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Thermal Expansion of Technical Solids at Low Temperatures

A Compilation From the Literature

U.S. DEPARTMENT OF COMMERCE
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Thermal Expansion of Technical Solids at Low Temperatures *

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Robert J. Corruccini and John J. Gniewek

Tables are given of the linear contraction relative to 293 °K, $(L_{293}-L_T)/L_{293}$, and the linear expansion coefficient, $dL/L_{293}dT$, of thirty elements, forty-five alloys, twenty-two other inorganic substances and twenty plastics and elastomers in the temperature range, 0 to 300 °K.

Introduction

This publication was intended to fill a need among designers of cryogenic equipment for a compilation of thermal expansion data on cryogenic materials. The literature search relied primarily on Physics Abstracts and is believed to provide complete coverage of the published literature through 1958. It was found that very few additional references were derived from subsequently searching other sources.

Wherever possible, data have been presented throughout the range, 0 to 300 °K. However, the region below 100° K is of predominant importance in cryogenic engineering, and, hence, many substances of interest have been omitted because data were not available below 100 °K.

Certain substances which are usually used as fluids in cryogenics have been omitted. These are helium, hydrogen, deuterium, neon, nitrogen, carbon monoxide, fluorine, argon, oxygen, air, and methane. Various properties of all phases of these substances are being compiled separately at this laboratory.

The published data usually consisted of unsmoothed values of length change. It was necessary to adjust these to our adopted reference temperature of 293 °K, to smooth and interpolate at rounded values of temperature, and to differentiate. Most of the results are given in table 2.

The references on which the resulting data were based are indicated in each table as "Sources of above data". All other sources of low temperature data for each substance are listed as "Other references". The selection of best sources will not be justified in detail. In general it was based on the precision of the data, the original authors' estimates of accuracy, and the quality of the samples. The bibliography gives complete references to the sources associated with the tables of data. In addition, it contains selected references on theory, experimental techniques, and measurements of other substances which were outside our scope but which were thought to be of more than average interest. The bibliography attempts to be complete only with regard to the substances listed in table 1.

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Table 3 gives data on some miscellaneous substances that did not fit into the format of table 2. It was not practical to extend these data in any way, and so they are quoted almost verbatim from the original sources.

Materials of construction often are anisotropic as a result of forming operations. This is especially noticeable with metals having highly anisotropic crystal lattices, such as zinc, and with plastics based on chain polymers. The degree of preferred orientation in such materials may be uncontrolled and, consequently, measurements of the linear thermal expansion may vary greatly with sample history and orientation. Measurements that are made in only one direction of such a material can be given little weight. Wherever a complete set of linear expansions along mutually perpendicular directions were available, we calculated the mean linear expansion for presentation in table 2. This quantity is to a very good approximation one-third the volume expansion and is the linear expansion that would be observed in the absence of preferred orientation. Although such a condition may not often be perfectly realizable, it represents average behavior and is a precisely defined physical quantity. In order to show the maximum possible variation in the linear expansion with orientation we have given in table 4 representative values along the principal crystallographic axes for some of the more anisotropic elements. These data were taken directly from the literature without smoothing.

Thermal cycling of polycrystalline materials in which the crystallites are anisotropic produces internal stresses. In extreme cases plastic deformation can result. This has been observed in tin, cadmium, and zinc by Boas and Honeycombe [1947] and in graphite by Hidnert [1934] and Baskin and Meyer [1955].

There are two main classes of experimental methods using macroscopic and X-ray lattice parameter techniques, respectively. In a few cases [Glover, 1954; Gott, 1942; Smith, 1954] appreciable differences in thermal expansion by the two methods have been found, amounting to over 10 percent at the worst. However, others have found no difference exceeding experimental error except near the melting point [Austin, Saini, Weigle, and Pierce, 1940; Berry, 1953; Connell and Martin, 1951; van Duijn and van Galen, 1957; Feder and Nowick, 1958; Hume-Rothery and Andrews, 1942; Hume-Rothery and Boultbee, 1949; Hume-Rothery and Strawbridge, 1947; Simmons and Baluffi, 1959, 1960; Wagner and Beyer, 1936]. Such differences, if real, would require high concentrations of vacancies or nonuniform distribution of lattice defects. The dimensional effects produced by lattice defects have been analyzed by Eshelby [1953, 1954, 1956], Miller and Russell [1952, 1953], and Toupin and Rivlin [1960]. The effect of impurities in metals is illustrated by measurements due to Hume-Rothery and Boultbee [1949]. The effect of elastic strain has been examined by Rosenfield and Averbach [1956] and the effect of plastic deformation has been examined by Hordon, Lement, and Averbach [1958].

Smoothing and interpolation were necessary with many substances in order to obtain tables that were sufficiently detailed to be useful. It was a common situation to find published values of length change at fairly small intervals from ambient temperature to about liquid air temperature, then a single value (often from a different source) of the length change between 78, 83, or 90 °K and 20 °K. By adjusting these length changes to a common starting temperature, T_{ref}, such as 293 °K, the data could have been correlated by finding a best fit to one of the Gruneisen equations, which we write in the form,

$$\frac{L_{\mathrm{ref}}-L_T}{L_{\mathrm{ref}}}=\frac{U_{\mathrm{ref}}-U_T}{a[1-b(U_T-U_0)]}.$$

Here U is internal energy, and a and b are constants to be evaluated by fitting the equation to the data. However this is a laborious procedure due to the necessity of constructing in advance a complete table of U versus T for each substance. Consequently a quicker procedure was adopted in many cases, which consisted of smoothing and interpolating graphically down to about 90 °K and using the Gruneisen relation only at lower temperatures. Here the term, $b(U_T-U_0)$, is negligible, and internal energy can be replaced by enthalpy. The latter quantity had already been tabulated by us as part of another compilation. The constant, a, can then be determined from any single value of length change below about 90 °K, such as, from 90 to 20 °K. By differentiation, a is also the constant of proportionality between dL/LdT and C_P. The error resulting from these simplifications of the formula is appreciable only for soft substances of high atomic weight, e.g., lead, indium, mercury. A more serious error is indicated by recent experiments and refinements of theory showing that some variation in the constant, a, will generally occur at temperatures lower than about one third of the Debye temperature. See, for example, Barron [1955], Bijl and Pullan [1954, 1955], Dheer and Surange [1958], Figgins, Jones, and Riley [1956], Gibbons [1958], Rubin, Altman, and Johnston [1954], Simmons and Balluffi [1957]. Because of this effect, the values interpolated by means of the formula are accurate only to one or two figures. Also there is a lower limit to the applicability of the formula. This is the temperature below which the linear term in the specific heat due to electrons is appreciable. Mikura [1941] and Visvanathan [1951] have shown that a corresponding linear term in dL/LdT should appear, but the coefficient of this term has been calculated only for the free-electron case.

