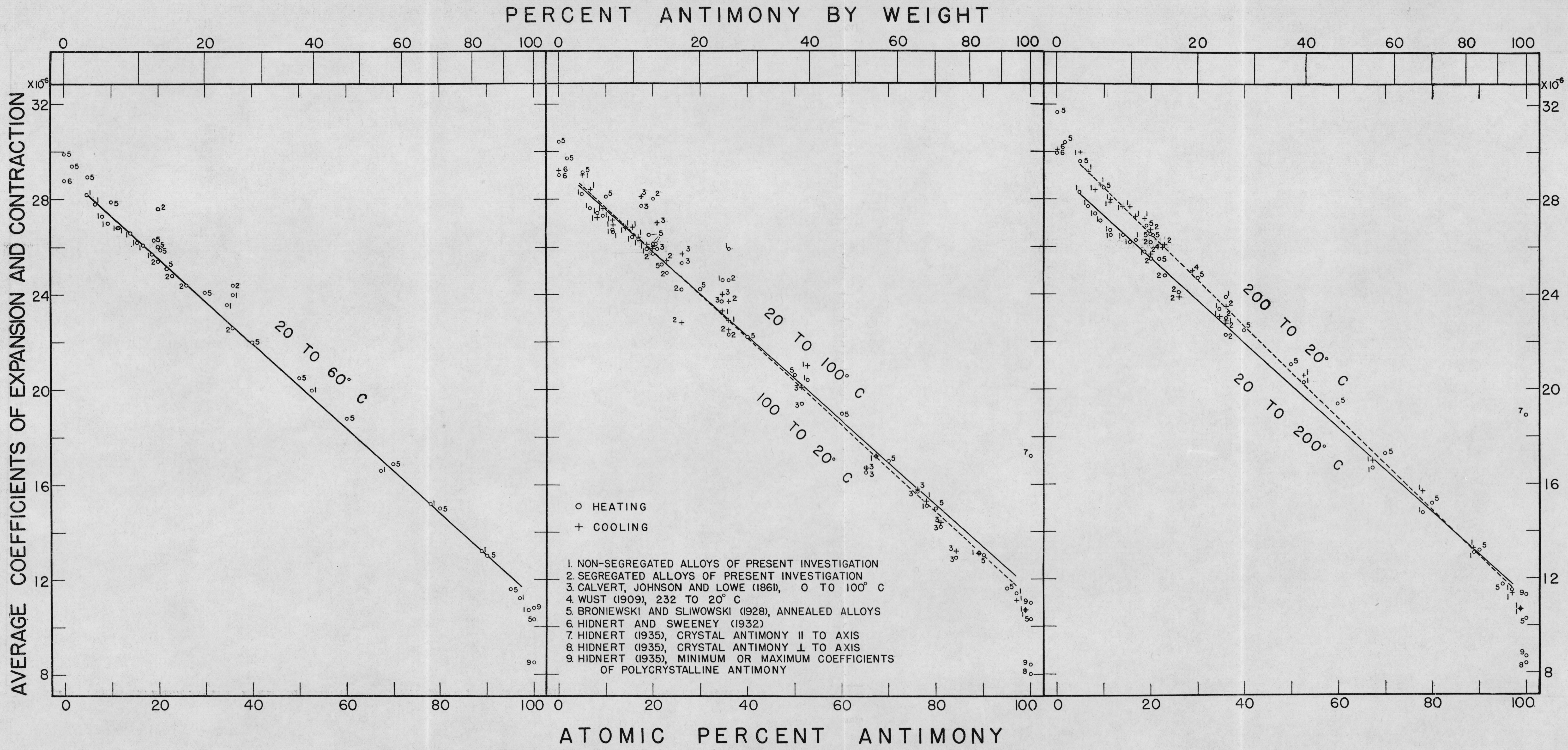

FIGURE 6.—*Relations between coefficients of expansion, coefficients of contraction, and antimony contents of lead-antimony alloys.*

The straight lines represent equations 1 to 5 derived from data obtained in the present investigation on nonsegregated alloys.

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TABLE 3.—*Average coefficients of linear expansion of cast lead-antimony alloys*

