RP 29

THERMAL EXPANSION OF MAGNESIUM AND SOME OF ITS ALLOYS

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ABSTRACT

This paper gives data on the linear thermal expansion of 6 samples of cast and extruded magnesium and 11 samples of cast and extruded magnesium alloys (magnesium-aluminum and magnesium-aluminum-manganese alloys). The samples of magnesium were investigated over various temperature ranges between −183° and +500° C. and most of the alloys between room temperature and 300° C.

Three types of apparatus were used in this research, and a summary of available data by previous observers on the thermal expansion of magnesium and some magnesium alloys is given.

The following average equation represents the expansion of magnesium between 20° and 500° C.:

$$L_t = L_o\ [1 + (24.80\ t + 0.00961\ t^2)\ 10^{-6}]$$

The coefficients of expansion of extruded magnesium and the alloys investigated are slightly less than those for the cast materials. A comparison of the average expansion curve obtained in the present investigation on magnesium, with data from previous observers, is shown graphically.

The relations between the chemical composition and the coefficients of expansion of the magnesium alloys are shown in a figure. The addition of 0 to 10 per cent aluminum to magnesium causes practically no change in the coefficients of expansion. Small additions of manganese (0.9 and 0.3 per cent) to magnesium and magnesium-aluminum alloys cause slight changes in the coefficients of expansion.

The table in the summary gives a comparison of the average coefficients of expansion of the materials investigated.

CONTENTS

I. INTRODUCTION

This paper gives the results of an investigation on the linear thermal expansion of pure magnesium, magnesium-aluminum alloys, and magnesium-aluminum-manganese alloys. Magnesium, the lightest structurally used metal, and its alloys are coming into greater prominence for materials of construction where low density and strength are important factors; for example, in aircraft manufacture and for moving parts of gasoline engines.

The earliest available observations on the thermal expansion of magnesium were those by Fizeau in 1869. However, up to the present time no data on the expansion of the alloys mentioned were available.

In the present investigation expansion determinations were made between −183° and +500° C. Six samples of cast and extruded magnesium were examined over various temperature ranges between −183° and +500° C. and 11 specimens of cast and extruded magnesium alloys between room temperature and 400° C. The maximum aluminum content of the magnesium-aluminum alloys is 10.4 per cent, and the maximum aluminum content and maximum manganese content of the magnesium-aluminum-manganese alloys are 4.1 and 0.9 per cent, respectively.

The authors wish to express their appreciation for the cooperation by the American Magnesium Corporation, Niagara Falls, N. Y., and Aluminum Co. of America, New Kensington, Pa. The former furnished the samples of magnesium and magnesium alloys and information about the preparation, and the latter company analyzed the samples used in the investigation. Acknowledgment is due to H. W. Bearce, Wilmer Souder, and H. W. Gillett, of the Bureau of Standards, and J. D. Edwards, of the Aluminum Co. of America, for valuable suggestions.

II. PREVIOUS DETERMINATIONS

The results obtained by previous observers on the thermal expansion of magnesium and some magnesium alloys are summarized in Table 1. In this table, a_t represents the instantaneous coefficient or rate of expansion at $t°$ C., L_t represents the length at $t°$ C., and L_0 the length at 0° C. For additional information the reader should refer to the original papers.

TABLE 1.—*Summary of expansion data on magnesium and magnesium alloys by previous observers*

Observer	Date	Material	Temperature or temperature range	Coefficient of linear expansion per °C.	Expansion equation	Remarks
			° *C.*	$\times 10^{-6}$		
Fizeau [1]	1869	Magnesium	40	26.94		
			0 to 100	27.62		
Voigt [2]	1893	do	15.4	25.15	$a_t=[26.05+0.064(t-30)]10^{-6}$ between 15° and 40° C.	
			16.5	25.16		
			32.3	26.26		
			33.0	26.15		
			40.0	26.73		
Stadthagen [4]	1901	Magnalium [5]	12 to 39	23.8		Aluminum-base alloy with about 13 per cent magnesium. (The average coefficient of expansion of pure aluminum [3] is 23.1×10^{-6} for the same temperature range.)
Grüneisen [6]	1910	Magnesium [7]	−183 to 15	21.40		The expansion was determined by comparison with the expansion of platinum. The accuracy is approximately 1 per cent. For two temperature ranges Grüneisen [8] showed that the ratio of the average coefficient of expansion and the average specific heat is approximately constant.
			+17 to 100	26.07		
			19 to 100	26.09		
Hidnert [9]	1919	Magnesium [10] (cast)	−40	24.3	$L_t=L_0[1+(25.03t+0.00892t^2)10^{-6}]$ between −63° and +300° C.	The probable error of L_t is $\pm 0.000007\ L_0$. The observations on cooling lie below the expansion curve on heating. At the end of the test the specimen was 0.01 per cent shorter than at the beginning.
			−20	24.7		
			0	25.0		
			+20	25.4		
			40	25.7		
			60	26.1		
			80	26.5		
			100	26.8		
			120	27.2		
			140	27.5		
			160	27.9		
			180	28.2		
			200	28.6		
			220	29.0		
			240	29.3		
			260	29.7		
			280	30.0		
Souder and Hidnert [11]	1919	Dow metal [12]	20 to 400	27.0		
Hodgman [13]	1920	Magnesium (cast)	20 to 100	26.86		
		Magnesium (wrought)	20 to 100	26.73		

Footnotes at end of table.

TABLE 1.—*Summary of expansion data on magnesium and magnesium alloys by previous observers*—Continued

Observer	Date	Material	Temperature or temperature range	Coefficient of linear expansion per °C.	Expansion equation	Remarks
			° *C.*	$\times 10^{-6}$		
Disch [14]	1921	Magnesium [15]	20 to 100	[16] 25.9	$L_t = L_o[1+(25.07t+0.00936t^2)10^{-6}]$ between 20° and 500° C.	The expansion equation was derived by Scheel from the data by Disch and Schulze.
			20 to 200	[16] 27.1		
			20 to 300	[16] 28.2		
			20 to 400	[16] 29.0		
			20 to 500	[16] 29.9		
Schulze [14]	1921	do.[17]	20 to 100	[16] 25.6		
			20 to 200	[16] 26.9		
			20 to 300	[16] 28.3		
			20 to 400	[16] 29.0		
			20 to 500	[16] 30.0		
Disch [18]	1921	Electron [19] metal	0 to 100	[16] 28.4	$L_t = L_o[1+(28.24t+0.00165t^2)10^{-6}]$ between 0° and 300° C.	
			0 to 200	[16] 28.6		
			0 to 300	[16] 28.7		
Jubitz [20]	1926					For the range from 20° to 40° C. the expansion of worked magnesium (drawn from 10 to 5.5 mm. diameter at 200° C.) is slightly less than the expansion of cast magnesium.
Portevin and Le Chatelier.[21]	1926	Magnesium alloys [22]				The thermal expansion of magnesium alloys is nearly equal to that for pure magnesium. It is increased by the addition of zinc and lead and decreased by copper, nickel, and especially silicon. The expansion of magnesium is also decreased by the addition of aluminum, if the aluminum content is less than the limit of the solid solution. No quantitative data on expansion were given.