Anomalies in the thermal expansion may occur for various reasons. In fact, dilatometry is a useful tool for exploring solid-state transformations. Some examples of substances showing low temperature anomalies are Dy (ferromagnetic Curie point), KH_2PO_4 (ferroelectric Curie point), MnO (anti-ferromagnetic transformation or Neel point), N_2 (first order phase change), CH_4 (rotational transition) and soft rubbers ("glass" transition).

Articles by Bijl [1957], Gruneisen [1926], and Hume-Rothery [1945] may be consulted for general background on the representation of thermal expansion.

Published thermal expansion data vary greatly in precision. Some papers show as many as five significant figures in $\Delta L/L$ and four in the derivative. However, comparisons between careful investigations on the same pure materials indicate that absolute accuracies better than one percent are seldom attained.

Descriptions of dilatometric techniques will be found in many of the articles selected as "Sources of Data." In addition the bibliography contains selected articles prefixed (T) which are devoted solely to techniques.

The assistance of Vincent D. Arp, Mrs. Marjorie Fewlass, and W. R. Slinkman is gratefully acknowledged.

TABLE 1. *List of substances*

Elements (*See table 2.1*)	*Alloys* (*See table 2.2*)	*Other inorganics* (*See table 2.3*)
Aluminum	Aluminum 2024–T4 [a]	Carbolloy [b]
Antimony	Aluminum 7075–T6 [a]	Carbon dioxide
Beryllium	Aluminum 25 [b]	Glasses:
Bismuth	Aluminum bronze	Optical (misc.) [c]
Cadmium	Beryllium copper	Pyrex
Carbon (diamond)	Brass	Silica
Carbon (graphite)	Bronze [b]	Ice
Chromium	Cast alloys (misc.) [b]	Indium antimonide
Copper	Cast iron [b]	Quartz
Germanium	Constantan	Magnesium oxide
Gold	Contracid	
Indium	German silver	*Plastics and elastomers*
Iron	Inconel	(*See table 2.4*)
Lead	Inconel-X [a]	Araldite
Magnesium	Invar	Catalin
Manganese	Magnesium AN–M–29 [a]	Dynakon
Mercury	Monel	Fluorothene
Molybdenum	K-Monel [a]	Kel-F
Nickel	Soft solder (50 Pb 50 Sn)	Laminac
Niobium [d]	Steels:	Lucite
Palladium	SAE 1010 [a]	Nylon
Platinum	SAE 1020	Panelyte
Rhodium	SAE 1095	Plexiglas
Silicon	SAE 6150 [b]	Polystyrene
Silver	SAE 52100	Polythene
Sodium	AISI 301	Rubber:
Tantalum	AISI 302	Hard
Tin	AISI 304	Silastic 160
Titanium	AISI 310	Selectron
Tungsten	AISI 316	Teflon
Zinc	AISI 322	Tenite
	AISI 330	Vinylite
	AISI 347	
	AISI 410	
	Miscellaneous [b]	
	Titanium RC–130–B	
	Titanium Ti-150–A	

[a] See table 3.2. [b] See table 3.1. [c] See table 3.3. [d] Also termed Columbium.

TABLE 2.1. *Linear thermal contraction and coefficients of linear thermal expansion*

Elements

T	Aluminum $10^5\frac{L_{293}-L_T}{L_{293}}$	Aluminum $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Antimony [b] $10^5\frac{L_{293}-L_T}{L_{293}}$	Antimony [b] $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Beryllium [b] $10^5\frac{L_{293}-L_T}{L_{293}}$	Beryllium [b] $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Bismuth [b] $10^5\frac{L_{293}-L_T}{L_{293}}$	Bismuth [b] $\frac{10^6}{L_{293}}\frac{dL}{dT}$	Cadmium [b] $10^5\frac{L_{293}-L_T}{L_{293}}$	Cadmium [b] $\frac{10^6}{L_{293}}\frac{dL}{dT}$
deg K		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0	[a] 415	0	[a] 250	0	[a] 131	0	[a] 323	0	[a] 733	0
10	[a] 415	[a] 0.05	[a] 250	[a] 0.1			[a] 323	[a] 1.1	[a] 733	[a] 1.1
20	415	.2	[a] 250	[a] .8	[a] 131	[a] .01	321	[a] 3.4	729	[a] 6.2
30	414	.9	[a] 248	[a] 2.4	[a] 131	[a] .03	316	[a] 6.1	[a] 720	[a] 11.6
40	413	2.2	[a] 245	[a] 4.1	[a] 131	[a] .07	309	7.8	[a] 706	[a] 15.8
50	410	3.8	[a] 240	[a] 5.6	[a] 131	[a] .13	300	9.1	[a] 689	[a] 19.0
60	405	5.5	[a] 234	[a] 7.0	[a] 131	[a] .2	291	10.0	[a] 669	[a] 21.4
70	399	7.4	[a] 226	[a] 7.9	[a] 130	[a] .4	280	10.7	[a] 646	[a] 23.2
80	391	9.1	218	8.5	[a] 130	[a] .6	269	11.2	[a] 622	[a] 24.6
90	381	10.7	209	8.9	129	[a] .9	258	11.6	597	25.6
100	370	12.2	200	9.3	128	1.3	246	11.9	571	26.4
120	343	14.6	181	9.7	124	2.2	222	12.2	517	27.8
140	312	16.5	162	10.0	119	3.4	198	12.5	460	28.7
160	277	17.9	142	10.2	111	4.7	173	12.7	402	29.3
180	240	19.0	121	10.4	100	5.9	147	12.8	343	29.7
200	201	20.0	100	10.5	87.3	7.1	121	12.9	284	30.0
220	160	20.8	78.9	10.6	72.0	8.2	95.5	13.0	223	30.2
240	118	21.5	57.5	10.7	54.6	9.2	69.4	13.1	163	30.4
260	75	22.1	35.9	10.8	35.2	10.1	43.3	13.1	102	30.6
273	45	22.5	21.8	10.9	21.8	10.6	26.2	13.1	61.9	30.8
280	30	22.7	14.2	10.9	14.3	10.8	17.1	13.1	40.3	30.9
293	0	23.0	0.0	10.9	0.0	11.2	0.0	13.1	0.0	31.1
300	−16	23.2	−7.7	11.0	−7.9	11.4	−9.2	13.1	−21.8	31.2
Sources of above data	Altman, Rubin, and Johnston 1954		Erfling 1939		Erfling 1939 Hidnert and Sweeney 1927		Erfling 1939		Gruneisen and Goens 1924	
Other refs.	Ayres 1905 Bijl and Pullan 1955 Buffington and Latimer 1926 Ebert 1928 Figgins, Jones, and Riley 1956 Gibbons 1958 Henning 1907 Hordon, Lement, and Averbach 1958 Hume-Rothery and Strawbridge 1947 Lindemann 1911 Nix and MacNair 1941 Shearer 1905		Dorsey 1907 Gruneisen 1910		Head and Laquer 1952		Dorsey 1907 Gruneisen 1910 Jacobs and Goetz 1937 Wunnenberg, Fischer, and Sapper 1930		Borelius and Johansson 1924 Dorsey 1907 Gruneisen 1910 McLennan and Monkman 1929	

[a] Estimated using Gruneisen correlation as explained in Introduction.
[b] Anisotropic. The above values were calculated from the relation, Mean Value = ⅓(‖) + ⅔(⊥), where (‖) and (⊥) signify the same property measured parallel and perpendicular, respectively, to the trigonal (Sb, Bi) or hexagonal (Be, Cd) axis. See table 4 for representative values of the (‖) and (⊥) expansions.

