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Thermal Expansion of Aluminum and Some Aluminum Alloys

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Data are given on the linear thermal expansion of aluminum and some aluminum-beryllium, aluminum-copper, aluminum-sillcon, aluminum-copper-iron, aluminum-copper-magnesium, aluminum-copper-nickel, aluminum-silicon-copper, aluminum-silicon-magnesium, aluminum-copper-nickel-magnesium, aluminum-copper-tin-zinc, aluminum-silicon-copper-manganese, aluminum-silicon-copper-nickel, aluminum-silicon-nickel-copper-manganese, and aluminum-silicon-nickel-copper-molybdenum alloys for various temperature ranges between $-50°$ and $+400°$ C. The addition of beryllium, copper, or silicon to aluminum causes a decrease in the coefficients of expansion. Copper has a greater effect than beryllium, and silicon has the greatest effect of these three alloying elements. Ternary diagrams are shown that indicate the effects of composition on the coefficients of expansion of aluminum-copper-nickel and aluminum-silicon-copper alloys. The effects of additions of two or three elements (copper, nickel, manganese, and molybdenum) on the coefficients of expansion of aluminum-silicon alloys are indicated in a figure.

1. Introduction

Data on the linear thermal expansion of the samples of aluminum and of some aluminum alloys (binary, ternary, quaternary, etc.) listed in table 1 were obtained during the past quarter of a century.[1] These results are based on a number of independent tests and investigations, the specific purposes of which in general were not related.

It is the object of this paper to report coefficients of expansion during heating and cooling of the samples for various temperature ranges between $-50°$ and $+400°$ C and to establish correlations between the coefficients of expansion and the chemical composition of the annealed aluminum alloys.

2. Materials Investigated

The samples of aluminum and of aluminum alloys were obtained from Aluminum Company of America, Cleveland, Ohio and New Kensington, Pa., Brush Beryllium Co., Cleveland, Ohio, Bureau of Aeronautics, Navy Dept., Washington, D. C., Cooper-Wilford Beryllium Co., Philadelphia, Pa., National Advisory Committee for Aeronautics, Washington, D. C., and Naval Aircraft Factory, Philadelphia, Pa. The length of each sample used in the determinations of linear thermal expansion was 200 mm (7.9 in.) for the range from $-50°$ to $+20°$ C. and 300 mm (11.8 in.) for the range from $+20°$ to 400° C. The cross sections of the samples, their treatments, and chemical compositions are given in table 1.[2] Most of the values for chemical composition were furnished by the manufacturers or organizations that submitted the samples.

3. Apparatus

The fused-quartz tube and dial-indicator method and the precision micrometric method were used for determinations of linear thermal expansion of the samples for the ranges from $-50°$ to $+20°$ C and from $+20°$ to 400° C, respectively. These methods were described by Hidnert and Souder [3].

4. Results and Discussion

Expansion curves on heating and on cooling were plotted from the observations on the samples of aluminum and aluminum alloys at various temperatures between $-50°$ and $+400°$ C. Table 1 gives coefficients of expansion and coefficients of contraction that were computed from these curves, some of which are shown in figures 5 to 9, inclusive. The last column of the table shows, for most of the samples, the changes in length (at room temperature) that occurred as a result of the heating and cooling in the thermal-expansion tests.

Table 1, A, gives coefficients of expansion of two samples of cast aluminum and two samples of annealed aluminum. The coefficients of expansion of the samples of annealed aluminum are slightly less than the coefficients for cast aluminum.

Table 2 gives a comparison of coefficients of expansion of annealed aluminum in the present investigation, with those determined by Nix and MacNair [4] and Taylor, Willey, Smith, and Edwards [5] by the interference method. Taylor and his coworkers indicated that recrystallization and grain growth, or changes at the interfaces between specimen and the interferometer plates, such as growth of the oxide film on the aluminum, are some of the sources of error.

Table 1, B, gives coefficients of expansion of three aluminum-beryllium alloys containing 35, 40, and 71 percent of beryllium by weight (62, 67, and 88 atomic percent).

Figure 1 indicates coefficients of expansion for aluminum-beryllium alloys of the present investigation and those obtained by Hidnert and Sweeney [6] in a previous investigation, for the ranges 20° to 100° C and 20° to 300° C. The coefficients of expansion obtained in the second heating are indicated in the figure and represent values for annealed alloys. The coefficients of expansion obtained in the first heating of the cast alloy (sample 1630) containing

[1] W. T. Sweeney of the Bureau assisted the senior author during the early work.
[2] Figures in brackets indicate the literature references at the end of this paper.

TABLE 1. *Coefficients of linear expansion of aluminum and some aluminum alloys*

Sample	Chemical composition (by weight)										Treatment	Diameter or cross section of sample	Test No.[b]	Average coefficients of expansion per degree centigrade						Change in length after heating and cooling[c]
	Al[a]	Cu	Si	Mg	Ni	Fe	Mn	Be	Sn	Other elements				−50° to +20° C	20° to 100° C	20° to 200° C	20° to 250° C	20° to 300° C	20° to 400° C	
A. ALUMINUM																				
	%	%	%	%	%	%	%	%	%	%		*in.*			$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	%
821[d]											Cast in graphite mold	1/4 by 9/16	1H	----	23.8	24.8	25.3	25.8	26.7	(e)
828[d]												5/16 by 9/16	1H	----	23.7	24.7	25.2	25.7	26.7	(f)
821AN	99.952	0.019	0.014	----	--	0.015	--	--	--	----------	Annealed at 500° C for 1 hr and cooled slowly in furnace.	1/4 by 7/16	1H	----	23.5	24.6	----	25.5	----	−0.000
													1C	----	23.4	24.6	----	25.6	----	
													2H	----	23.5	24.6	----	25.5	----	−.001
													2C	----	23.7	24.6	----	25.5	----	
828AN												5/16 by 7/16	1H	----	23.3	24.4	----	25.3	----	−.002
													1C	----	23.2	24.4	----	25.4	----	
													2H	----	23.3	24.4	----	25.4	----	−.001
													2C	----	23.4	24.4	----	25.5	----	
B. ALUMINUM-BERYLLIUM ALLOYS																				
															$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$		
1671	66.5	-----	0.5 to 1.0	0.5 to 1.0	--	--	--	35	--	----------	Forged, solution heat treated at about 600° F (316° C), quenched, and aged at about 300° F (149° C).	3/4	1H	----	16.7	17.9	----	18.2	----	−0.005
													1C	----	16.6	----	18.3	18.5	----	
													2H	----	16.3	----	18.3	18.6	----	+.002
													2C	----	16.6	----	18.2	18.5	----	
1657	60	-----	----	----	--	--	--	40	--	Ag trace	Cast at 2,300° F (1,260° C), heat treated at 1,025° F (552° C) for 24 hr, hot forged to 3/4 inch diameter, annealed 4 hours at 1,025° F (552° C), quenched in water, cold worked to 5/8-in. diameter.	5/8	1H	----	16.6	17.3	----	17.4	----	−.007
													2H	----	16.6	17.1	----	17.8	----	+.006
1630	27.9	Not detected	<0.04	0.5	--	0.25	--	71.3	--	----------	Cast in iron mold	3/8	1H	----	14.8	[g] 15.1	----	16.6	(h)	------
C. ALUMINUM-COPPER ALLOYS																				
														$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$		$\times10^{-6}$		
967AN	93.41	5.81	0.36	----	--	0.42	--	--	--	----------	Heated cast sample to 500° C and cooled slowly; reheated to 300° C and cooled slowly.	5/16 by 1/2	1H	----	22.9	23.9	----	24.6	----	−0.004
													1C	----	22.8	23.9	----	24.8	----	
													[i] 2H	20.9						
													3H	20.9						
968AN												5/16 by 1/2	1H	----	23.0	24.0	----	24.8	----	−.003
													1C	----	23.0	23.9	----	24.9	----	
													2H	21.0						
830AN	91.14	7.68	.39	----	--	.46	0.33	--	--	----------	Heated cast sample to 500° C and cooled slowly; reheated to 300° C and cooled slowly.	5/16 by 1/2	1H	----	22.7	23.7	----	24.5	----	−.005
													1C	----	22.8	23.7	----	24.6	----	
													2H	20.7						
831AN	91.13	7.87	.33	----	--	.45	.22	--	--	----------	Heated cast sample to 500° C and cooled slowly; reheated to 300° C and cooled slowly.	1/4 by 7/16	1H	----	22.7	23.7	----	24.4	----	−.006
													1C	----	22.7	23.7	----	24.6	----	
													2H	20.6						
832AN											Heated cast sample to 300° C and cooled slowly; reheated to 300° C and cooled slowly.	5/16 by 7/16	1H	----	22.4	23.5	----	24.4	----	−.005
													1C	----	22.4	23.5	----	24.5	----	
969AN	89.22	9.95	.39	----	--	.44	--	--	--	----------	Heated cast sample to 500° C and cooled slowly; reheated to 300° C and cooled slowly.	5/16 by 1/2	1H	----	22.5	23.6	----	24.3	----	−.003
													1C	----	22.4	23.6	----	24.4	----	
													2H	20.8						
970AN												5/16 by 1/2	1H	----	22.5	23.6	----	24.4	----	−.003
													1C	----	22.5	23.7	----	24.5	----	
971AN	87.30	11.88	.39	----	--	.43	--	--	--	----------	Heated cast sample to 500° C and cooled slowly; reheated to 300° C and cooled slowly.	5/16 by 1/2	1H	----	22.2	23.2	----	24.1	----	−.004
													1C	----	22.4	23.3	----	24.2	----	
													2H	20.7						
972AN												3/8 by 1/2	1H	----	22.5	23.5	----	24.2	----	−.003
													1C	----	22.4	23.5	----	24.3	----	