1 Fizeau, Comp. Rend., **68**, p. 1125; 1869; or Pogg. Ann. d. Physik u. Chem., **18** (138), p. 26; 1869.

2 Voigt, Wiedemann Annalen der Physik und Chemie, **49**, p. 697; 1893.

3 Hidnert, B. S. Sci. Paper No. 497 (**19**, p. 697; 1925).

4 Stadthagen, Deutsche Mech.-Ztg., p. 21; 1901.

5 Al 85.89, Mg 12.71, Si 0.71, Fe 0.46, Cu 0.08 per cent. Density 2.538.

6 Grüneisen, Annalen der Physik, **33**, p. 33; 1910.

7 From C. A. F. Kahlbaum (in Germany).

8 Grüneisen, Annalen der Physik, **33**, p. 65; 1910.

9 Hidnert, Thesis, George Washington University; 1919.

10 Mg 99.89, Cu 0.03, Fe 0.08. Chlorides trace, Si, C, Pb, Sn, Zn, Ca, K not detected; other elements present in not more than traces. The density of the sample before the investigation was 1.737 g/cm³ at 20° C.

11 Unpublished data obtained at the Bureau of Standards in 1919.

12 Magnesium alloy from Dow Chemical Co., Midland, Mich. The company states that this sample had a calculated composition of approximately 8.5 per cent aluminum, with the balance magnesium.

13 Hodgman, Physical Review, **15**, p. 218; 1920.

14 Scheel, Zeitschrift für Physik, **5**, p. 167; 1921.

15 Temperature coefficient of electrical resistance at 20° C., 3.8 to 3.9×10^{-3}.

16 Computed from data given by observer.

17 Same material as used by Disch.

18 Disch, Zeitschrift für Physik, **5**, p. 173; 1921.

19 From Chemischen Fabrik Griesheim-Elektron, Frankfurt a. M., Germany. Disch states that electron is an aluminum-magnesium alloy. For additional information consult B. S. Circular No. 346, p. 302.

20 Jubitz, Zeitschrift für Technische Physik, **7**, p. 522; 1926.

21 Portevin and Le Chatelier, Comptes Rendus, **182**, p. 382; 1926.

22 Determinations were made on samples in the drawn and annealed state. The maximum contents of the metals added to magnesium were as follows: Al 7, Cd 6, Cu 13, Mn 4, Ni 15, Pb 5, Si 1.5, and Zn 5 per cent.

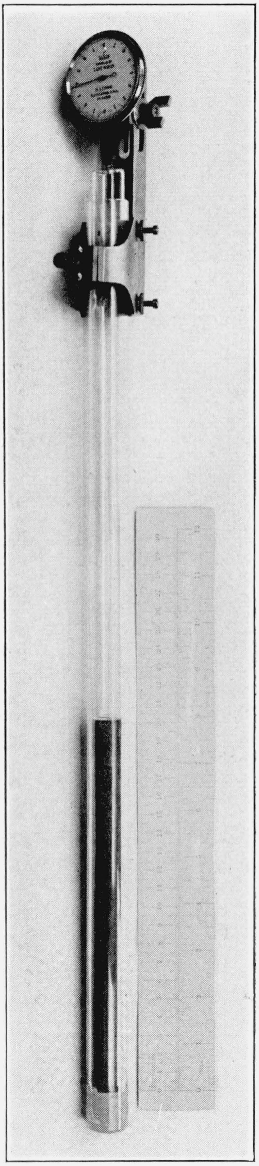

FIG. 1.—*Fused quartz tube expansion apparatus*

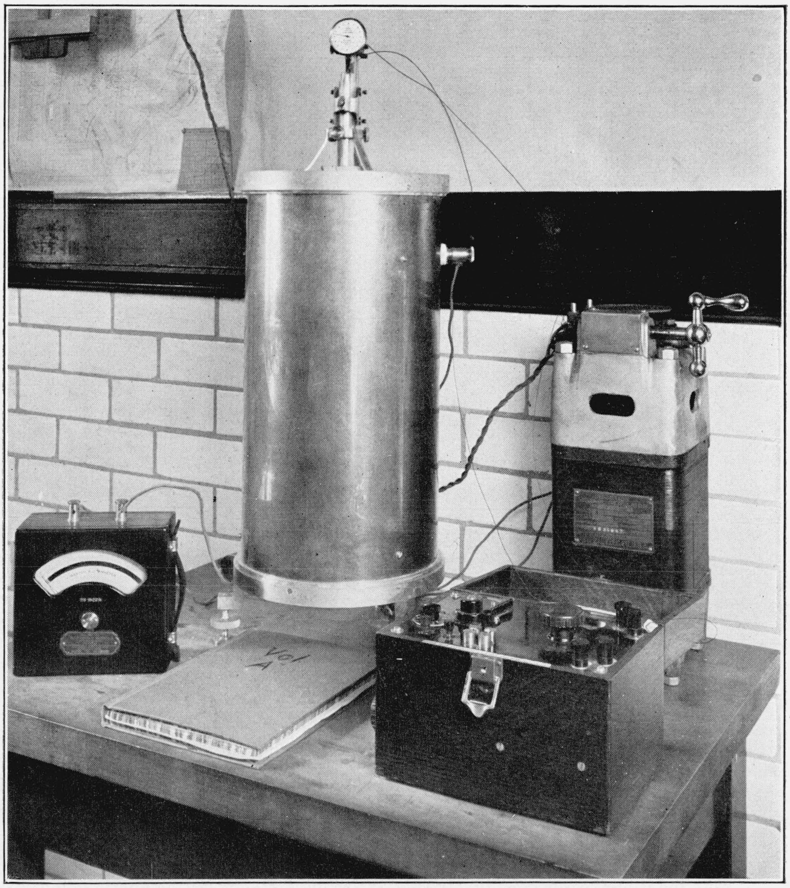

FIG. 2.—*Fused quartz tube expansion apparatus and auxiliary equipment*

III. MATERIALS INVESTIGATED

The samples investigated are classified into three groups, as given in Table 2. This table also gives the chemical composition of the samples of magnesium and magnesium alloys.

The pure magnesium and the magnesium content of the alloys were of exceptional purity. The magnesium was made by the electrolysis of magnesium oxide dissolved in a fused fluoride bath and was subsequently purified by the sublimation process developed by H. E. Bakken, United States Patent 1594344, August 3, 1926.