TABLE 2.1. *Linear thermal contraction and coefficients of linear thermal expansion*—Continued

Elements

T	Carbon [c] (diamond [b])		Chromium [d]		Copper		Germanium		Gold	
	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$
deg K		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0	[a] 24.3	0	[a] 98.5	0	[a] 326	0	[a] 92	0	[a] 324	0
10	[a] 24.3	[a] 0.00004			[a] 326	[a] 0.04				
20	[a] 24.3	[a] .0003	[a] 98.5	[a] .03	326	.3			323	[a] 2.4
30	[a] 24.3	[a] .0008	[a] 98.4	[a] .09	325	1.0			[a] 319	[a] 4.8
40	[a] 24.3	[a] .002	[a] 98.3	[a] .2	324	2.3	92.2	.07	[a] 313	[a] 6.7
50	[a] 24.3	[a] .004	[a] 97.9	[a] .5	321	3.8	92.1	.20	[a] 306	[a] 8.2
60	[a] 24.3	[a] .007	97.3	.84	316	5.5	91.9	.39	[a] 297	[a] 9.2
70	[a] 24.2	[a] .01	96.2	1.27	310	7.0	91.4	.67	[a] 288	[a] 10.0
80	[a] 24.2	[a] .02	94.7	1.75	302	8.4	90.5	1.05	278	[a] 10.6
90	[a] 24.1	[a] .03	92.7	2.19	293	9.5	89.3	1.54	267	11.1
100	[a] 24.0	[a] .04	90.3	2.59	283	10.5	87.4	2.20	256	11.5
120	[a] 23.7	[a] .08	84.5	3.25	260	12.0	81.9	3.25	233	12.1
140	23.1	.14	77.4	3.8	235	13.2	74.9	3.91	208	12.5
160	22.1	.21	69.3	4.3	208	14.1	67.0	4.29	182	12.8
180	20.6	.30	60.3	4.7	179	14.7	58.3	4.58	156	13.1
200	18.6	.40	50.5	5.1	149	15.2	48.7	4.82	129	13.3
220	16.0	.52	40.0	5.4	118	15.6	39.0	5.03	102	13.5
240	12.6	.65	29.1	5.5	87	15.9	28.9	5.23	74.4	13.7
260	8.5	.78	18.0	5.6	55	16.2	18.3	5.42	47.0	13.9
273	6.9	.87	10.7	5.6	33	16.4	11.3	5.53	27.8	14.0
280	3.7	.92	6.9	5.5	22	16.5	7.4	5.59	18.7	14.0
293	0.0	1.0	0.0	5.1	0	16.7	0.0	5.67	0.0	14.1
300	−2.1	1.1	−3.5	5.0	−11	16.8	−4.0	5.75	−10.2	14.1
Sources of above data	Thewlis and Davey 1956		Erfling 1939		Rubin, Altman, and Johnston 1954		Gibbons 1958		Ebert 1928 Nix and MacNair 1941	
Other refs.	Cohen and Olie 1910 Rontgen 1912		Disch 1921 Fine, Greiner and Ellis 1951 Hidnert 1941		Adenstedt 1936 Aoyama and Ito 1939 Beenakker and Swenson 1955. Bijl and Pullan 1955 Borelius and Johansson 1924 Buffington and Latimer 1926 Dorsey 1907 Fraser and Hollis-Hallet 1955 Henning 1907 Keesom, van Agt, and Jansen 1926 Keyston, MacPherson, and Guptill 1959 Krupkowski and de Haas 1928 Lindemann 1911 Nix and MacNair 1941 Simmons and Balluffi 1957 Simon and Bergmann 1930		Fine 1953 McSkimin 1953 Nitka 1937		Dorsey 1907, 1908 Gruneisen 1910	

[a] Estimated using Gruneisen correlation as explained in Introduction.

[b] The above values are for "gem quality" diamond. Thewlis and Davey also measured industrial diamond but obtained an anomalous minimum near 0° C. Following are some selected values of $10^6(dL/LdT)$ for their industrial diamond: 175° K 0.7, 200° K 0.6, 260° K −0.1 (min), 300° K +0.3.

[c] *Graphite* lattice parameters have been measured at low temperatures by Baskin and Meyer [1955] and by Walker, McKinstry, and Wright [1953]. The largest value reported for any of the expansion coefficients was 29×10^{-6} deg^{-1} K and was for the translaminar direction at 77° K and above. Expansions parallel to the laminae were too small to detect. In addition fragmentary and discordant macroscopic measurements lying within the above limits have been reported by Cohen and Olie [1910], Dewar [1902], and Erfling [1939]. Hidnert [1934] systematically measured the macroscopic expansions of several polycrystalline artificial graphites and obtained values of $10^6(dL/LdT)$ at room temperature ranging from 0.6 to 4. The latter values define the probable range of commercial bonded graphites. These values would be expected to trend toward zero with decreasing temperature.

[d] Hidnert found that the density and expansion coefficient of new electrolytic chromium were unstable. This was attributed to the large initial hydrogen content. The metal is stabilized by annealing. The table is based on the more pure of two vacuum-annealed samples measured by Erfling. The results with the less pure sample were about 10% higher. There was a minimum in the expansion coefficient at room temperature. This anomaly has been confirmed by Fine et al., and coincides with the antiferromagnetic transition (Neel point) found by Corliss, Hastings, and Weiss [1959].