Sample	Chemical composition, by weight		Antimony content in atomic percentage	Average coefficients [a] of expansion per degree centigrade					Average coefficients [a] of contraction per degree centigrade			Change in length after heating and cooling [b]	Density [a] at 25° C
	Lead	Antimony		20 to 60° C	60 to 100° C	100 to 200° C	20 to 100° C	20 to 200° C	200 to 100° C	100 to 20° C	200 to 20° C		
	Percent	*Percent*		$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	*Percent*	g/cm³
996 [c]	96.9	2.9	4.8	28.2	28.2	28.3	28.2	28.3	30.7	29.0	30.0	−0.031	10.979
995	95.9	4.0	6.6	27.8	27.4	27.7	27.6	27.7	29.9	28.4	29.2	−.029	10.975
994	94.9	4.9	8.1	27.3	27.6	27.4	27.4	27.4	29.4	27.2	28.4	−.019	10.948
993	94.1	5.7	9.3	27.0	27.6	27.0	27.3	27.1	29.3	27.6	28.6	−.027	10.880
992 [d]	92.8	7.0	11.4	26.8	26.6	26.8	26.7	26.7	28.6	27.1	27.9	−.023	10.798
991	92.7	7.1	11.5	26.8	26.4	26.5	26.6	26.5	28.9	26.9	28.0	−.021	10.766
990	91.0	8.8	14.1	26.6	27.0	26.2	26.8	26.5	28.4	26.8	27.7	−.024	10.676
989	90.0	9.8	15.6	26.2	26.6	26.0	26.4	26.2	28.4	26.8	27.7	−.028	10.598
997	89.1	10.7	16.9	26.1	26.6	26.3	26.3	26.3	27.9	26.4	27.3	−.017	10.478
998	87.9	11.9	18.7	25.7	26.2	25.7	25.9	25.8	28.1	26.1	27.2	−.027	10.458
999	87(?)	13(?)	20(?)	(25.4)	(26.0)	(25.3)	(25.7)	(25.5)	(27.3)	(26.0)	(26.7)	−.022	(10.415)
1452	87(?)	13(?)	20(?)	(27.6)	(28.4)	(24.8)	(28.0)	(26.2)	(25.5)	(25.9)	(25.7)	+.006	(10.381)
1000 [e]	85(?)	15(?)	23(?)	(24.8)	(25.0)	(24.7)	(24.9)	(24.8)	(26.8)	(25.4)	(26.1)	−.025	(10.269)
1145	83(?)	17(?)	26(?)	(24.4)	(24.0)	(24.0)	(24.2)	(24.1)	(24.8)	(22.8)	(23.9)	+.002	(10.138)
1453A	76.2	23.8	34.7	23.6	25.6	22.4	24.6	23.4	23.0	23.3	23.1	+.006	9.626
1453	75.2	24.8	36.0	24.0	27.9	22.3	25.9	23.9	22.8	22.9	22.9	+.019	9.676
1062	75(?)	25(?)	36(?)	(24.4)	(24.7)	(21.7)	(24.6)	(23.0)	(23.1)	(22.5)	(22.8)	+.003	(9.598)
1146 [f]	75(?)	25(?)	36(?)	(22.6)	(22.1)	(22.4)	(22.3)	(22.3)	(23.4)	(23.7)	(23.5)	−.021	(9.683)
				(22.8)	(23.2)	(22.9)	(23.0)	(22.9)	(23.9)	(22.9)	(23.4)	−.010	
1063	60.4	39.6	52.7	20.0	20.7	20.2	20.4	20.3	20.4	21.0	20.6	−.007	8.833
1064	45.2	54.7	67.3	16.6	17.8	16.3	17.2	16.7	16.8	17.2	17.0	−.005	8.190
1065 [f]	32.3	67.6	78.0	15.2	15.0	14.5	15.1	14.8	16.1	15.3	15.7	−.017	7.649
				15.0	15.4	15.5	15.2	15.4	16.0	15.1	15.6	−.002	
1066	17.4	82.5	88.9	13.2	13.1	13.1	13.1	13.1	13.6	13.1	13.3	−.004	7.124
1147	5.0	95.0	97.0	11.2	11.6	11.5	11.4	11.5	11.7	11.1	11.4	+.001	6.702
1148	2.0	98.0	98.8	10.7	10.7	10.8	10.7	10.7	10.8	10.7	10.7	.000	6.682

[a] Values in parentheses represent coefficients of expansion and contraction, or densities obtained on segregated alloys.
[b] The plus (+) sign indicates an increase in length and the minus (−) sign a decrease in length.
[c] Coefficient of expansion between −12 and +20° C, 28.0×10^{-6}.
[d] Coefficient of expansion between −12 and +20° C, 26.3×10^{-6}.
[e] Coefficient of expansion between −12 and +20° C, 24.5×10^{-6}.
[f] Coefficients given on the second line were obtained on the second heating and cooling.