TABLE 2.—*Chemical composition of magnesium and magnesium alloys*

Material	Sample	Chemical analyses [1]						Treatment
		Magnesium [2]	Aluminum	Manganese	Silicon	Iron	Copper	
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
Magnesium	1268A	99.996	(3)	(3)	0.002	<0.001	<0.001	Extruded at 410° C.
	1269, 1269 I, 1269A [4]	99.99	0.00	0.00	.000	.005	.002	Cast in vacuum furnace at 665° C.
	1270, 1270A [5]	99.97	.02	.00	.004	.007	.002	Extruded at 425° C.
Magnesium-aluminum alloys.	1271	95.61	4.36	.00	.004	.018	.007	Extruded at 350° C.
	1272	95.52	4.44	.00	.018	.020	.006	Cast in vacuum furnace at 680° C.
	1273	93.70	6.26	.00	.008	.026	.008	Extruded at 330° C.
	1274	93.73	6.22	.00	.018	.024	.009	Cast in vacuum furnace at 680° C.
	1275	89.58	10.35	.00	.016	.040	.016	Extruded at 330° C.
	1276	89.75	10.19	.00	.014	.034	.008	Cast in vacuum furnace at 680° C.
	1277	90.14	9.75	.00	.068	.033	.012	Extruded at 330° C., held at 425° C. for 8 hours, quenched, and then aged at 175° C. for 72 hours.
	1277A	89.84	10.04	.00	.076	.033	.010	
Magnesium-aluminum-manganese alloys.	1278	95.58	4.10	.27	.014	.025	.011	Extruded at 390° C.
	1279	95.53	4.14	.27	.018	.029	.009	Cast in vacuum furnace at 690° C.
	1280	99.05	.01	.91	.004	.020	.003	Cast at 670° C.

1 The analysis on sample 1268A was made by J. P. Hancock, of this bureau, and the analyses on the other samples were made by the technical direction bureau, Aluminum Co. of America.
2 Per cent magnesium determined by difference.
3 Not detected.
4 Duplicate of sample 1269.
5 Duplicate of sample 1270.

IV. APPARATUS

Three types of equipment were used in this research, namely: (*a*) Precision comparator;[1] (*b*) interferometer;[2] (*c*) fused-quartz tube.

Types (*a*) and (*b*) are described in previous bureau publications. A short description of (*c*) follows:

A fused-quartz-tube apparatus was used in some determinations of the expansion of magnesium between −183° and +20° C. The authors have improved this type of apparatus from a similar type

1 Souder and Hidnert, B. S. Sci. Paper No. 524 (**21**, p. 1; 1926).
2 Peters and Cragoe, B. S. Sci. Paper No. 393 (**16**, p. 449; 1920).

used abroad and recommend this type for commercial laboratories where data of the highest precision are not necessary. With this equipment, which has been used for various temperature ranges between −183° and +1,000° C., it is possible to obtain an accuracy of better than 2 per cent. A short description of the equipment appeared in Technical News Bulletin of the Bureau of Standards No. 123, page 2; 1927.

Figure 1 shows a fused-quartz tube closed at one end, with a sample (20 cm) in place ready for heating or cooling. A movable

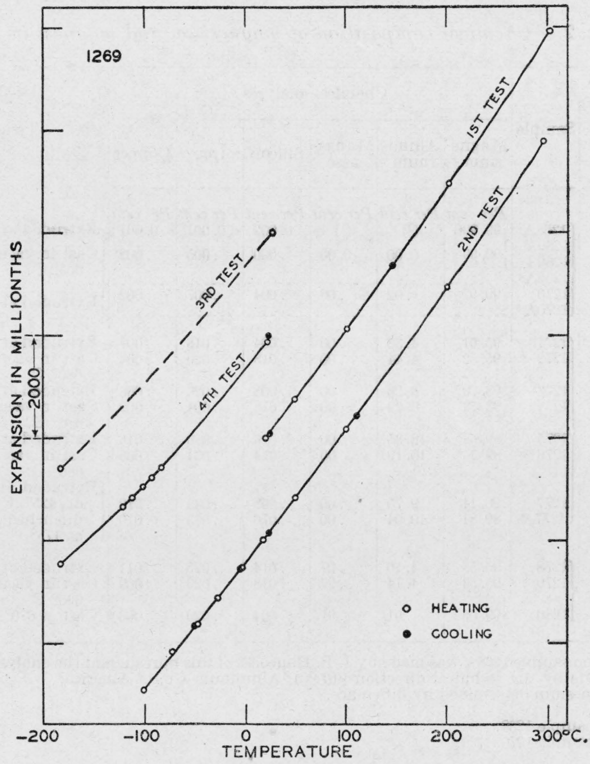

FIG. 3.—*Linear thermal expansion of cast magnesium (99.99 per cent) from −183° to +300° C.*

fused-quartz rod rests on top of the sample and extends above the open end of the tube. The bottoms of the tube and the movable rod are ground concave and the ends of the sample convex in order to secure satisfactory contacts. The top of the movable rod, on which an indicator gauge rests, is flat. Heating is effected by placing the tube containing the sample in a water or oil bath or electrical furnace (fig. 2) extending well above the top of the sample. Low temperatures are secured by using proper cooling baths. In the present investigation liquid oxygen was used. A thermocouple placed inside the fused-quartz tube near the center of the sample indicates the temperature. An indicator gauge fastened near the top of the tube registers the differential expansion between the sample and an equivalent length (20 cm) of fused quartz. A small correction for the expansion [3] of fused quartz is made.

Figures 1 and 2 show the fused-quartz-tube apparatus and auxiliary equipment.

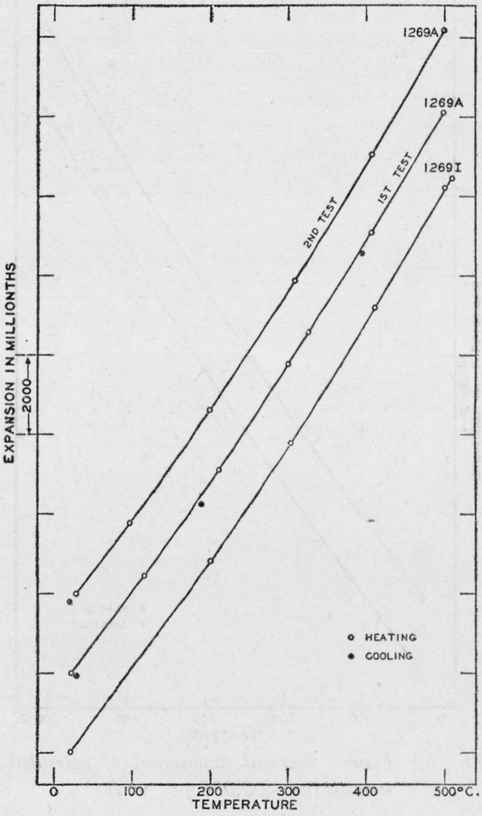

FIG. 4.—*Linear thermal expansion of cast magnesium (99.99 per cent) from 20° to 500° C.*

V. RESULTS

The results obtained on magnesium, magnesium-aluminum alloys, and magnesium-aluminum-manganese alloys are given in the following subsections. The expansion curves of all samples investigated are shown in figures. In all cases the coefficients of expansion were derived from the observations on heating.

[3] Souder and Hidnert, B. S. Sci. Paper No. 524 (**21**, p. 1; 1926).

1. MAGNESIUM

The linear thermal expansion of six samples of magnesium containing about 99.99 per cent magnesium were investigated over various temperature ranges between −183° and +500° C. Since preliminary work on small pieces of magnesium showed that this metal oxidized in air at about 550° C., the maximum temperature of the expansion tests did not exceed this temperature.