TABLE 2.1. *Linear thermal contraction and coefficients of linear thermal expansion*—Continued

Elements

T	Indium [f]		Iron		Lead [b]		Magnesium [c]		α-Manganese [d]		β-Manganese [e]	
	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$10^6 \frac{dL}{L_{293}\,dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$10^6 \frac{dL}{L_{293}\,dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$10^6 \frac{dL}{L_{293}\,dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$10^6 \frac{dL}{L_{293}\,dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$10^6 \frac{dL}{L_{293}\,dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$10^6 \frac{dL}{L_{293}\,dT}$
deg K		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0	[a]706	0	[a]198	0	[a]708	0	[a]490	0				
5					708	0.3						
10	[a]706	[a]2			707	3.2	[a]490	[a]0.05				
20	701	7	198	[a]0.1	700	[a]11	490	[a].4				
30	691	13	[a]198	[a].3	[a]686	[a]17	[a]489	[a]1.4				
40	676	17	[a]197	[a].7	[a]667	[a]20	[a]486	[a]3.3				
50	658	19.1	[a]196	[a]1.3	[a]646	[a]22	[a]482	[a]5.7				
60	638	20.4	[a]195	[a]2.0	[a]624	[a]23	[a]475	[a]8.1				
70	617	21.5	[a]192	[a]2.8	[a]601	[a]24	[a]466	[a]10.3				
80	595	22.4	[a]189	[a]3.5	[a]577	[a]24	454	12.2	380			
90	572	23.2	185	4.2	552	25	441	13.9	372	9.8	420	
100	549	23.9	181	4.9	528	25	427	15.4	361	11.9	406	14.6
120	500	25.2	170	6.3	477	25.6	393	17.6	334	14.4	375	17.0
140	448	26.3	156	7.6	425	26.3	356	19.4	304	16.0	339	18.5
160	394	27.2	140	8.6	372	26.8	316	21.0	271	17.3	301	19.7
180	339	27.9	122	9.4	318	27.2	273	22.2	235	18.4	260	20.7
200	282	28.6	102	10.0	263	27.5	227	23.2	197	19.4	218	21.6
220	224	29.3	82	10.5	208	27.8	180	23.9	158	20.3	174	22.4
240	165	30.1	60	10.9	152	28.2	132	24.4	116	21.0	128	23.2
260	104	30.8	38	11.3	96	28.5	82.9	24.8	73.5	21.8	81.3	24.0
273	63	31.3	23	11.4	58	28.8	50.4	25.1	44.9	22.2	49.9	24.5
280	42	31.5	15	11.5	38	28.9	32.9	25.2	29.3	22.4	32.6	24.8
293	0	32.0	0	11.6	0	29	0.0	25.4	0.0	22.7	0.0	25.4
300	−22	32.2	−8	11.7	−20	29	−17.8	25.5	−16.0	22.9	−17.9	25.7
Sources of above data	Swenson 1955		Ebert 1928; Nix and MacNair 1941		Dheer and Surange 1958; Ebert 1928; Nix and MacNair 1942; Olsen and Rohrer 1957		Ebert 1928; Goens and Schmid 1936; Head and Laquer 1952		Erfling 1940		Erfling 1939	
Other refs.	Graham, Moore, & Raynor 1955; Hidnert and Blair 1943		Adenstedt 1936; Dorsey 1907; Owen and Williams 1954; Simon and Bergmann 1930		Dorsey 1908; Gruneisen 1910; Head and Laquer 1952; Lindemann 1911; McLennan, Allen, and Wilhelm 1931		Gruneisen 1910; Hidnert and Sweeney 1928		Disch 1921			

[a] Estimated using Gruneisen correlation as explained in Introduction.

[b] Superconducting lead has a slightly greater volume and a slightly smaller expansion coefficient than normal lead according to data by Olsen and Rohrer covering the region from 1 to the transition temperature, 7.2 °K. For example, the difference in expansion coefficients at 5 °K is about 10%.

[c] Anisotropic. The above values were calculated from the relation, Mean Value=1/3(‖)+2/3(⊥), where (‖) and (⊥) signify the same property measured parallel and perpendicular, respectively, to the hexagonal axis. See table 4 for representative values of the (‖) and (⊥) expansions.

[d] α-Mn is the form that is stable at low temperatures. It has an antiferromagnetic transition at about 95 °K which would make extrapolation of the above values uncertain.

[e] β-Mn is stable between 730 and about 1100 °C. Erfling's sample was prepared by quenching from 1100 °C in vacuum. There were insufficient specific heat data to make a reliable extrapolation below 90 °K.

[f] Anisotropic, tetragonal. Graham, Moore, and Raynor gave values of the lattice parameters down to 90 °K that show great anisotropy in the thermal expansion. Their low temperature data are not sufficiently accurate or detailed to serve as the basis of an extended table of values, so the more extensive data of Swenson on a polycrystalline sample were used. The contractions tabulated above are about 8% smaller than the average linear contractions derivable from the data of Graham, Moore, and Raynor. The data of Hidnert and Blair, also on a polycrystalline sample, are still smaller.

TABLE 2.1. *Linear thermal contraction and coefficients of linear thermal expansion*—Continued

Elements

T	γ-Manganese [b]		Mercury [c]		Molybdenum		Nickel		Niobium [e]		Palladium	
	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{234}-L_T}{L_{234}}$	$\frac{10^6}{L_{234}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$
deg K		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0	[a] 257	0	[a] 844	0	[a] 95	0	[a] 224	0	[a] 143	0	[a] 241	0
10			[a] 841	[a] 7	[a] 94.9	[a] 0.01						
20	[a] 257	[a] 0.3	[a] 830	[a] 15	[a] 94.8	[a] .06	224	[a] 0.2	[a] 143	[a] 0.3	[a] 241	[a] 0.5
30	[a] 256	[a] 0.7	[a] 812	[a] 21	[a] 94.7	[a] .2	[a] 224	[a] .5	[a] 143	[a] 0.9	[a] 240	[a] 1.3
40	[a] 255	[a] 1.4	[a] 788	[a] 26	[a] 94.4	[a] .5	[a] 223	[a] 1.0	[a] 141	[a] 1.7	[a] 238	[a] 2.5
50	[a] 253	[a] 2.4	[a] 760	[a] 29	[a] 93.8	[a] .8	[a] 221	[a] 1.9	[a] 139	[a] 2.4	[a] 235	[a] 3.8
60	[a] 250	[a] 3.5	[a] 730	[a] 31	[a] 92.7	[a] 1.2	[a] 219	[a] 2.8	[a] 137	[a] 3.1	[a] 231	[a] 4.9
70	[a] 246	[a] 4.5	[a] 697	[a] 33	[a] 91.3	[a] 1.7	[a] 216	[a] 3.8	133	3.6	[a] 225	[a] 5.9
80	[a] 241	[a] 5.5	663	[a] 34.5	89.4	[a] 2.1	211	[a] 4.7	129	4.0	[a] 219	[a] 6.7
90	[a] 235	[a] 6.3	628	35.9	87.1	2.48	206	5.5	125	4.4	211	7.4
100	[a] 228	[a] 7.2	592	37.0	84.4	2.80	201	6.1	121	4.7	204	8.1
120	[a] 213	[a] 8.5	516	38.8	78.2	3.39	187	7.5	111	5.2	187	9.0
140	[a] 194	[a] 9.7	437	40.2	71.1	3.77	171	8.8	99.4	5.6	168	9.7
160	[a] 174	[a] 10.6	355	42.1	63.2	4.13	152	9.8	87.7	5.9	148	10.2
180	[a] 152	[a] 11.5	268	44.6	54.6	4.42	132	10.5	75.5	6.2	127	10.7
200	128	12.3	176	47.8	45.6	4.63	111	11.0	63.0	6.4	105	10.9
220	103	13.0	76	52.2	36.2	4.78	88	11.5	50.0	6.6	83.3	11.2
230			22	55.3								
[d] 234			0	57.2								
240	76.2	13.7			26.5	4.89	65	11.9	36.7	6.7	60.8	11.3
260	48.3	14.2			16.6	4.98	41	12.2	23.1	6.8	38.0	11.4
273	29.6	14.6			10.1	5.02	25	12.3	14.1	6.9	23.1	11.5
280	19.3	14.7			6.6	5.04	16	12.4	9.2	6.9	15.0	11.5
293	0.0	15.0			0.0	5.07	0	12.6	0.0	7.0	0.0	11.6
300	−10.6	15.1			−3.6	5.09	−9	12.6	−5.0	7.0	−8.1	11.6
Sources of above data	Erfling 1940		Carpenter and Oakley 1931 Hill 1935		Erfling 1939 Nix and MacNair 1942		Krupkowski and deHaas 1928 Nix and MacNair 1941		Erfling 1942		Nix and MacNair 1942	
Other refs.			Dewar 1902 Gruneisen and Sckell 1934 Sapper and Biltz 1931		Disch 1921 Schad and Hidnert 1919		Adenstedt 1936 Altman, Rubin, and Johnston 1954 Aoyama and Ito 1939 Chevenard 1926 Disch 1921 Henning 1907 Simon and Bergmann 1930		Hidnert and Krider 1933		Henning 1907 Scheel 1907	