The following equations for the temperature ranges from 20 to 100°, 20 to 200°, 100 to 20°, and from 200 to 20° C, were similarly derived by the method of least squares:

$$_{20}a_{100}=(29.31-0.1773\text{Sb})10^{-6} \quad (2)$$

$$_{20}a_{200}=(29.08-0.1786\text{Sb})10^{-6} \quad (3)$$

$$_{100}a_{20}=(29.44-0.1826\text{Sb})10^{-6} \quad (4)$$

$$_{200}a_{20}=(30.41-0.1941\text{Sb})10^{-6} \quad (5)$$

In these equations Sb represents the atomic percentage of antimony between the limits of 4.8 and 97.0 atomic percent. In equations 2 and 3, $_{20}a_{100}$ and $_{20}a_{200}$ represent the average coefficients of expansion between 20 and 100°, and between 20 and 200° C, respectively. In equations 4 and 5, $_{100}a_{20}$ and $_{200}a_{20}$ represent the average coefficients of contraction between 100 and 20°, and between 200 and 20° C, respectively. The probable errors of $_{20}a_{100}$, $_{20}a_{200}$, $_{100}a_{20}$, and $_{200}a_{20}$ are $\pm0.6\times10^{-6}$, $\pm0.3\times10^{-6}$, $\pm0.3\times10^{-6}$ and $\pm0.2\times10^{-6}$, respectively.

Figure 6 shows the relations between the coefficients of expansion and the antimony contents of cast lead-antimony alloys. Values for lead [3] and for monocrystalline and polycrystalline antimony [4] are included in the figure. Equations 1, 2, and 3 are represented in figure 6 by solid lines, and equations 4 and 5 by dashed or broken lines. Values obtained from previous investigators are included in this figure for comparison. Broniewski and Sliwowski's [10] values for lead and the lead-rich lead-antimony alloys appear to be too high. Their coefficients of expansion for lead are appreciably higher than nearly all of the results reported by other investigators.

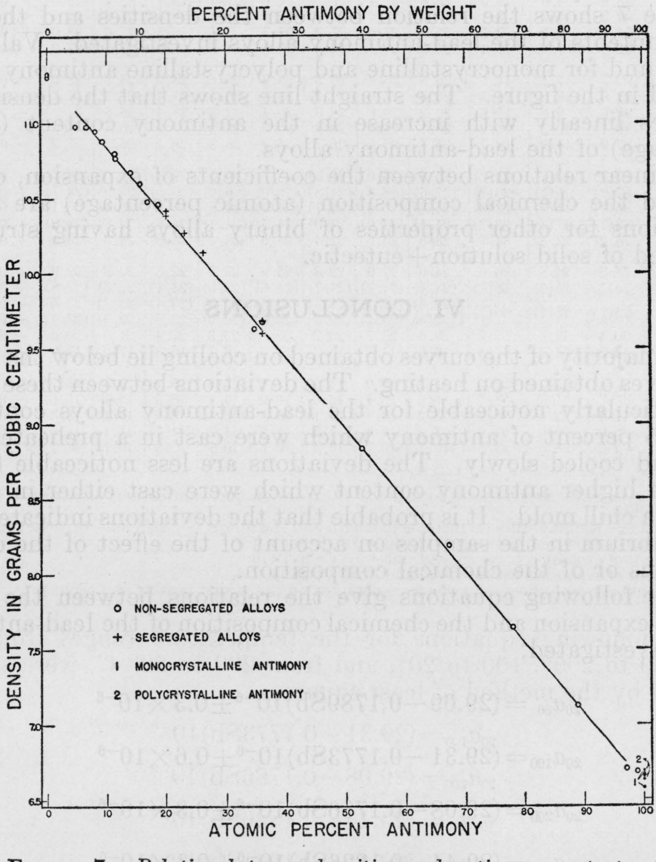

FIGURE 7.—*Relation between densities and antimony contents of lead-antimony alloys.*

Equations 1 to 5 and the straight lines in figure 6 show that the coefficients of expansion of the lead-antimony alloys decrease linearly with increase in the antimony content from about 5 to 97 atomic percent (3 to 95 percent, by weight). These alloys, which lie between the solid solutions at the lead end and the antimony end of the equilibrium diagram, consist of an excess of one or the other solid solution.

Some deviations from these linear relations were anticipated at both ends of the equilibrium diagram. At the lead end the deviations are slight for the ranges from 20 to 60° C and from 20 to 100° C, but the deviation is 0.9×10^{-6} for the range from 20 to 200° C. The deviations are more evident near the antimony end of the diagram for the antimony-richest alloy and for pure antimony.

The coefficients of expansion of the lead-antimony alloys cover a wide range of values. It is possible to select lead-antimony alloys that have approximately the same coefficients of expansion as iron, nickel, gold, copper, silver, aluminum, magnesium, and many of their alloys, at temperatures below 200° C.

Figure 7 shows the relation between the densities and the antimony contents of the lead-antimony alloys investigated. Values for lead [3] and for monocrystalline and polycrystalline antimony [4] are included in the figure. The straight line shows that the density also decreases linearly with increase in the antimony content (atomic percentage) of the lead-antimony alloys.

The linear relations between the coefficients of expansion, or density, and the chemical composition (atomic percentage) are typical of relations for other properties of binary alloys having structures composed of solid solution+eutectic.