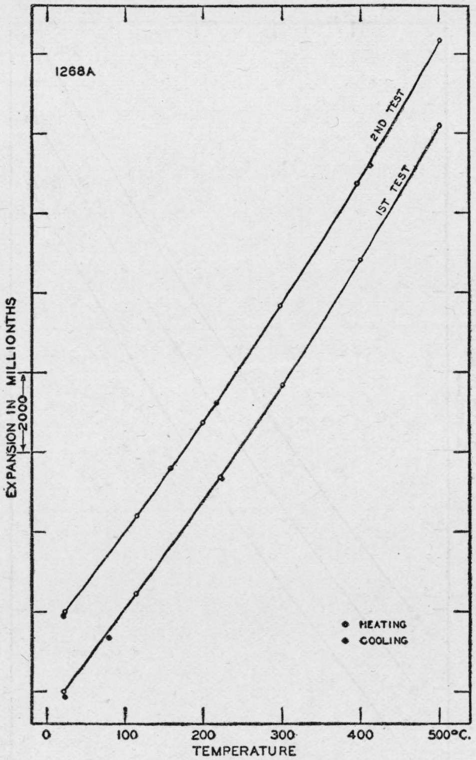

FIG. 5.—*Linear thermal expansion of extruded magnesium (99.996 per cent)*

The results obtained on cast and extruded magnesium are shown in Figures 3 to 7, inclusive. The coefficients of expansion which were derived from the expansion curves are given in Table 3. The last column in this table shows the differences in length before and after the expansion tests. The plus (+) sign indicates an increase in length and the minus (−) sign a decrease in length.

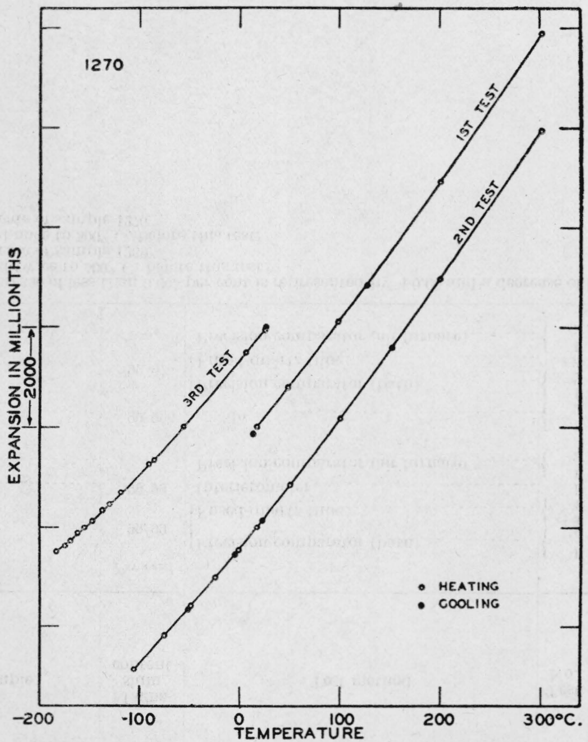

FIG. 6.—*Linear thermal expansion of extruded magnesium (99.97 per cent) from −183° to +300° C.*

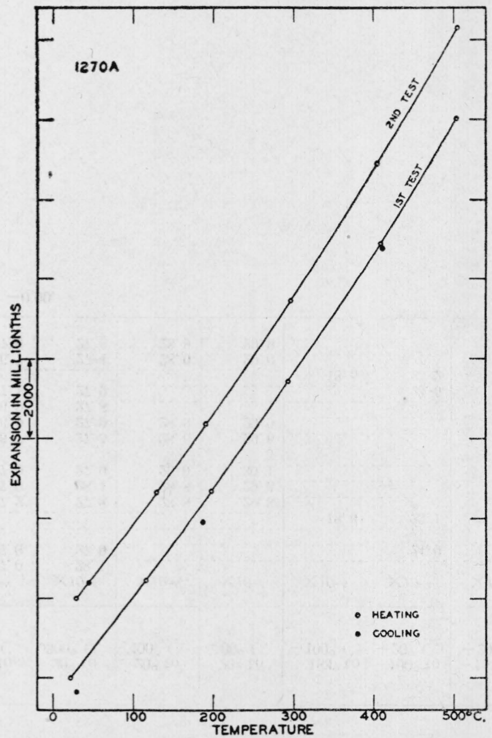

FIG. 7.—*Linear thermal expansion of extruded magnesium (99.97 per cent) from 20° to 500° C.*

TABLE 3.—*Average coefficients of expansion and length changes of magnesium*

Sample	Magnesium content	Test method	Test No.	Average coefficients of expansion per °C. 20° to 100° C.	20° to 200° C.	20° to 300° C.	20° to 400° C.	20° to 500° C.	−183° to −100° C.	−100° to +20° C.	−183° to +20° C.	Change[1] in length due to heat treatment received during test
	Per cent			$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	*Per cent*
Cast:												
1269	99.99	Precision comparator (bath)	1	26.1	27.0	28.1	----	----	----	----	----	0.00
			2	26.0	27.0	27.9	----	----	----	24.9	----	.00
		Fused-quartz tube	[2] 3	----	----	----	----	----	----	----	21.9	.00
			4	----	----	----	----	----	18.6	23.1	21.2	−.01
1269 I	99.99	Interferometer	1	----	27.2	27.8	28.8	29.8	----	----	----	----
1269A [3]	----	Precision comparator (air furnace)	1	26.6	27.0	28.1	28.8	29.6	----	----	----	−.02
			2	26.0	27.0	27.9	29.0	30.1	----	----	----	+.00
Extruded:												
1268A	99.996	do	1	26.4	26.7	27.5	28.6	29.6	----	----	----	−.01
			2	26.2	26.9	27.9	28.9	29.9	----	----	----	−.00
		Precision comparator (bath)	1	26.0	26.9	27.8	----	----	----	----	----	−.00
1270	99.97		2	26.0	27.1	27.9	----	----	----	23.5	----	.00
		Fused-quartz tube	[4] 3	----	----	----	----	----	18.5	23.2	21.3	−.00
1270A [5]	----	Precision comparator (air furnace)	1	26.3	26.7	27.4	28.0	29.0	----	----	----	−.06
			2	26.4	27.0	27.8	28.9	29.9	----	----	----	.00

[1] An increase of less than 0.005 per cent is represented by +0.00 and a decrease of less than 0.005 by −0.00.
[2] Heated twice to 500° C. before this test.
[3] Duplicate of sample 1269.
[4] Heated once to 500° C. before this test.
[5] Duplicate of sample 1270.

Table 4 gives expansion equations for samples 1269, 1269 I, 1269A, and 1268A. These equations were derived, by the method of least squares, from the observations on heating. ΔL represents the expansion or change in length from 20° C. to any temperature t between 20° and 500° C., L_t represents the length of the metal at any temperature t between 20° and 500° C., and L_o the length at 0° C.