[a] Estimated using Gruneisen correlation as explained in Introduction.
[b] γ-Mn is a ductile form that is stable between about 1100 and 1135 °C when pure. It is often found as a separate phase in manganese alloys. Erfling's sample was produced by electrolytic deposition.
[c] Anisotropic. The above values were calculated from the relation, Mean Value=⅓(‖)+⅔(⊥), where (‖) and (⊥) signify the same property measured parallel and perpendicular, respectively, to the trigonal axis. See table 4 for representative values of the (‖) and (⊥) expansions.
[d] Melting point of mercury.
[e] Also termed columbium.

TABLE 2.1. *Linear thermal contraction and coefficients of linear thermal expansion*—Continued

Elements

T	Platinum		Rhodium		Silicon		Silver		Sodium [b]	
	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$
deg K		*deg⁻¹ K*		*deg⁻¹ K*		*deg⁻¹ K*		*deg⁻¹ K*		*deg⁻¹ K*
0	[a] 195	0	[a] 160	0	[a] 22	0	[a] 413	0	[a] 1430	0
10	[a] 195	[a] 0.08					[a] 413	[a] 0.1	[a] 1430	[a] 0.7
20	[a] 195	[a] 0.5	[a] 160	[a] 0.09			412	[a] 1	[a] 1430	[a] 5
30	[a] 194	[a] 1.5	[a] 160	[a] .4			[a] 410	[a] 3	[a] 1420	[a] 11
40	[a] 192	[a] 2.6	[a] 159	[a] .9	21.6	−0.05	[a] 405	[a] 6	[a] 1400	[a] 17
50	[a] 189	[a] 3.8	[a] 158	[a] 1.7	21.7	−.20	[a] 398	[a] 8	[a] 1380	[a] 23
60	[a] 185	[a] 4.7	156	[a] 2.5	22.0	−.41	[a] 389	[a] 10	[a] 1360	[a] 29
70	[a] 180	[a] 5.4	153	3.2	22.5	−.59	[a] 378	[a] 12	[a] 1330	[a] 33
80	[a] 174	[a] 6.0	149	3.9	23.2	−.77	366	[a] 13	1290	[a] 38
90	168	6.5	145	4.5	24.0	−.51	353	13.6	1250	42.4
100	161	6.8	140	5.0	24.3	−.31	339	14.6	1210	46.3
120	147	7.3	129	5.9	24.7	+.01	308	15.9	1110	52.4
140	132	7.7	117	6.5	24.3	.31	276	16.5	998	56.9
160	116	8.0	104	6.9	23.4	.65	242	16.9	881	60.4
180	99.4	8.3	89.3	7.3	21.7	1.05	208	17.3	757	63.1
200	82.4	8.5	74.5	7.6	19.1	1.49	173	17.7	629	65.2
220	65.0	8.6	59.1	7.8	15.9	1.83	137	18.1	497	66.7
240	47.5	8.7	43.4	8.0	11.8	2.07	100	18.5	363	67.8
260	29.6	8.8	27.2	8.1	7.8	2.22	63	18.8	227	68.4
273	18.0	8.8	16.6	8.2	4.8	2.28	38	19.0	137	68.6
280	11.6	8.9	10.8	8.3	3.3	2.30	25	19.1	89.4	68.7
293	0.0	8.9	0.0	8.4	0.0	2.32	0	19.2	0.0	68.8
300	−6.4	8.9	−5.9	8.4	−1.4	2.33	−13	19.3	−48.2	68.8
Sources of above data	Nix and MacNair 1942		Erfling 1939 Valentiner and Wallot 1915		Gibbons 1958		Ebert 1928 Nix and MacNair 1942		Siegel aud Quimby 1938	
Other refs.	Dorsey 1907 Henning 1907 Onnes and Clay 1906 Scheel 1907 Scheel and Heuse 1907 Valentiner and Wallot 1915		Head and Laquer 1952		Erfling 1942 Fine 1953 Simon and Bergmann 1930 Valentiner and Wallot 1915		Ayres 1905 Buffington and Latimer 1926 Dorsey 1907 Henning 1907 Keesom and Jansen 1927 Keesom and Kohler 1933 Lindemann 1911 Owen and Williams 1954 Shearer 1905		Barrett 1956 Dewar 1902 Swenson 1955	

[a] Estimated using Gruneisen correlation as explained in Introduction.

[b] It has recently been shown (Barrett 1956, Hull and Rosenberg 1959) that sodium partially transforms at low temperatures from the normal body-centered cubic structure to close-packed hexagonal. The transformation is of the martensitic type and is promoted by cold-working at the low temperatures. The above values include an extrapolation downwards from the region where the bcc structure is stable. The effect of the transformation on the thermal expansion is not known, but is small, inasmuch as Barrett found the densities of the two forms at 5 °K to be the same within his experimental uncertainty. The fit of the Gruneisen relation to the data was not very satisfactory, and hence there is not much confidence in the extrapolated values above.