VI. CONCLUSIONS

1. A majority of the curves obtained on cooling lie below the expansion curves obtained on heating. The deviations between these curves are particularly noticeable for the lead-antimony alloys containing up to 15 percent of antimony which were cast in a preheated steel mold and cooled slowly. The deviations are less noticeable for the alloys of higher antimony content which were cast either in a sand mold or a chill mold. It is probable that the deviations indicate a lack of equilibrium in the samples on account of the effect of the casting conditions or of the chemical composition.

2. The following equations give the relations between the coefficients of expansion and the chemical composition of the lead-antimony alloys investigated.

$$ {}_{20}a_{60} = (29.09-0.1789\text{Sb})10^{-6} \pm 0.3\times 10^{-6} \tag{1}$$

$$ {}_{20}a_{100} = (29.31-0.1773\text{Sb})10^{-6} \pm 0.6\times 10^{-6} \tag{2}$$

$$ {}_{20}a_{200} = (29.08-0.1786\text{Sb})10^{-6} \pm 0.3\times 10^{-6} \tag{3}$$

$$ {}_{100}a_{20} = (29.44-0.1826\text{Sb})10^{-6} \pm 0.3\times 10^{-6} \tag{4}$$

$$ {}_{200}a_{20} = (30.41-0.1941\text{Sb})10^{-6} \pm 0.2\times 10^{-6} \tag{5}$$

In these equations Sb represents the atomic percentage of antimony between 4.8 and 97.0 atomic percent (2.9 to 95.0 percent of antimony by weight). In equations 1, 2, and 3, ${}_{20}a_{60}$, ${}_{20}a_{100}$, and ${}_{20}a_{200}$ represent the average coefficients of expansion between 20 and 60°, 20 and 100°, and between 20 and 200° C, respectively. In equations 4 and 5, ${}_{100}a_{20}$ and ${}_{200}a_{20}$ represent the average coefficients of contraction between 100 and 20°, and between 200 and 20° C, respectively.

The last term in each equation indicates the probable error of the coefficient of expansion. These equations show that the coefficients of expansion decrease linearly with increase in the atomic percentage of antimony.

3. The densities of the lead-antimony alloys also decrease linearly with increase in the atomic percentage of antimony.

4. The linear relations between the coefficients of expansion, or density, and the chemical composition (atomic percentage) are typical of relations for other properties of binary alloys having structures composed of solid solution+eutectic.

5. The coefficients of expansion of the lead-antimony alloys cover a wide range of values. It is possible to select lead-antimony alloys that have approximately the same coefficients of expansion as iron, nickel, gold, copper, silver, aluminum, magnesium, and many of their alloys.

VII. REFERENCES

The numbers in brackets are the citation numbers given throughout this paper for the references herein.

[1] Data by Hidnert and Sweeney obtained in 1923 on the linear thermal expansion of one sample of cast lead and various cast lead-antimony alloys between 20 and 60° C were published in 1924 by Vinal, Storage Batteries (John Wiley & Sons, Inc., New York, N. Y.).
[2] Hidnert and Sweeney, Phys. Rev. **10**, 296 (1930).
[3] Hidnert and Sweeney, BS J. Research **9**, 703 (1932) RP500.
[4] Hidnert, J. Research NBS **14**, 523 (1935) RP784.
[5] Goodrich, Trans. Faraday Soc. **25**, 531 (1929).
[6] Daniell, Phil. Mag. [3] **1**, p. 197, 261 (1832).
[7] Calvert, Johnson, and Lowe, Chem. News, **3**, p. 315, 357, 371 (1861).
[8] Vicentini and Omodei, Rendiconti della R. Accad. dei Lincei **4**, 1° Sem., p. 718; 2° Sem., p. 19 (1888).
[9] Wüst, Metallurgie, **6**, 769 (1909).
[10] Broniewski and Sliwowski, Rev. Mét. **25**, 397 (1928).
[11] Plüss, Z. anorg. allgem. Chem. **93**, 1 (1915).
[12] Ewen and Turner, J. Inst. Metals **4**, 128 (1910).
[13] Gontermann, Z. anorg. Chem. **55**, 419 (1907).
[14] Dean, Hudson, and Fogler, J. Ind. Eng. Chem. **17**, 1246 (1925).
[15] Schumacher and Nix, Proc. Inst. Metals Div., Am. Inst. Min. Met. Eng., p 195 (1927).
[16] Schumacher and Bouton, J. Am. Chem. Soc. **49**, 1667 (1927).
[17] Endo, Sci. Rep. Tohôku Imperial Univ., Series 1, **16** (no. 2), 201 (1927).
[18] Obinata and Schmid, Metallwirtschaft **12**, 101 (1933).
[19] Hidnert, Sci. Pap. BS **17**, 91 (1922) S410.
[20] Souder and Hidnert, Sci. Pap. BS **21**, 1 (1926) S524.

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