D. ALUMINUM-SILICON ALLOYS																				
													$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$		
1203	86.01	0.15	13.08	-----	-----	0.76	-----	-----	-----	-----	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	-----	j 19.7	j 20.1	j 20.6	j 21.3	-----	−0.002
1203A												5/16	1H	18.3						
1204	81.80	.12	17.27	-----	-----	.81	-----	-----	-----	-----	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	-----	18.8	19.1	19.7	20.1	-----	−.003
1204A												5/16	1H	17.1	-----	-----	-----	-----	-----	-----
E. ALUMINUM-COPPER-IRON ALLOYS																				
													$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$		
k l 1353	89.3	9.0	0.4	0.3	-----	1.0	0.03	-----	-----	-----	Heated for 20 hr at 225° C and air cooled.	5/16	1H 2H	----- 20.7	22.3	23.3	23.8	24.1	-----	+0.001
h 1096	88.30	10.09	.21	.26	-----	1.14	-----	-----	-----	-----	Cast in iron mold.	1	1H 1C	----- -----	22.5 22.7	25.4 22.7	-----	-----	-----	+.050
h 1097											Heated to 750° F (399° C) and cooled very slowly.	1	1H 1C	----- -----	22.3 22.5	23.3 23.3	-----	-----	-----	+.000
F. ALUMINUM-COPPER-MAGNESIUM ALLOYS m																				
														$\times10^{-6}$	$\times10^{-6}$		$\times10^{-6}$	$\times10^{-6}$	
n 1778	93.09	4.41	0.10	1.41	0.01	0.25	0.67	-----	-----	Zn 0.02, Cr .01, Pb .01, Bi .01, Ti .01.	Solution heat treated at 920°F (493° C) for 1 hr, quenched in water and aged at room temperature.	1	1H 1C	----- -----	23.1 22.4	23.4 23.5	-----	23.8 -----	24.9 26.2	−0.051
n 1778A											Same treatment as sample 1778, then aged at 700° F (371° C) for 100 hr.	1	1H 1C	----- -----	23.0 22.8	23.6 23.7	-----	24.5 -----	25.9 26.0	−.001
n 1778B											Same treatment as sample 1778, then aged at 800° F (427° C) for 500 hr.	1	1H 1C	----- -----	22.8 23.0	23.7 23.9	-----	24.3 -----	25.5 25.8	−.009
G. ALUMINUM-COPPER-NICKEL ALLOYS m																				
														$\times10^{-6}$	$\times10^{-6}$		$\times10^{-6}$	$\times10^{-6}$	
o 1776	92.23	3.98	0.58	0.64	2.01	0.45	0.05	-----	-----	Zn 0.02, Cr .01, Pb .01, Bi .01, Ti .01.	Solution heat treated at 960° F (516° C) for 1 hr, quenched in water, and aged at 340° F (171° C) for 10 hr.	1	1H 1C	----- -----	23.0 22.4	23.6 23.4	-----	25.2 -----	25.9 25.1	+0.029
o 1776A											Same treatment as sample 1776, then aged at 700° F (371° C) for 100 hr.	1	1H 1C	----- -----	22.4 22.3	23.2 23.4	-----	24.1 -----	24.8 25.2	−.014
o 1776B											Same treatment as sample 1776, then aged at 800° F (427° C) for 500 hr.	1	1H 1C	----- -----	23.0 22.2	23.7 23.4	-----	24.5 -----	25.4 25.2	+.007
H. ALUMINUM-SILICON-COPPER ALLOYS																				
													$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$		
1198	81.80	4.03	13.35	-----	-----	0.82	-----	-----	-----	-----	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H 1C	----- -----	j 19.8	j 20.6	21.0	j 21.4 21.6	-----	−0.006
1198A												5/16	1H	17.7	-----	-----	-----	-----	-----	
p 1098	80.45	9.08	10.16	-----	-----	.31	-----	-----	-----	-----	Cast in iron mold	1	1H	-----	20.4	22.3	-----	-----	-----	+.031
p 1099											Heated to 750° F (399° C) and cooled very slowly.	1	1H 1C	----- -----	20.0 20.4	21.0 21.0	-----	-----	-----	+.002
1199	78.00	7.91	13.35	-----	-----	.74	-----	-----	-----	-----	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	-----	j 19.4	j 20.1	20.6	j 20.9	-----	−.004
1199A												5/16	1H	17.6	-----	-----	-----	-----	-----	-----
1207	76.74	14.14	8.31	-----	-----	.81	-----	-----	-----	-----	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	-----	j 19.6	j 20.1	20.6	j 21.0	-----	−.006
1270A												5/16	1H	18.3	-----	-----	-----	-----	-----	-----

See footnotes at end of table.