TABLE 4.—*Expansion equations of magnesium*

Sample	Test No.	Expansion equations	Probable error of ΔL or L_t
Cast:			
1269, 1269 I, 1269A	1	$\Delta L=25.50\ (t-20)\ 10^{-6}+0.00871\ (t-20)^2\ 10^{-6}$ $L_t=L_o\ [1+(25.15\ t+0.00871\ t^2)\ 10^{-6}]$	$\times L_o$ ±0.000022
1269, 1269A	2	$\Delta L=25.15\ (t-20)\ 10^{-6}+0.01021\ (t-20)^2\ 10^{-6}$ $L_t=L_o\ [1+(24.74\ t+0.01021\ t^2)\ 10^{-6}]$	±.000007
Extruded:			
1268A	1	$\Delta L=24.85\ (t-20)\ 10^{-6}+0.00982\ (t-20)^2\ 10^{-6}$ $L_t=L_o\ [1+(24.46\ t+0.00982\ t^2)\ 10^{-6}]$	±.000025
1268A	2	$\Delta L=25.26\ (t-20)\ 10^{-6}+0.00971\ (t-20)^2\ 10^{-6}$ $L_t=L_o\ [1+(24.87\ t+0.00971\ t^2)\ 10^{-6}]$	±.000016

The following average equations may be given as the most probable second-degree equations for the expansion of cast magnesium and extruded magnesium between room temperature and 500° C.:

Cast magnesium:

$$L_t=L_o\ [1+(24.94\ t+0.00946\ t^2)\ 10^{-6}] \quad (1)$$

Extruded magnesium:

$$L_t=L_o\ [1+(24.66\ t+0.00976\ t^2)\ 10^{-6}] \quad (2)$$

Average of equations (1) and (2):

$$L_t=L_o\ [1+(24.80\ t+0.00961\ t^2)\ 10^{-6}] \quad (3)$$

The average coefficients of expansion for various temperature ranges given in Table 5 were computed from equations (1), (2), and (3).

TABLE 5.—*Average coefficients of expansion of magnesium*

Temperature range (in °C.)	Average coefficient of expansion per °C.		
	Cast magnesium	Extruded magnesium	Average
	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
20 to 100	26.1	25.8	26.0
100 to 200	27.8	27.6	27.7
200 to 300	29.7	29.5	29.6
300 to 400	31.6	31.5	31.5
400 to 500	33.5	33.4	33.4
20 to 200	27.0	26.8	26.9
20 to 300	28.0	27.8	27.9
20 to 400	28.9	28.8	28.8
20 to 500	29.9	29.7	29.8

The coefficients of expansion of extruded magnesium are slightly less than those for cast magnesium. Jubitz [4] also found that worked magnesium expands slightly less than cast magnesium. The largest variation in the coefficients given in Table 5 is 0.3×10^{-6}.

The instantaneous coefficients or rates of expansion of cast magnesium and extruded magnesium from 0° to 500° C. are shown in Figure 8. The coefficients increase with temperature. The greatest variation (0.3×10^{-6}) in the rates of expansion of the cast and extruded metal occurs at 0° C. Above this temperature the variation decreases with temperature.

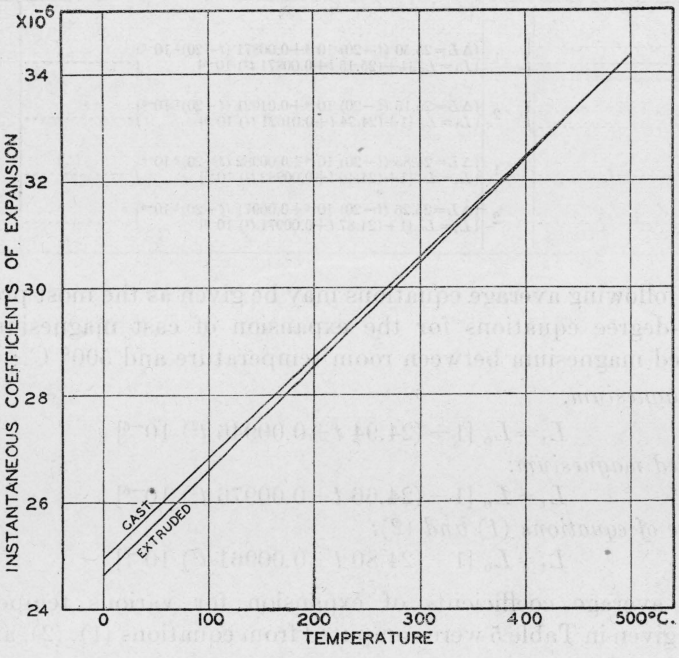

FIG. 8.—*Instantaneous coefficients of expansion of magnesium*

Figure 9 shows a comparison of the average expansion curve obtained in the present investigation on magnesium, with data from previous observers. The curve was derived from equation (3) and the data at low temperatures. The values of nearly all observers show good agreement.

2. MAGNESIUM-ALUMINUM ALLOYS

Eight samples of magnesium-aluminum alloys containing various percentages of aluminum (4 to 10 per cent) were investigated. Al samples except 1277A were investigated by the precision-comparator

[4] See Table 1, p. 773.

method (bath) from room temperature to 300° C. The interference method was used for sample 1277A from room temperature to 400° C.

Figures 10 to 13, inclusive, show the observations obtained on the magnesium-aluminum alloys. The expansion curves of all samples except 1277 and 1277A are regular. The curves for samples 1277 and 1277A which received special heat treatment,[5] show critical regions above 200° C.

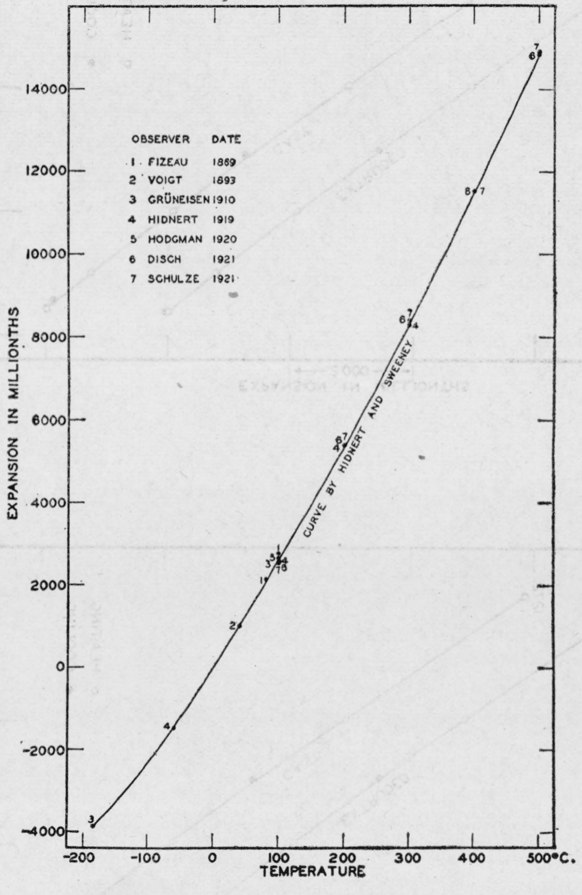

Fig. 9.—*Comparison of the average expansion curve obtained in the present investigation on magnesium with data from previous observers*

The average coefficients of expansion given in Table 6 were derived from the expansion curves of the magnesium-aluminum alloys. This table also indicates the differences in length before and after the expansion tests. The plus (+) sign signifies an increase in length and the minus (−) sign a decrease in length.

[5] Extruded at 330° C., held at 425° C. for 8 hours and quenched, and then aged at 175° C. for 72 hours.