Table 2.1. *Linear thermal contraction and coefficients of linear thermal expansion*—Concluded

Elements

T	Tantalum		Tin[c] (white)[b]		Titanium[d]		Tungsten		Zinc[e]	
	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$
deg K		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$*K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0	[a] 143	0	[a] 447	0	[a] 151	0	[a] 85.8	0	[a] 683	0
10	[a] 143	[a] 0.05	[a] 447	[a] 0.7			[a] 85.8	[a] 0.007	[a] 683	[a] 0.3
20	[a] 143	[a] 0.4	[a] 445	[a] 3	151	[a] 0.08	[a] 85.8	[a] .06	682	[a] 3
30	[a] 142	[a] 1.1	[a] 441	[a] 6	151	.3	[a] 85.7	[a] .2	[a] 677	[a] 8
40	[a] 141	[a] 2.0	[a] 433	[a] 9	150	.6	[a] 85.3	[a] .6	[a] 667	[a] 13
50	[a] 138	[a] 2.8	[a] 423	[a] 11	149	1.2	[a] 84.5	[a] 1.0	[a] 652	[a] 17
60	[a] 135	[a] 3.5	[a] 412	[a] 12	148	2.0	[a] 83.3	[a] 1.5	[a] 633	[a] 21
70	[a] 131	[a] 4.1	399	[a] 13	145	2.7	[a] 81.7	[a] 1.8	[a] 611	[a] 22
80	[a] 127	[a] 4.5	385	14.2	142	3.4	[a] 79.7	[a] 2.2	[a] 588	[a] 23
90	122	[a] 4.9	371	15.0	139	4.0	[a] 77.4	[a] 2.4	565	23.6
100	117	5.2	356	15.6	134	4.5	[a] 74.8	[a] 2.7	541	24.2
120	106	5.5	324	16.4	125	5.3	69.1	3.06	492	25.3
140	95.1	5.8	290	17.1	113	6.0	62.7	3.38	440	26.3
160	83.5	5.9	255	17.7	101	6.5	55.6	3.66	386	27.3
180	71.5	6.0	219	18.2	87.4	6.9	48.1	3.89	331	28.1
200	59.3	6.1	183	18.7	73.2	7.3	40.1	4.07	274	28.7
220	47.0	6.2	145	19.1	58.3	7.6	31.9	4.20	216	29.1
240	34.4	6.3	106	19.5	42.9	7.8	23.4	4.30	157	29.4
260	21.6	6.5	66.7	19.9	27.0	8.0	14.7	4.39	98	29.6
273	13.1	6.5	40.7	20.1	16.5	8.2	8.9	4.44	60	29.7
280	8.5	6.6	26.5	20.3	10.8	8.2	5.8	4.46	39	29.8
293	0.0	6.6	0.0	20.5	0.0	8.3	0.0	4.49	0	29.9
300	−4.6	6.6	−14.4	20.6	−5.9	8.4	−3.2	4.52	−21	30.0
Sources of above data	Nix and MacNair 1942		Erfling 1939		Altman, Rubin, and Johnston 1954 Erfling 1942		Nix and McNair 1942		Gruneisen and Goens 1924	
Other refs.	Disch 1921 Hidnert 1929		Cohen and Olie 1910 Dorsey 1907 Gruneisen 1910		Head and Laquer 1952 Hidnert 1943		Disch 1921 Hidnert and Sweeney 1925		Borelius and Johansson 1924 Dorsey 1908 Gruneisen 1910 Head and Laquer 1952 Lindemann 1911 McLennan and Monkman 1929	

[a] Estimated using Gruneisen correlation as explained in Introduction.

[b] Anisotropic. The above values were calculated from the relation, Mean Value $=\frac{1}{3}(\|)+\frac{2}{3}(\perp)$, where $(\|)$ and $(\perp)$ signify the same property measured parallel and perpendicular, respectively, to the tetragonal axis. See table 4 for representative values of the $(\|)$ and $(\perp)$ expansions.

[c] Thewlis and Davey (1954) measured the lattice parameter of *grey tin*, a brittle form with diamond-type lattice that is stable below 18° C. Their data cover the range, −130 to +20 °C, and are represented by a constant expansion coefficient, $dL/LdT=4.7\times10^{-6}$ deg^{-1} C. See also Cohen and Olie (1910). The ordinary ductile variety (white tin) if pure may transform to grey tin at low ambient temperatures but is stabilized by impurities.

[d] Titanium, having hexagonal crystal structure, should expand anisotropically. However, no lattice parameter or single crystal measurements are available to indicate the magnitude of this effect at low temperatures. The above data at 100 °K or higher are based on an average of two strips cut by Erfling perpendicular to one another from a rolled sheet. Although Altman et al., and Head and Laquer both measured samples from bar stock of unknown history, their results were within 3% of Erfling's average values, thus indicating that effects due to preferred orientation are small. The largest effect of this kind was shown by a wire measured by Erfling. Its axial expansion was as much as 13% greater than the above values. The table values below 100 °K are based on Altman et al.

[e] Anisotropic. The above values were calculated from the relation, Mean Value $=\frac{1}{3}(\|)+\frac{2}{3}(\perp)$, where $(\|)$ and $(\perp)$ signify the same property measured parallel and perpendicular, respectively to the hexagonal axis. See table 4 for representative values of the $(\|)$ and $(\perp)$ expansions. The data on polycrystalline zinc are discordant. Thus the expansion coefficients of Dorsey and of Head and Laquer are as much as 20% lower than values above, while those of Gruneisen and of Lindemann are less than one-third as great. These differences are attributable to the exceptional anisotropy of zinc combined with uncontrolled preferred orientation of the crystallites. It is evidently difficult to prevent such preferred orientation, and the expansions of various samples of polycrystalline zinc could conceivably cover a wide range of values between the limits set by the $(\|)$ and $(\perp)$ values.

TABLE 2.2. *Linear thermal contraction and coefficients of linear thermal expansion*