TABLE 1. *Coefficients of linear expansion of aluminum and some aluminum alloys*—Continued

Sample	Chemical composition (by weight) Al [a]	Cu	Si	Mg	Ni	Fe	Mn	Be	Sn	Other elements	Treatment	Diameter or cross section of sample	Test No. [b]	Average coefficients of expansion per degree centigrade −50° to +20° C	20° to 100° C	20° to 200° C	20° to 250° C	20° to 300° C	20° to 400° C	Change in length after heating and cooling [c]
I. ALUMINUM-SILICON-MAGNESIUM ALLOYS [m]																				
															$\times 10^{-6}$	$\times 10^{-6}$		$\times 10^{-6}$	$\times 10^{-6}$	
[q] 1779	84.40	0.89	12.18	1.20	0.87	0.41	0.01	------	------	Zn 0.02, Cr .01, Ti .01.	Solution heat treated at 960° F (516° C) for 1 hr, quenched in water, aged at 340° F (171° C) for 12 hr.	1	1H	------	20.0	21.1	------	22.4	23.2	+0.063
													1C	------	18.6	19.8	------	------	21.6	
[q] 1779A											Same treatment as sample 1779, then aged at 700° F (371° C) for 100 hr.	1	1H	------	19.8	20.4	------	20.8	21.5	+.022
													1C	------	------	------	------	20.3	21.3	
[q] 1779B											Same treatment as sample 1779, then aged at 800° F 427° C) for 500 hr.	1	1H	------	19.4	20.5	------	21.0	21.8	+.021
													1C	------	18.6	19.6	------	------	21.3	
J. ALUMINUM-COPPER-NICKEL-MAGNESIUM ALLOYS [m]																				
															$\times 10^{-6}$	$\times 10^{-6}$		$\times 10^{-6}$	$\times 10^{-6}$	
[r] 1777	91.56	3.89	0.58	1.43	2.14	0.31	0.01	------	------	Zn 0.02, Cr .01, Pb .01, Bi .01, Ti .03.	Solution heat treated at 960° F (516° C) for 1 hr, quenched in water, aged at 340° F 171° C) for 10 hr.	1	1H	------	23.0	23.4	------	24.4	25.9	+0.039
													1C	------	22.6	23.6	------	------	25.1	
[r] 1777A											Same treatment as sample 1777, then aged at 700° F (371° C) for 100 hr.	1	1H	------	22.6	24.1	------	24.3	25.1	+.002
													1C	------	22.6	------	------	24.3	25.0	
K. ALUMINUM-COPPER-TIN-ZINC ALLOYS																				
														$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$		
[s, t] 1649	94.0	1.8	0.2	0.6	------	0.6	0.02	------	1.3	Zn 1.1 Cr 0.2 Ti .23	Sand cast	3/8	1H	------	23.3	24.6	25.4	------	------	+0.022
													1C	------	------	------	24.6	------	------	
[s, t] 1649A											Heated to 650° F (343° C), held for 2 hrs and cooled slowly in furnace.	3/8	1H	------	22.8	24.0	------	25.1	------	−.000
													1C	------	23.2	24.2	------	25.1	------	
[s, t] 1649B											Same treatment as sample 1649A.	3/8	1H	21.6	------	------	------	------	------	------
L. ALUMINUM-SILICON-COPPER-MANGANESE ALLOY																				
														$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$		
1205	74.50	3.18	20.29	------	------	0.96	1.07	------	------	------	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	------	[j] 17.4	[j] 18.0	18.5	[j] 18.8	------	+0.002
1205A											do	5/16	1H	15.9	------	------	------	------	------	------

M. ALUMINUM-SILICON-COPPER-NICKEL ALLOYS

														$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$		
1267	77.99	7.21	6.78	--------	7.18	0.84	------	------	------	----------	Annealed	5/16	1H	--------	20.0	21.0	--------	([u])	--------	--------
1267A											do	5/16	1H	17.9	--------	--------	--------	--------	--------	--------
1200	77.83	4.05	13.22	--------	4.12	.78	------	------	------	----------	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	--------	[j] 18.5	[j] 18.9	19.4	[j] 19.8	--------	−0.005
1200A											do	5/16	1H	16.9	--------	--------	--------	--------	--------	--------
[p] 1100	76.02	9.86	9.79	--------	4.03	.30	------	------	------	----------	Cast in iron mold	1	1H	--------	19.4	21.8	--------	--------	--------	+.039
													1C	--------	19.6	19.6	--------	--------	--------	
[p] 1101											Heated to 750° F (399° C) and cooled very slowly.	1	1H	--------	19.3	20.0	--------	--------	--------	.000
													1C	--------	19.8	20.0	--------	--------	--------	
1208	75.66	9.78	10.23	--------	3.91	.42	------	------	------	----------	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	--------	[j] 18.8	[j] 19.1	19.8	[j] 20.2	--------	−.002
1208A											do	5/16	1H	17.5	--------	--------	--------	--------	--------	--------
1201	73.89	8.02	13.19	--------	4.10	.80	------	------	------	----------	do	5/16	1H	--------	[j] 18.0	[j] 18.7	18.8	[j] 19.3	--------	+.001
1201A											do	5/16	1H	16.5	--------	--------	--------	--------	--------	--------

N. ALUMINUM-SILICON-NICKEL-COPPER-MANGANESE ALLOY

															$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$		
1206	71.46	3.14	19.30	--------	4.18	0.84	1.08	------	------	----------	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	--------	[j] 16.6	[j] 17.0	[j] 17.3	[j] 17.8	--------	0.000

O. ALUMINUM-SILICON-NICKEL-COPPER-MOLYBDENUM ALLOY

														$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$		
1202	76.59	4.13	12.68	--------	4.44	0.80	------	------	------	Mo 1.36	Normalized (1 hr at 400° C and cooled slowly).	5/16	1H	--------	[g] 18.2	[g] 18.9	19.3	[g] 19.6	--------	0.003
1202A											do	5/16	1H	17.3	--------	--------	--------	--------	--------	--------

[a] Aluminum by difference (except for sample 1630 on which beryllium was determined by difference).
[b] H indicates that the coefficients of expansion were obtained on heating and C on cooling.
[c] Determined from the expansion curve on heating and the contraction curve (or final observation) on cooling. The plus sign indicates an increase in length and the minus sign a decrease in length.
[d] Coefficients of expansion on this cast sample were published in 1924 by Hidnert [1].
[e] After heating to 618° C and cooling to room temperature, sample was about 0.01% longer than the length before heating.
[f] After heating to 609° C and cooling to room temperature, sample was about 0.02% longer than the length before heating.
[g] Published previously (through J. B. Johnson) in Rev. Sci. Instr. **12**, 286 (1941).
[h] Between 20° and 350° C, coefficient of expansion 17.3 × 10^{-6}.
[i] Before this test, sample was cooled to −50° C and heated to +20° C.
[j] Determined in 1926 by P. Hidnert and W. T. Sweeney of the National Bureau of Standards and published in 1933 by Kempf [2].
[k] Trade name, 122 alloy (sand and permanent mold casting.).
[l] Chemical composition was determined by spectrographic analysis by the Spectrochemistry Section of the Bureau.
[m] The samples were rolled before the heat treatments.
[n] Trade name, 24S alloy.
[o] Trade name, 18S alloy.
[p] Modified by the Alpax process.
[q] Trade name, 32S alloy.
[r] Trade name, XB18S alloy.
[s] Aluminum alloy Al–31, Navy Aeronautical Specification M–397 (Mar. 15, 1940).
[t] Chemical composition was determined by chemical and spectrochemical analysis by the Chemistry Division of the National Bureau of Standards.
[u] Sample bent slightly between 200° and 300° C.