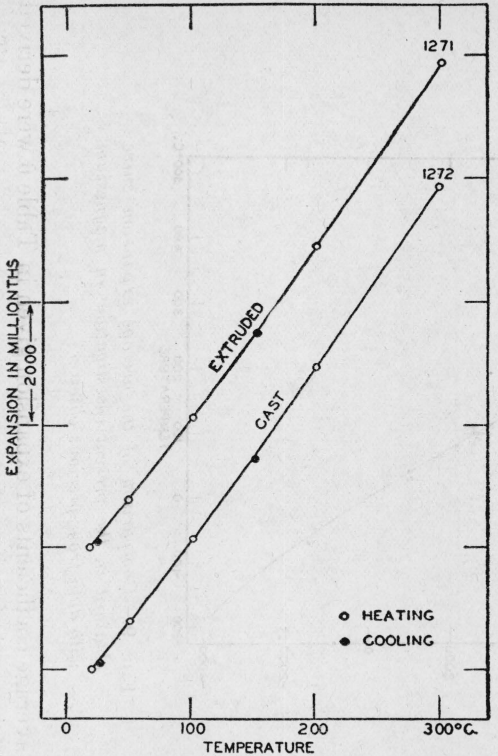

Fig. 10.—*Linear thermal expansion of magnesium-aluminum alloys (4 per cent aluminum)*

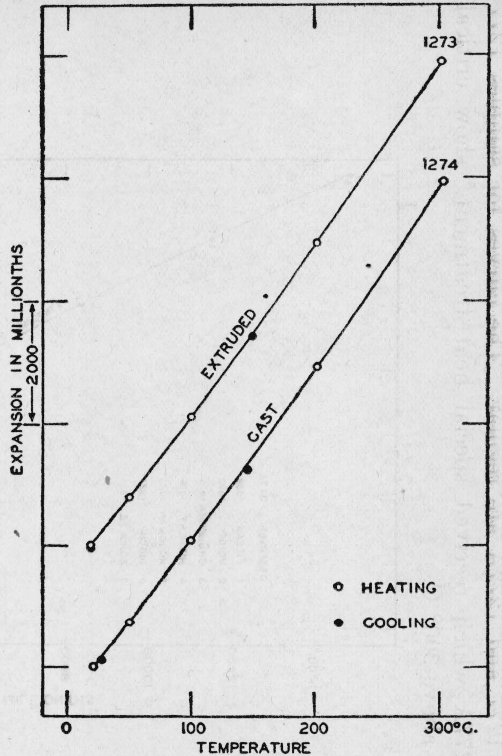

Fig. 11.—*Linear thermal expansion of magnesium-aluminum alloys (6 per cent aluminum)*

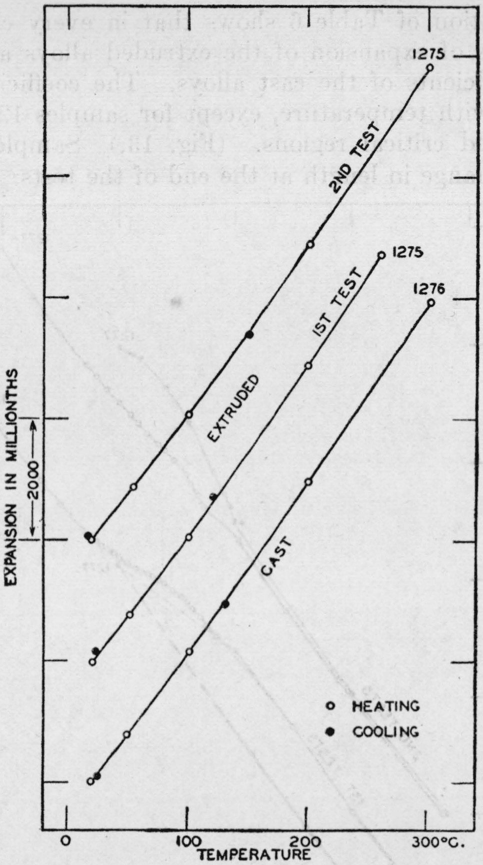

FIG. 12.—*Linear thermal expansion of magnesium-aluminum alloys (10 per cent aluminum)*

TABLE 6.—*Average coefficients of expansion and length changes of magnesium aluminum alloys*

Sample	Aluminum content	Treatment	Average coefficients of expansion per °C.						Change in length due to heat treatment received during test
			20° to 50° C.	20° to 100° C.	20° to 200° C.	20° to 300° C.	200° to 300° C.	300° to 400° C.	
	Per ct.		×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	Per ct.
1272	4.44	Cast in vacuum furnace at 680° C.	25.9	26.4	27.4	28.0	------	------	−0.01
1271	4.36	Extruded at 350° C.	25.5	25.8	26.9	27.8	------	------	−.01
1274	6.22	Cast in vacuum furnace at 680° C.	25.3	26.4	27.2	28.0	------	------	−.00
1273	6.26	Extruded at 330° C.	26.0	26.2	27.1	27.9	------	------	−.00
1277	9.75	Extruded at 330° C., held at 425° C. for 8 hours, quenched, and then aged at 175° C. for 72 hours.	25.3	25.4	26.5	------	14.4	------	−.14
			------	[1] 25.7	27.8	------	29.8	------	+.04
1277A	10.04	Same as 1277	------	26.0	26.1	------	17.0	21.7	------
			------	[1] 25.8	26.9	------	22.6	26.1	------
1276	10.19	Cast in vacuum furnace at 680° C.	25.3	26.2	27.3	28.1	------	------	−.00
1275	10.35	Extruded at 330° C.	24.9	25.9	27.2	[2] 28.3	------	------	+.01
			[1] 24.7	25.6	26.9	27.7	------	------	+.01

[1] Values on this horizontal line were obtained on a second heating. [2] From 20° to 250° C.

An examination of Table 6 shows that in every case except one the coefficients of expansion of the extruded alloys are slightly less than the coefficients of the cast alloys. The coefficients of expansion increase with temperature, except for samples 1277 and 1277A, which indicated critical regions. (Fig. 13.) Sample 1277 showed the greatest change in length at the end of the tests.

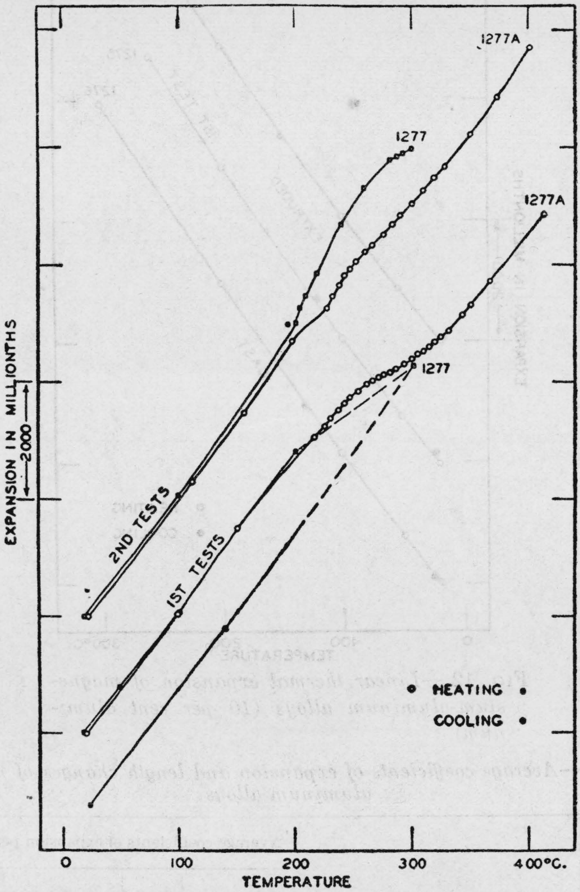

FIG. 13.—*Linear thermal expansion of magnesium-aluminum alloys (10 per cent aluminum)*