Alloys

T	Aluminum bronze [b]		Beryllium copper [c]		Brass, yellow [d]		Constantan [e]		Contracid [f]		German silver [g]	
	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$
deg K		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0			[a] 316	0	[a] 384	0			[a] 232	0	[a] 376	0
10			316	[a] 0.04	[a] 384	[a] 0.1			[a] 232	[a] 0.01	[a] 376	[a] 0.2
20			316	[a] .09	383	.5	269		232	[a] .06	[a] 376	[a] .5
30			316	.5	382	1.8			232	.3	375	1.3
40			315	1.4	380	3.7			231	.9	373	3.2
50			313	2.7	375	5.8			230	1.8	369	5.1
60			309	4.3	368	7.6	258	4.6	228	2.8	362	6.8
70			304	6.5	360	9.2	253	5.6	224	3.9	354	8.4
80			296	8.4	350	10.6	247	6.6	220	5.0	345	9.7
90	265	9	287	9.6	339	11.8	240	7.5	214	5.9	335	10.8
100	255	10	277	10.4	326	12.9	232	8.3	208	6.8	323	11.8
120	235	11	255	11.6	299	14.4	214	9.6	193	8.2	298	13.6
140	213	11	231	12.4	269	15.4	194	10.6	176	9.3	269	14.9
160	189	12	206	13.2	237	16.3	172	11.4	156	10.2	238	15.9
180	164	13	179	13.8	204	16.9	148	12.1	135	10.8	205	16.7
200	137	14	151	14.5	169	17.4	124	12.6	113	11.3	170	17.3
220	110	14	121	15.2	134	17.8	98.1	13.0	90.2	11.7	135	17.8
240	81	15	90	16.0	98.4	18.1	71.8	13.3	66.4	12.1	99	18.1
260	51	15	57	16.7	61.8	18.5	45.0	13.5	41.9	12.4	62	18.3
273	[a] 32	[a] 16	35	17.2	37.3	18.7	27.3	13.6	25.4	12.6	37	18.5
280	[a] 21	[a] 16	23	17.4	24.6	18.8	17.8	13.7	16.9	12.8	24	18.5
293	[a] 0	[a] 16	0	17.9	0.0	19.0	0.0	13.7	0.0	13.0	0	18.6
300	[a] −11	[a] 16	−13	18.1	−13.3	19.1	−9.6	13.8	−9.1	13.1	−13	18.6
Sources of above data	Fontana 1948		Beenakker and Swenson 1955		Altman, Rubin, and Johnston 1954		Aoyama and Ito 1939 Krupkowski and deHaas 1928		Altman, Rubin, and Johnston 1952		Beenakker and Swenson 1955	
Other refs.	Jaffee and Ramsey 1948				Beenakker and Swenson 1955 Fraser and Hollis-Hallet 1955 Henning 1907 Keyston, MacPherson, and Guptill 1959		Henning 1907 Krupkowski 1929					

[a] Estimated

[b] 9 Al, ≈1 Fe, 0.5 Ni, 0.5 Sn, bal. Cu. The accuracy of the original data is estimated as not better than ±10%. Jaffee and Ramsey give data above 170 °K for three compositions in various physical conditions.

[c] 2 Be, 0.3 Co, bal. Cu (BERYLCO 25). Originally half-hard, then heat treated for 2 hours at 200 °C. No observable difference was found in the thermal expansions for the two states of hardness.

[d] 65 Cu, 35 Zn.

[e] 50 Cu, 50 Ni. The name Constantan is applied to binary alloys in the range, 60 to 45 Cu, 40 to 55 Ni. The most common composition is 55 Cu, 45 Ni. The above expansion data should represent all Constantans within a few percent. Small expansion anomalies of magnetic origin occur in this system. The ferromagnetic Curie points range from about 0 °K for 40% Ni to roughly 150 °K for 55% Ni.

[f] 60 Ni, 15 Cr, 16 Fe, 7 Mo.

[g] Composition unknown. The compositions of alloys known by this name usually lie within the limits, 45 to 62 Cu, 10 to 30 Ni, 20 to 35 Zn.

Table 2.2. *Linear thermal contraction and coefficients of linear thermal expansion*—Continued

Alloys

T	Inconel [b]		Invar [c]	Monel [d]		Soft solder [e]		Steel, SAE 1020 [f]		Steel, SAE 1095 [g]	
	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$
deg K		*deg*$^{-1}$ *K*			*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0	[a] 229	0	[a] 52	[a] 251	0			[a] 202	0		
10	[a] 229		52	[a] 251	[a] 0.03						
20	229	[a] 0.03	52	251	[a] .2			202	[a] 0.1		
30	229	.3	52	251	.6			201	.3		
40	228	1.0	52	250	1.4			201	.8		
50	227	1.9	52	248	2.3			200	1.4		
60	224	2.8	52	245	3.4			198	2.3		
70	221	3.8	51	241	4.6			195	3.1		
80	217	4.8	50	236	5.7			192	4.0	213	6.7
90	211	5.7	49	230	6.7	467	19.6	187	4.8	206	6.9
100	205	6.5	47	223	7.5	447	20.0	182	5.5	199	7.2
120	191	7.9	43	206	8.9	407	20.7	170	6.8	184	7.8
140	174	9.1	39	187	9.9	365	21.4	155	7.8	168	8.3
160	154	10.0	34	167	10.8	321	22.2	138	8.7	151	8.9
180	134	10.7	29	144	11.5	276	22.9	120	9.4	132	9.8
200	112	11.2	23	121	12.0	229	23.5	101	9.9	112	10.4
220	89.1	11.6	18	96.4	12.5	182	24.1	80.7	10.4	90.5	11.3
240	65.6	12.0	14	70.9	12.9	133	24.6	59.6	10.8	67.1	12.0
260	41.4	12.3	8.6	44.7	13.3	83	25.0	37.7	11.1	42.5	12.6
273	25.2	12.5	5.2	27.1	13.5	51	25.2	22.9	11.4	26.0	12.8
280	16.6	12.6	3.4	15.1	13.6	33	25.3	15.1	11.5	17.0	12.9
293	0.0	12.9	0	0.0	13.8	0	25.4	0.0	11.7	0.0	13.2
300	−9.0	13.0	−1.8	−9.7	13.9	−18	25.5	−8.3	11.9	−9.3	13.3
Sources of above data	Altman, Rubin, and Johnston 1952		Beenakker and Swenson 1955	Altman, Rubin, and Johnston 1952		Dorsey 1907		Altman, Rubin, and Johnston 1952		Werner 1924	
Other refs.	Lucks and Deem 1958		Chevenard 1914 Gregg 1954 Masumoto 1934 Molby 1912 Scheel 1921	Ackerman 1936 Aoyama and Ito 1939 Fraser and Hollis-Hallet 1955 Krupkowski and de Haas 1928				Beenakker and Swenson 1955 Dorsey 1910 Gregg 1954			

[a] Estimated.
[b] 80 Ni, 14 Cr, 6 Fe.
[c] The expansions of the Invar alloys are sensitive to composition and heat treatment [see Metals Handbook, ASM, 1948, pp. 601–5]. The above data are for an alloy believed to be 42 Ni, 0.8 Mn, bal. Fe, annealed [Lloyd B. Nesbitt, private communication]. Although Beenakker and Swenson referred to this as "Invar", this composition approximates the alloy, Dumet, used for sealing to glass. In the iron-nickel alloy system, the minimum value of room temperature expansion coefficient occurs at about 36% Ni.
[d] 67 Ni, 30 Cu, 1.5 Fe, "cold-rolled".
[e] 50 Pb, 50 Sn.
[f] 0.18 C, 0.33 Mn, 0.01 Si, bal. Fe. According to Beenakker and Swenson, *cast iron* had the same thermal expansion as 1020 steel within their experimental uncertainty of $\pm 3\times10^{-5}$ in $\Delta L/L$.
[g] The above data are the average of two German steels that approximated the specification of SAE 1095. The steels were both "hard" and could be represented by the approximate composition: 1.1 C, 0.2 Si, 0.3 Mn, 0.02 S, 0.03 P. Their expansion coefficients differed from each other by about 10%. The expansion coefficients in the "soft" condition were also measured and were lower than the above values by 10% at 80 °K to 16% at 300 °K.