TABLE 2. *Comparison of coefficients of linear expansion of annealed aluminum*

Observer	Date	Purity of aluminum	Average coefficients of expansion per degree centigrade			
			20° to 100°C	20° to 200°C	20° to 300°C	20° to 400°C
		Percent				
Nix and MacNair	1941	99.997	23.9×10⁻⁶	24.3×10⁻⁶	25.3×10⁻⁶	26.5×10⁻⁶
Taylor, Willey, Smith, and Edwards.	1938	99.996	[a] 23.9	[a] 24.6	[a] 25.4$_5$	[a] 26.5
Hidnert and Krider	1951	99.952	[b] 23.4	[b] 24.5	[b] 25.5	----------
Mean			23.7	24.5	25.4	26.5

[a] Average value for 3 specimens.
[b] Average value for 2 samples (total of 8 determinations on heating and cooling).

the highest content of beryllium and mean values [3] for annealed aluminum (0% of beryllium) are included in the figure. This figure shows that the addition of beryllium to aluminum decreases the coefficients of expansion. The relation between the chemical composition (atomic percent) and the coefficients of expansion for each temperature range is approximately linear,[4] which is in agreement with the theory

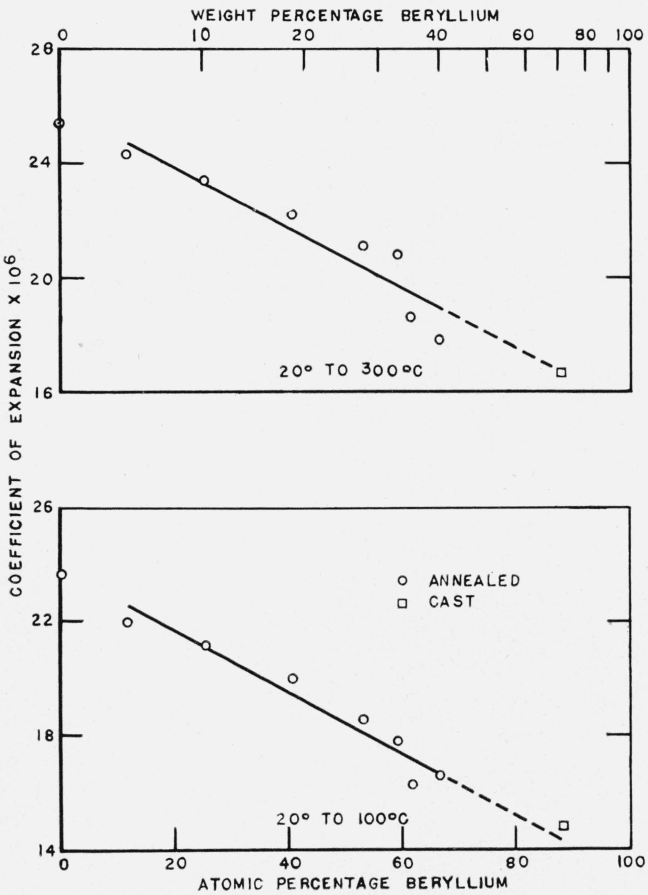

FIGURE 1. *Coefficients of linear thermal expansion of aluminum-beryllium alloys.*

Average values for aluminum taken from table 2.

[3] From table 2.
[4] In figures 1 to 4, the straight lines were not extended to 0 atomic percent because there are solid solutions near this percentage.

for the eutectiferous portion of the equilibrium diagram [7] for aluminum-beryllium alloys.

Table 1, C, gives coefficients of expansion of nine samples of annealed aluminum-copper alloys containing from 5.8 to 11.9 percent of copper by weight (2.6 to 5.4 atomic percent). For each sample, the coefficients of expansion on heating agree closely with the corresponding coefficients on cooling. The maximum deviation is $\pm 0.2 \times 10^{-6}$.

Figure 2 shows the relations between the chemical composition (atomic percent of copper) of annealed aluminum-copper alloys and the average coefficients of expansion for three temperature ranges on heating. This figure includes coefficients of expansion obtained by Bollenrath [8], Kempf [2], and Willey and Fink [9] on annealed aluminum-copper alloys and mean values (table 2) on annealed aluminum (0% of copper).

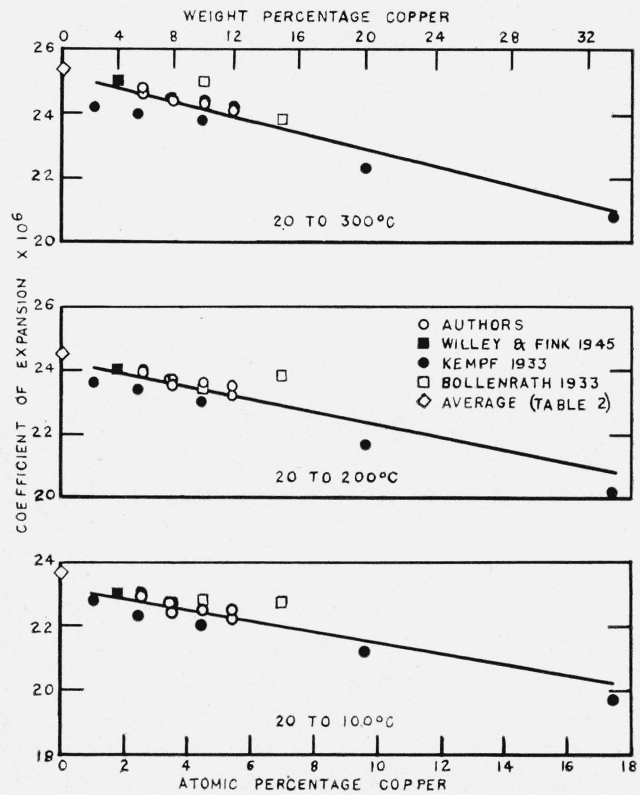

FIGURE 2. *Coefficients of linear thermal expansion of annealed aluminum-copper alloys.*

The values for annealed aluminum-copper alloys for each temperature range may be represented by a straight line and indicate that the coefficient of expansion decreases with increase in the atomic percent of copper. A linear relation is to be expected between the chemical composition (atomic percent) and the coefficients of expansion of these alloys represented by the eutectiferous portion of the aluminum end of the aluminum-copper equilibrium diagram [10].

Figure 3 shows the average coefficients of expansion of two samples of annealed aluminum-silicon alloys in table 1, D, and the coefficients of expansion of other annealed aluminum-silicon alloys investigated by Hidnert [1], Broniewski and Smialowski [11], Kempf [2], and Barber [12], for three temperature ranges. The silicon content of the alloys range from 1.3 to 40 percent by weight (1.2 to 39 atomic percent). As Broniewski and Smialowski appeared to have made measurements only at room temperature, the boiling point of naphthalene (218° C), and at liquid-air temperature [13], the coefficients of expansion [5] that were computed from their data for the range 20° to 200° C only, are shown in figure 3.