Extruded at 330° C., held at 425° C. for 8 hours, quenched and then aged at 175° C. for 72 hours

It is interesting to note that for the range from 20° to 300° C. the coefficients of expansion of these magnesium-aluminum alloys are practically the same as the coefficients of expansion of aluminum-copper alloys [6] containing from 4 to 12 per cent copper. From the point of view of expansion there is therefore no gain or loss in substituting magnesium-aluminum alloys for aluminum-copper alloys used in pistons.

[6] Hidnert, B. S. Sci. Paper No. 497 (**19**, p. 697; 1925).

Figure 14 shows the relations between the chemical composition (per cent aluminum by weight) of the magnesium-aluminum alloys and the average coefficients of expansion for three temperature ranges. The values for 0 per cent aluminum or 100 per cent magnesium were taken from the previous subsection. This figure also includes data on magnesium-aluminum-manganese alloys, which will be discussed in the following subsection. For any temperature range indicated in the figure, the coefficient of expansion is practically constant for the magnesium-aluminum alloys containing from 0 to 10 per cent aluminum. The curves show, as was noted before, that the coeffi-

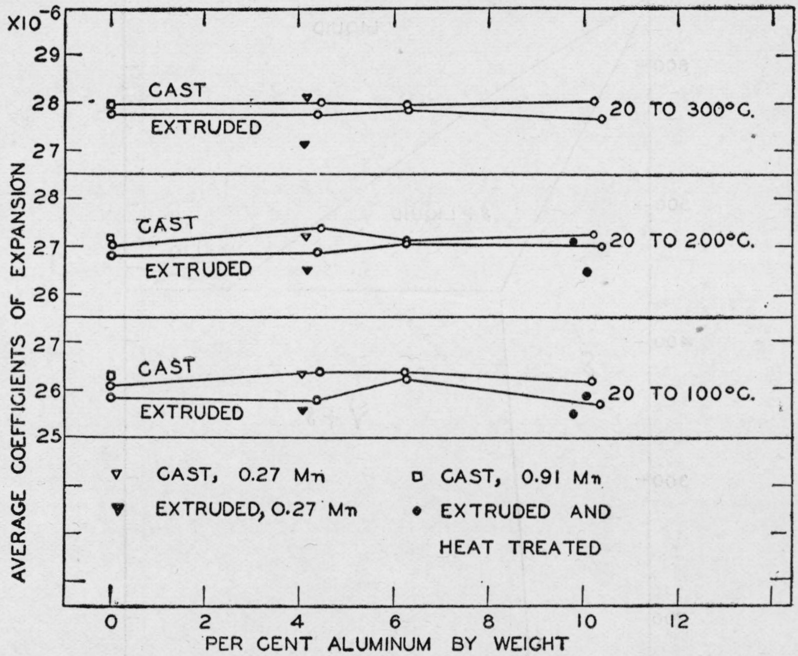

FIG. 14.—*Relations between the aluminum content and the coefficients of expansion of magnesium-aluminum alloys, and some effects of small additions of manganese to these alloys*

cients of expansion of the extruded magnesium-aluminum alloys are slightly less than the coefficients of the cast alloys.

For a comparison of the constitution of the magnesium-aluminum alloys and the coefficients of expansion the reader should refer to Figures 14 and 15. The latter figure shows a portion of the magnesium-aluminum equilibrium diagram determined by Hanson and Gayler.[7] According to the diagram, magnesium retains about 11 per cent aluminum in solid solution at 435° C. and the solubility decreases slightly as the temperature falls. Experiments [8] conducted by the Aluminum Co. of America indicate that the solubility de-

[7] Hanson and Gayler, J. Inst. of Metals (London), **24** (No. 2), p. 201; 1920.
[8] Handbook on Magnesium, American Magnesium Corporation.

creases more rapidly with falling temperature than is indicated by the diagram of Hanson and Gayler. The phase δ is a solid solution of aluminum in magnesium, and γ is the next phase produced by the addition of aluminum to δ. Opportunity for heat treatment by solution quenching and precipitation hardening exists in magesium-aluminum alloys containing about 10 per cent aluminum. (See fig. 13.) The relation between the chemical composition and the

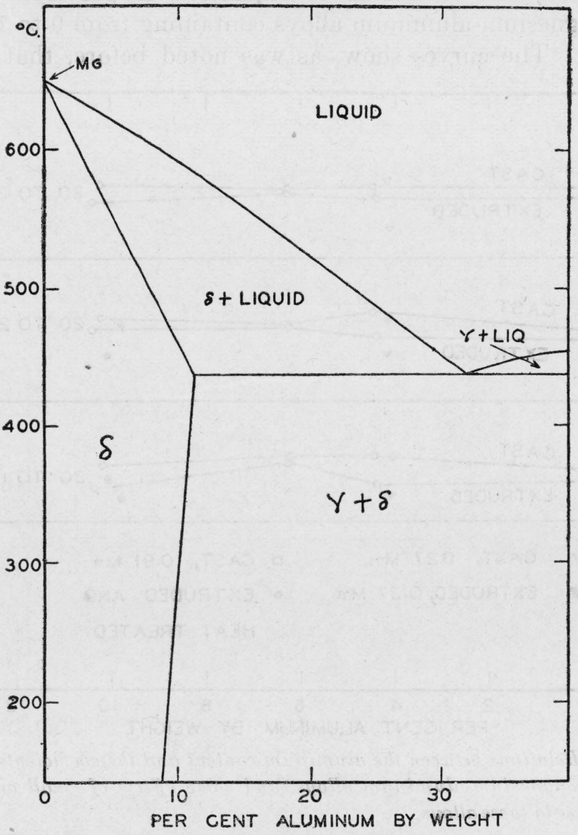

Fig. 15.—*Equilibrium diagram of magnesium-aluminum alloys (after Hanson and Gayler)*

coefficients of expansion for each temperature range shown in Figure 14 is approximately linear.

3. MAGNESIUM-ALUMINUM-MANGANESE ALLOYS

Three samples of magnesium-aluminum-manganese alloys containing less than 1 per cent manganese were investigated by the precision-comparator method (bath) from room temperature to 300° C.

Figures 16 and 17 show the observations. The expansion curves of these alloys are regular.

Table 7 gives the average coefficients of expansion which were derived from the expansion curves of the magnesium-aluminum-manganese alloys. This table also indicates the differences in length before and after the expansion tests. The minus (−) sign signifies a decrease in length.