The relation between the chemical composition (atomic percent) of these eutectiferous alloys [14] and the coefficients of expansion for each temperature

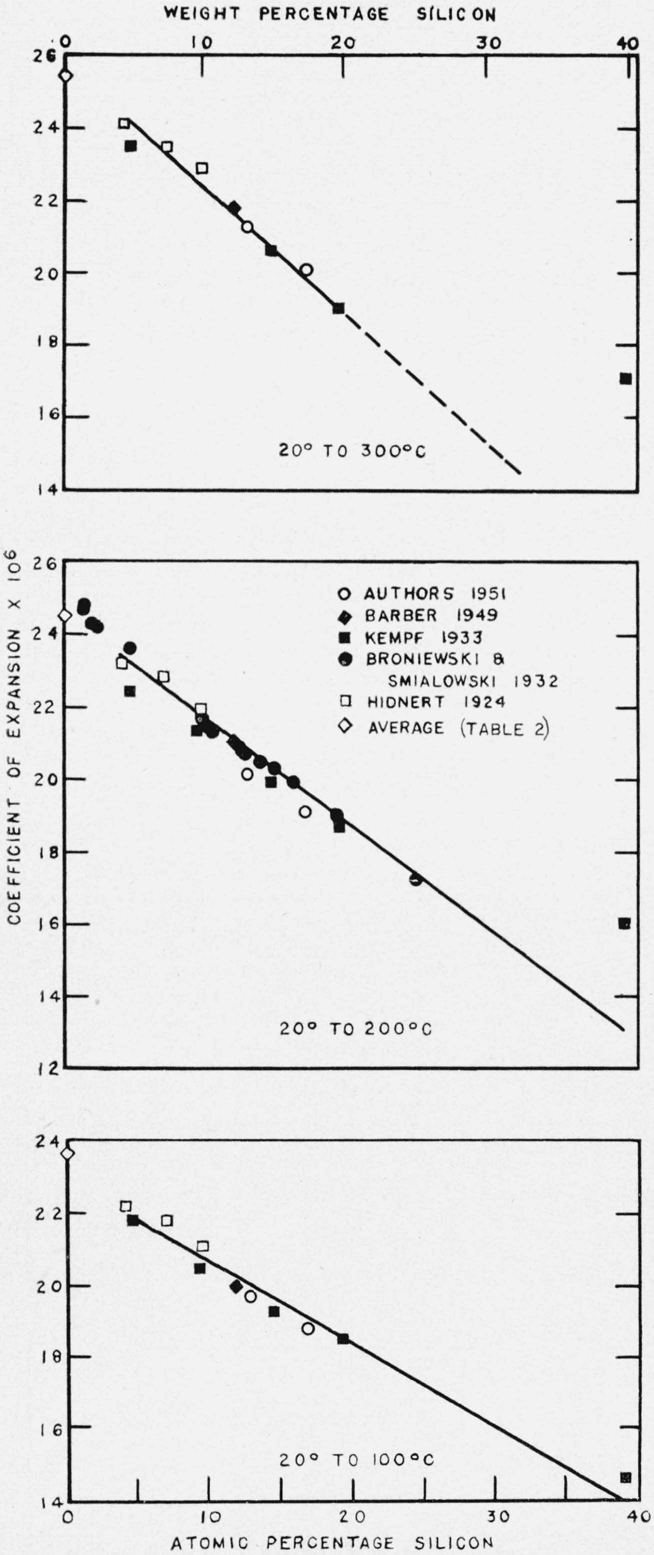

FIGURE 3. *Coefficients of linear thermal expansion of annealed aluminum-silicon alloys.*

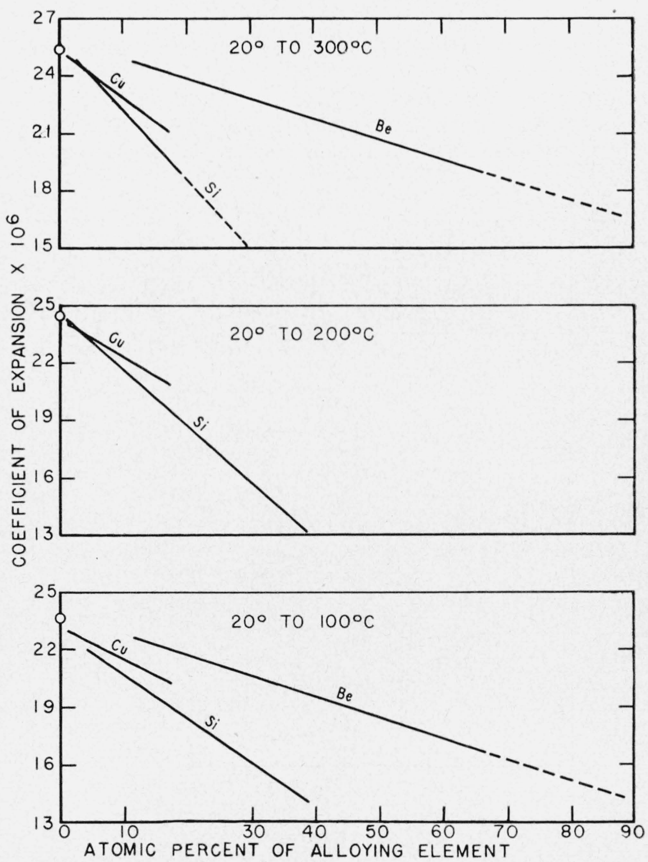

FIGURE 4. *Effects of beryllium, copper, and silicon on coefficients of linear thermal expansion of aluminum.*

[5] For alloys containing from 1.2 to 24.4 atomic percent of silicon. The present authors estimated that these alloys contained less than 1 percent of iron.

TABLE 3. *Coefficients of expansion of annealed aluminum-iron and aluminum-copper-iron alloys by other observers*

Observer	Date	Chemical composition (by weight)		Average coefficients of expansion per degree centigrade		
		Cu	Fe	20° to 100° C	20° to 200° C	20° to 300° C
		%	%			
Kempf	1933	------	4.45	20.4×10^{-6}	22.3×10^{-6}	23.3×10^{-6}
			8.46	21.0	21.5	22.3
Maresca	1936	3.22	1.47	------	------	[a] 23.3
Kempf	1933	9.77	5.04	19.9	20.8	21.5
		9.88	1.06	21.2	21.9	22.7

[a] 20° to 275° C.

range may be represented by a straight line [6] similar to the linear relations indicated in figures 1 and 2 for the eutectiferous aluminum-beryllium and aluminum-copper alloys. The coefficients of expansion of the aluminum-silicon alloys for the three temperature ranges decrease with increase in the atomic percent of silicon.

It has been shown that the addition of beryllium, copper, or silicon to aluminum causes a decrease in the coefficients of expansion. Figure 4 shows a comparison of the effects of these alloying elements (atomic percent) for three temperature ranges. Copper has a greater effect than beryllium, and silicon has the greatest effect of these three alloying elements.

Table 1, E, gives average coefficients of expansion of three samples of aluminum-copper-iron alloys containing 9 and 10 percent of copper and 1 percent of iron by weight, respectively. The expansion curve (fig. 5) of cast sample 1096 shows a marked increase in the rate of expansion on heating between 150° and 200° C, probably due to precipitation or solution of soluble constituents, recrystallization, or release of strains. The curve on cooling from 200° C to room temperature was found to be regular. After cooling to room temperature, the sample was 0.050 percent longer than the length before heating.

The expansion curves of annealed samples 1097 and 1353 were found to be regular on heating and cooling. After cooling to room temperature, these samples were only 0.001 percent longer than the lengths before heating. The coefficients of expansion of these samples are slightly less than the coefficients of expansion of the annealed samples containing 10 percent of copper and 0.4 percent of iron (table 1, C).

Table 3 gives coefficients of expansion of several annealed aluminum-iron and aluminum-copper-iron alloys investigated by Kempf [2] and Maresca [15]. The coefficients of expansion of the annealed alu-

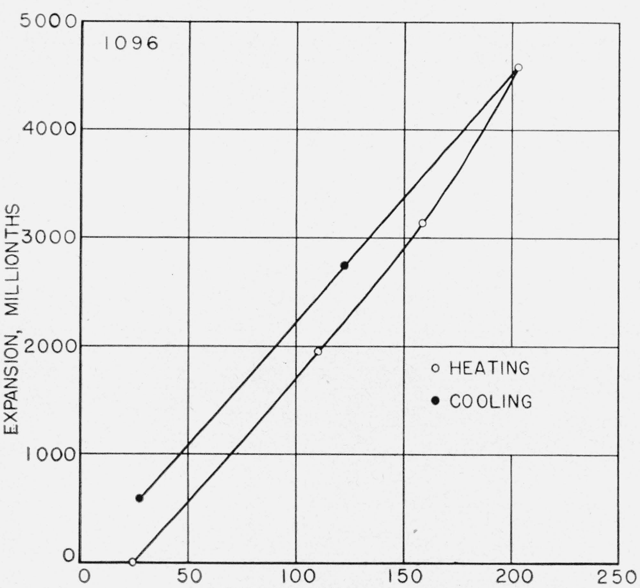

FIGURE 5. *Linear thermal expansion (in millionths per unit length) of cast aluminum-copper-iron alloy containing 10.1 percent of copper and 1.1 percent of iron by weight.*

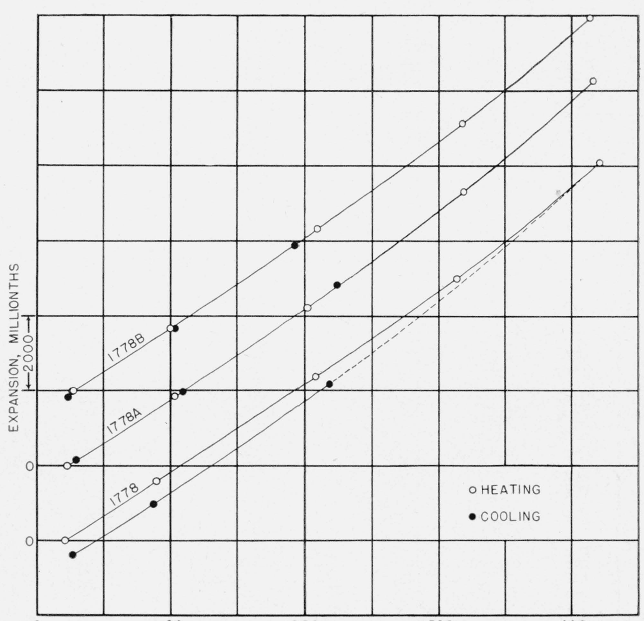

FIGURE 6. *Linear thermal expansion (in millionths per unit length) of aluminum-copper-magnesium alloys containing 4.4 percent of copper and 1.4 percent of magnesium by weight.*

Sample 1778, solution heat-treated at 920° F (493° C) for 1 hr, quenched in water and aged at room temperature; 1778A, same treatment as sample 1778, then aged at 700° F (371° C) for 100 hr; 1778B, same treatment as sample 1778, then aged at 800° F (427° C) for 500 hr.

[6] In deriving the straight line for the range 20° to 300° C, the authors ignored Kemp's value for the coefficient of expansion of the aluminum-silicon alloy containing the highest content of silicon.

minum-copper-iron alloys of the present investigation are about 1×10^{-6} greater than those reported by Kempf for an alloy containing 9.9 percent of copper and 1.1 percent of iron.

In an investigation of the physical properties of aluminum alloys at elevated temperatures as one phase of research by National Advisory Committee for Aeronautics on aircraft engine materials, determinations of the linear thermal expansion of samples of rolled aluminum-copper-magnesium, aluminum-copper-nickel, aluminum-silicon-magnesium, and aluminum-copper-nickel-magnesium alloys were made. The chemical composition and heat treatment of these samples are indicated under F, G, I, and J of table 1.

The observations obtained on heating and cooling the samples of aluminum-copper-magnesium, aluminum-copper-nickel, aluminum-silicon-magnesium, and aluminum-copper-nickel-magnesium alloys to various temperatures between room temperature and 800° F (427° C) are shown in figures 6 to 9. The expansion curves indicate that the linear thermal expansion of the samples increases with temperature. The contraction curves of the samples aged at 700° F (371° C) and at 800° F (427° C) lie closer to the expansion curves than the contraction and expansion curves of the samples aged at lower temperatures.

F, G, I, and J of table 1 give coefficients of expansion and coefficients of contraction of the heat-treated aluminum-copper-magnesium, aluminum-copper-nickel, aluminum-silicon-magnesium, and aluminum-copper-nickel-magnesium alloys. These

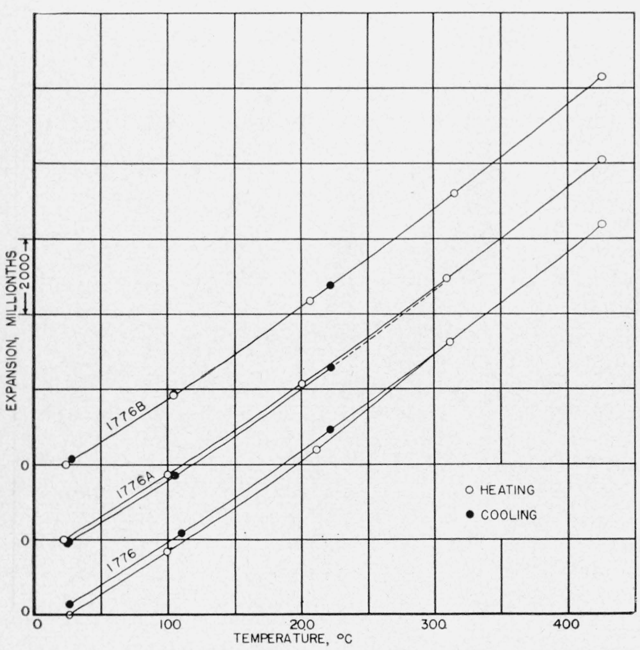

FIGURE 7. *Linear thermal expansion (in millionths per unit length) of aluminum-copper-nickel alloys containing 4.0 percent of copper and 2.0 percent of nickel by weight.*

Sample 1776, solution heat-treated at 960° F (516° C) for 1 hr, quenched in water, and aged at 340° F (171° C) for 10 hr; 1776A, same treatment as sample 1776, then aged at 700° F (371° C) for 100 hr; 1776B, same treatment as sample 1776, then aged at 800° F (427° C) for 500 hr.

coefficients were derived from the expansion and contraction curves in figures 6 to 9. The average difference between the coefficients of expansion of the samples aged at 700° F (371° C) and at 800° F (427° C) compared to the corresponding coefficients of the samples aged at lower temperatures is $\pm 0.6 \times 10^{-6}$/deg C, but the average difference between the coefficients of contraction of the samples aged at 700° F (371° C) and at 800° F (427° C) compared

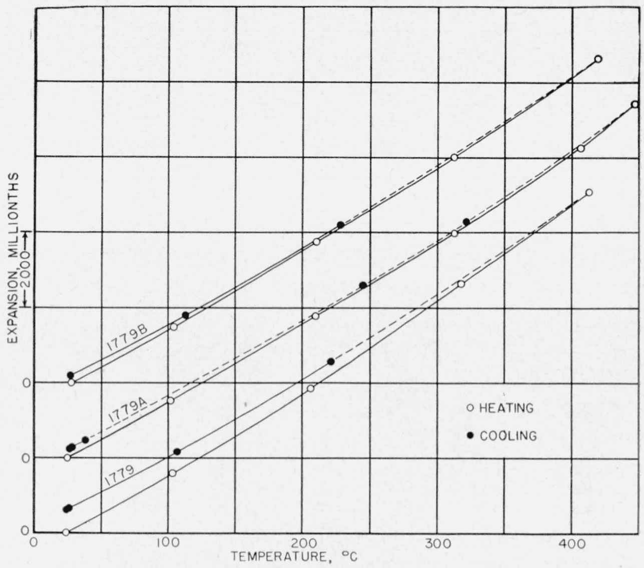

FIGURE 8. *Linear thermal expansion (in millionths per unit length) of aluminum-silicon-magnesium alloys containing 12.2 percent of silicon and 1.2 percent of magnesium by weight.*

Sample 1779, solution heat-treated at 960° F (516° C) for 1 hr, quenched in water, aged at 340° F (171° C) for 12 hr; 1779A, same treatment as sample 1779, then aged at 700° F (371° C) for 100 hr; 1779B, same treatment as sample 1779, then aged at 800° F (427° C) for 500 hr.