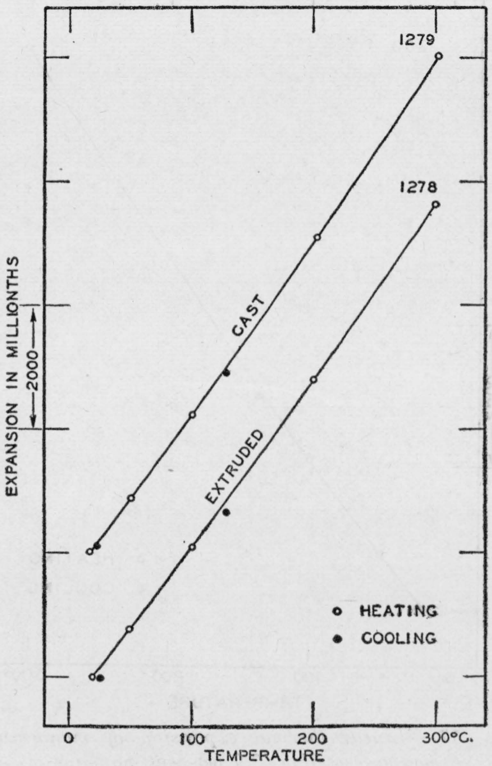

FIG. 16.—*Linear thermal expansion of magnesium-aluminum-manganese alloys (4.1 per cent aluminum and 0.3 per cent manganese)*

TABLE 7.—*Average coefficients of expansion and length changes of magnesium-aluminum-manganese alloys*

Sample	Content		Treatment	Average coefficients of expansion per °C.				Change in length due to heat treatment received during test
	Aluminum	Manganese		20° to 50° C.	20° to 100° C.	20° to 200° C.	20° to 300° C.	
	Per cent	*Per cent*		$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	*Per cent*
1279	4.14	0.27	Cast in vacuum furnace at 690° C	26.1	26.6	27.3	28.1	−0.01
1278	4.10	.27	Extruded at 390° C	24.9	25.6	26.4	27.2	−.02
1280	.01	.91	Cast at 670° C	26.0	26.3	27.2	27.9	−.01

The coefficients of expansion of the magnesium-aluminum-manganese alloys increase with temperature. The coefficients of the extruded alloy containing about 4 per cent aluminum and 0.3 per cent manganese are less than the coefficients of the corresponding cast alloy. The greatest deviation in the coefficients shown in the table is 1.2×10^{-6}.

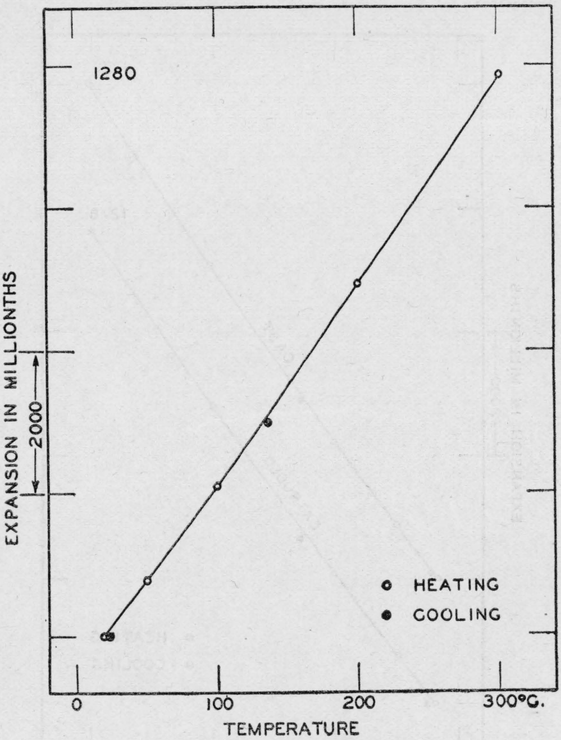

FIG. 17.—*Linear thermal expansion of magnesium-manganese alloy (0.9 per cent manganese)*

Data on the magnesium-aluminum-manganese alloys are shown in Figure 14 of the preceding subsection. The addition of 0.9 per cent manganese to magnesium caused a slight increase in the coefficients of expansion. The coefficients of the extruded ternary alloy containing about 4 per cent aluminum and 0.3 per cent manganese are less than the binary magnesium-aluminum alloys (cast and extruded) containing the same amount of aluminum.

VI. SUMMARY

This paper gives data on the linear thermal expansion of 6 samples of cast and extruded magnesium and 11 samples of cast and extruded magnesium alloys (magnesium-aluminum and magnesium-aluminum-manganese alloys). The samples of magnesium were investigated over various temperature ranges between $-183°$ and $+500°$ C. and most of the alloys between room temperature and 300° C. The previous history (preparation, treatment, chemical composition, etc.) of the specimens is included. The expansion curves of the samples are shown and discussed.

Three types of expansion apparatus were used in this research, and a summary of available data by previous observers on the thermal expansion of magnesium and some magnesium alloys is given.

The following equations are given as the most probable second-degree equations for the expansion of cast magnesium and extruded magnesium between room temperature and 500° C.

Cast magnesium:

$$L_t = L_0 \left[1 + (24.94\, t + 0.00946\, t^2)\, 10^{-6}\right] \quad (1)$$

Extruded magnesium:

$$L_t = L_0 \left[1 + (24.66\, t + 0.00976\, t^2)\, 10^{-6}\right] \quad (2)$$

Average of equations (1) and (2):

$$L_t = L_0 \left[1 + (24.80\, t + 0.00961\, t^2)\, 10^{-6}\right] \quad (3)$$

The coefficients of expansion of extruded magnesium are slightly less than those for cast magnesium. This fact also applies for the alloys investigated. Figure 9 shows a comparison of the average expansion curve (equation (3)) obtained in the present investigation on magnesium, with data from previous observers. The values of nearly all observers show good agreement.

Figure 14 shows the relations between the chemical composition of the magnesium-aluminum alloys and the average coefficients of expansion for three temperature ranges. The addition of 0 to 10 per cent aluminum to magnesium causes practically no change in the coefficients of expansion. The expansion curves of the magnesium-aluminum alloy (10 per cent aluminum) which was extruded and heat treated show critical regions above 200° C. Small additions of manganese (0.9 and 0.3 per cent) to magnesium and magnesium-aluminum alloys caused slight changes in the coefficients of expansion.

A comparison of the average coefficients of expansion of the materials investigated are given for several temperature ranges in the following table. For detailed data the reader should refer to the proper sections of the paper.

TABLE 8.—*Average coefficients of expansion of magnesium and magnesium alloys*

Material	Magnesium content	Average coefficients of expansion per °C.				
		20° to 100° C.	20° to 200° C.	20° to 300° C.	20° to 400° C.	20° to 500° C.
	Per ct.	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
Magnesium	99. 99	26. 0	26. 9	27. 9	28. 8	29. 8
Magnesium-aluminum alloys	90 to 96	25.4 to 26.4	26.1 to 27.8	27.7 to 28.1	------	------
Magnesium-aluminum-manganese alloys	96 to 99	25.6 to 26.6	26.4 to 27.3	27.2 to 28.1	------	------

WASHINGTON, July 17, 1928.