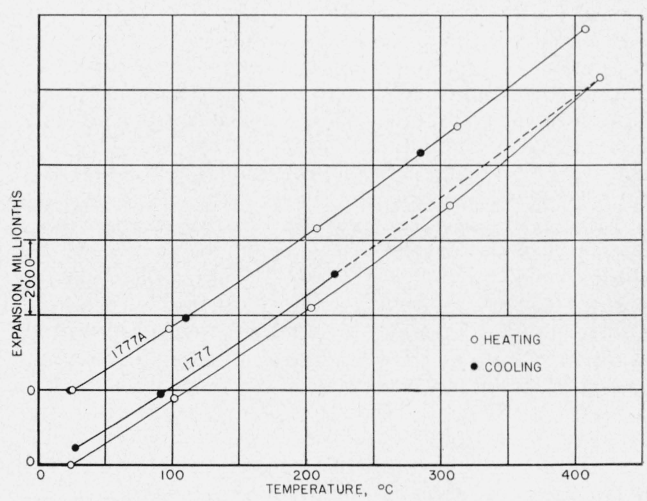

FIGURE 9. *Linear thermal expansion (in millionths per unit length) of aluminum-copper-nickel-magnesium alloys containing 3.9 percent of copper, 2.1 percent of nickel, and 1.4 percent of magnesium by weight.*

Sample 1777, solution heat-treated at 960° F (516° C) for 1 hr, quenched in water, aged at 340° F (171° C) for 10 hr; 1777A, same treatment as sample 1777, then aged at 700° F (371° C) for 100 hr.

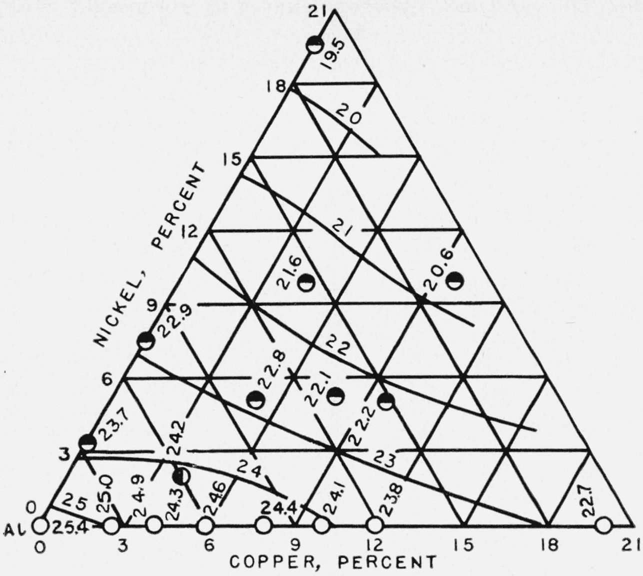

FIGURE 10. *Portion of ternary diagram indicating the effects of composition (percentage by weight) on the coefficients of linear expansion (in millionths per degree centigrade) of annealed aluminum-copper-nickel alloys for the range 20° to 300° C.*

○, From data in figure 2; ◐, authors (24.3); Willey and Fink (24.2); ◓ Kempf.

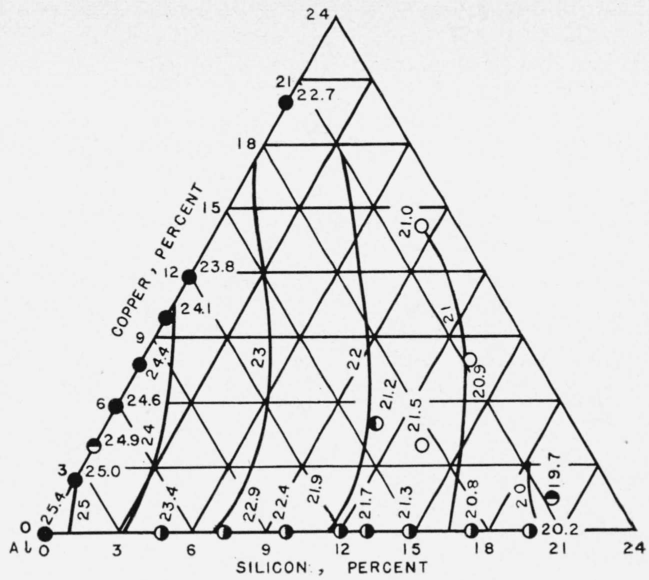

FIGURE 11. *Portion of ternary diagram indicating the effects of composition (percentage by weight) on the coefficients of linear expansion (in millionths per degree centigrade) of annealed or heat-treated aluminum-silicon-copper alloys for the range 20° to 300° C.*

○, Authors; ●, from data in figure 2; ◑, from data in figure 3; ◐, Barber (1949); ◓, Maresca (1936).

to the corresponding coefficients of the samples aged at lower temperatures is only $\pm 0.2 \times 10^{-6}$/deg C. The coefficients of expansion of the aluminum-silicon-magnesium alloy containing 12 percent of silicon are nearly 15 percent less than those for the aluminum-copper-magnesium, aluminum-copper-nickel, and aluminum-copper-nickel-magnesium alloys containing about 4 percent of copper.

The dimensional changes of the samples of aluminum-copper-magnesium, aluminum-copper-nickel, aluminum-silicon-magnesium, and aluminum-copper-nickel-magnesium alloys at room temperature after heating and cooling during the thermal-expansion determinations were less for the samples aged at 700° F (371° C) and at 800° F (427° C) than for those aged at lower temperatures (last column of table 1).

Figure 10 indicates average coefficients of expansion of annealed aluminum-copper-nickel alloys for the range from 20° to 300° C. Values obtained by Kempf [2] and Willey and Fink [9] are included in the ternary diagram. Coefficients of expansion of aluminum-copper alloys were taken from the straight line (20° to 300° C) shown in figure 2. The curves in figure 10 were derived from the data shown in this ternary diagram. Each curve (or straight line) called an isodil,[7] represents a constant coefficient of expansion for various ternary compositions for a definite temperature range.

The isodils for the annealed aluminum-copper-nickel alloys are nearly perpendicular to the aluminum-nickel side of the ternary diagram, and indicate the effects of composition on the coefficients of expansion of these alloys.

The coefficients of expansion of the heat-treated aluminum-silicon-magnesium alloy containing about 12 percent of silicon and 1 percent of magnesium are in close agreement with the coefficients of expansion reported by Willey and Fink [9] for an annealed and a heat-treated alloy of approximately the same composition.

Table 4 gives coefficients of expansion of aluminum-copper-nickel-magnesium alloys investigated by Bollenrath [8] and Barber [12]. The mean of the coefficients of expansion of these alloys for the ranges from 20° to 100° C and from 20° to 200° C is 0.7×10^{-6} smaller than the mean of the coefficients of expansion of the samples of the aluminum-copper-nickel-magnesium alloys of the present investigation for the corresponding temperature ranges. For the range from 20° to 300° C, the corresponding difference between the means of the coefficients of expansion is 0.3×10^{-6}.

Figure 11 indicates average coefficients of expansion of annealed or heat-treated aluminum-silicon-copper alloys for the range from 20° to 300° C. Values reported by Maresca [15] and Barber[8] [12] are included in the ternary diagram. Coefficients of expansion of aluminum-copper and aluminum-silicon were taken from the straight lines (20° to 300° C) shown in figures 2 and 3.

[7] The word "isodil" was derived in 1931 by Hidnert, from "iso" (Greek *isos*, meaning equal) and from the first three letters of "dilatation".

[8] Barber reported values ranging from 20.6 to 21.6×10^{-6} for 4 samples containing 11.0% of silicon and 5.0% of copper. The spread of the values is large, and apparently nominal values were reported for the chemical composition. Accordingly, the average of his values (21.2×10^{-6}), indicated in figure 11, was ignored in deriving the curves.

TABLE 4. *Coefficients of expansion of aluminum-copper-nickel-magnesium alloys by other observers*

Observer	Date	Chemical composition (by weight)						Treatment	Average coefficients of expansion per degree centigrade				
		Al [a]	Cu	Ni	Mg	Si	Fe		20° to 100° C	20° to 200° C	20° to 300° C	20° to 400° C	20° to 500° C
		%	%	%	%	%	%						
Bollenrath	1933	92.5	4	2	1.5	------	------	Annealed at 520° C for 24 hours and cooled to room temperature in 16 hours.	23.2×10^{-6}	23.8×10^{-6}	24.6×10^{-6}	25.5×10^{-6}	26.2×10^{-6}
Barber	1949	92.21	3.76	1.85	1.33	0.45	0.40	Wrought, quenched from 511° C in fairly hot water, and aged at room temperature.	21.4	22.5	23.8	------	------
								Same treatment as preceding, then given stability heat treatment at 300° C.	21.5	22.7	23.6	------	------

[a] By difference.

The isodils for the annealed or heat-treated aluminum-silicon-copper alloys are nearly perpendicular to the aluminum-silicon side of the ternary diagram, and indicate the effects of composition on the coefficients of expansion of these alloys.

Coefficients of expansion of a cast and of an annealed aluminum-copper-tin-zinc alloy containing about 2 percent of copper, 1 percent of tin, and 1 percent of zinc are given in table 1, K. The coefficients of expansion of the annealed sample for the temperature ranges to 200° C are less than the coefficients of expansion of the cast sample.

A comparison of the coefficient of expansion of the sample (1205) of annealed aluminum-silicon-copper-manganese alloy [9] from 20° to 300° C with the isodils for annealed aluminum-silicon-copper alloys in figure 11 indicates that the addition of 1.1 percent of manganese and nearly 1 percent of iron to a ternary aluminum-silicon-copper alloy containing 20 percent of silicon and 3 percent of copper, reduces the coefficient of expansion.

The effects of additions of copper and nickel to aluminum-silicon alloys are indicated in figure 12, which was prepared from the data shown in table 1, M, and in figure 3 and from data by Bollenrath [8], Bungardt and Schaitberger [16], and Barber [12]. In every case except one, the additions of copper and nickel caused a decrease in the coefficients of expansion.

The effects of the addition of 4.2 percent of nickel, 3.1 percent of copper, and 1.1 percent of manganese and of 4.4 percent of nickel, 4.1 percent of copper, and 1.4 percent of molybdenum to aluminum-silicon alloys are also indicated in figure 12. These additions caused a decrease of about 2×10^{-6}/deg C in the coefficients of expansion.

[9] Also contains nearly 1% of iron.

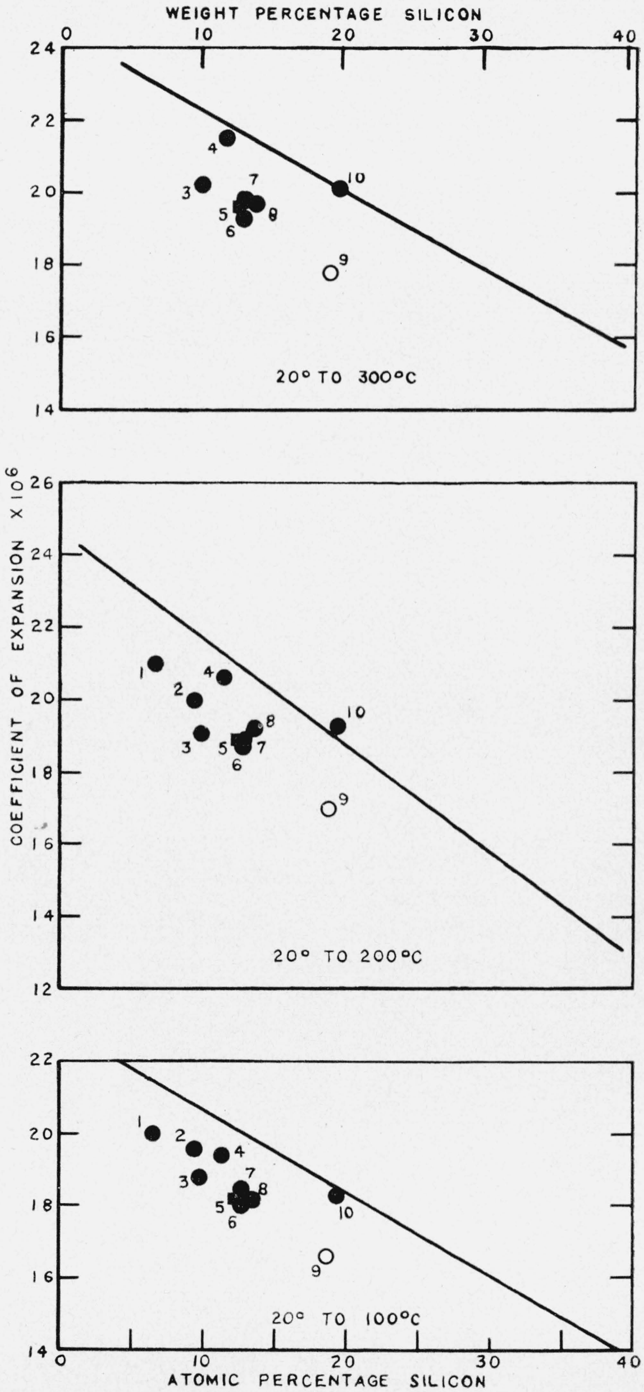

FIGURE 12. *Effects of additions of two or three elements* (Cu, Ni, Mn, *and* Mo, *percentage by weight*) *on coefficients of linear expansion of aluminum-silicon alloys.*

Coefficients of expansion of aluminum-silicon alloys represented by straight lines from figure 3. ●, Al-Si-Cu-Ni alloys; ○, Al-Si-Ni-Cu-Mn alloys; ■, Al-Si-Ni-Cu-Mo alloys. 1. Cu 7.2, Ni 7.2; 2. Cu 9.9, Ni 4.0; 3. Cu 9.8, Ni 3.9; 4. Cu 1.0, Ni 1.0; 5. Ni 4.4, Cu 4.1, Mo 1.4; 6. Cu 8.0, Ni 4.1; 7. Cu 4.0, Ni 4.1; 8. Cu 4.5, Ni 1.5; 9. Ni 4.2, Cu 3.1, Mn 1.1; 10. Cu 1.5, Ni, 1 percent by weight. 1, 2, 3, 5, 6, 7, and 9, authors; 4, Barber (1949); 8, Bungardt and Schaitberger (1939); 10, Bollenrath (1933).

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