TABLE 2.2. *Linear thermal contraction and coefficients of linear thermal expansion*—Continued

Alloys

T	Steel, SAE 52100 [b]		Steel, AISI 301 [c]		Steel, AISI 302 [d]		Steel, AISI 304 [e]		Steel, AISI 310 [f]		Steel, AISI 316 [g]	
	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$
deg K		*deg⁻¹ K*		*deg⁻¹ K*		*deg⁻¹ K*		*deg⁻¹ K*		*deg⁻¹ K*		*deg⁻¹ K*
0					[a] 316	0	[a] 296	0			[a] 297	0
10					316	[a] 0.04	296	[a] 0.01			297	[a] 0.04
20					316	[a] .09	296	.02			297	[a] .09
30					316	.5	296	.62			297	.5
40					315	1.4	296	1.1			296	1.4
50					313	2.7	294	2.3			294	2.7
60					309	4.3	291	4.3			290	4.3
70					304	6.5	285	6.1			285	6.5
80	198	6.2			296	8.3	279	7.5			277	8.2
90	192	6.6	267	9.6	287	9.6	271	8.7	246	8.9	269	9.4
100	185	6.9	257	10.1	277	10.4	261	9.6	237	9.1	259	10.2
120	171	7.3	236	11.0	255	11.6	241	10.9	218	9.8	237	11.3
140	156	7.6	213	11.8	231	12.4	218	12.0	198	10.7	214	12.1
160	140	8.2	188	12.5	206	13.2	193	12.8	176	11.4	189	12.7
180	123	8.9	163	13.1	179	13.8	167	13.4	152	12.1	163	13.2
200	105	9.7	136	13.6	151	14.5	139	14.0	127	12.7	136	13.6
220	84.4	10.6	109	14.1	121	15.2	111	14.5	101	13.2	109	14.1
240	62.4	11.3	80.1	14.5	89.6	16.0	81.7	14.9	74.5	13.6	80.1	14.5
260	39.4	11.7	50.5	15.0	57.0	16.7	51.4	15.3	46.9	14.0	50.6	15.0
273	24.0	11.9	30.9	15.3	35.0	17.2	31.4	15.5	28.6	14.2	30.9	15.3
280	15.6	12.0	20.2	15.4	22.9	17.4	20.5	15.6	18.7	14.3	20.2	15.4
293	0.0	12.1	0.0	15.7	0.0	17.9	0.0	15.9	0.0	14.5	0.0	15.7
300	−8.5	12.1	−11.0	15.8	−12.7	18.1	−11.1	16.0	−10.2	14.6	−11.0	15.8
Sources of above data	Werner 1924		Furman 1950		Beenakker and Swenson 1955		Altman, Rubin, and Johnston 1954 Beenakker and Swenson 1955		Furman 1950		Beenakker and Swenson 1955	
Other refs.			Lucks and Deem 1958				Fontana 1948 Fontana, Bishop, and Spretnak 1953 Furman 1950				Furman 1950 Lucks and Deem 1958	

[a] Estimated.

[b] The measurements were made on a German steel that approximated the specifications of SAE 52100. Its composition was 0.94 C, 0.27 Si, 0.34 Mn, 0.95 Cr, bal. Fe. The above data adequately represent two "hard" samples, one of which was "heated at 780 °C", the other "quenched from 850 °C in oil and tempered at 630 °C". The expansion coefficients in the "soft" condition were also measured and were about 8% lower than the above values at 80 °K, about the same from 125 to 200 °K, and about 10% lower at 300 ° K.

[c] 0.13 C, 0.80 Mn, 0.54 Si, 16.9 Cr, 7.25 Ni, bal. Fe. Annealed 30 min at 1950 °F and water quenched. After cooling to 80 °K and rewarming to room temperature a small permanent expansion was found to have occurred due to irreversible formation of ferrite.

[d] Composition and heat treatment of sample not stated. Composition limits for this alloy are: 0.08–0.20 C, 2 (max.) Mn, 1 (max.) Si, 17–19 Cr, 8–10 Ni, bal. Fe.

[e] Composition limits for this alloy are: 0.08 (max.) C, 2 (max.) Mn, 1 (max.) Si, 18–20 Cr, 8–11 Ni. Altman et al., found small irreversible effects and, below 35 °K, small negative values of expansion coefficient. While we have given their results inferior weight in this region, the effects were undoubtedly real and attributable to martensitic transformation on cooling [Reed and Mikesell, 1958]. In this alloy the extent of transformation that is produced by cooling is sensitive to composition and has been found to vary from zero to about 50% [R. P. Reed, private communication]. Complete transformation would be accompanied by a mean increase in linear dimension of roughly 1% [Ward, Jepson, and Rait, 1952; and Fiedler, Averbach, and Cohen, 1955].

[f] 0.11 C, 1.51 Mn, 0.42 Si, 0.01 S, 0.02 P, 27.2 Cr, 21.6 Ni, bal. Fe. Annealed 30 min at 1950 °F and water quenched.

[g] Composition and heat treatment of sample not stated. Composition limits for this alloy are: 0.10 (max.) C, 2 (max.) Mn, 1 (max.) Si, 16–18 Cr, 10–14 Ni, 2–3 Mo, bal. Fe.

TABLE 2.2. *Linear thermal contraction and coefficients of linear thermal expansion*—Concluded

Alloys

T	Steel, AISI 322 [b]		Steel, AISI 330 [c]		Steel, AISI 347 [d]		Steel, AISI 410 [e]		Titanium, RC-130-B [f]		Titanium, Ti-150-A [g]	
	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$	$10^5\frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}}\frac{dL}{dT}$
deg K		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0							[a] 176	0				
20							176	[a] 0.06				
30							176	.2				
40							176	.4				
50							175	.9				
60							174	1.6				
70							172	2.4	218	5.0	168	3.9
80							169	3.2	213	5.4	164	4.3
90			208	5.6	262	9.4	165	4.0	208	5.8	159	4.6
100	146	5	202	6.3	253	9.8	161	4.7	202	6.3	154	5.0
120	136	5	188	7.5	233	10.5	150	6.0	187	7.1	143	5.7
140	124	6	172	8.5	211	11.3	138	7.0	172	8.0	131	6.4
160	112	7	154	9.3	187	12.1	123	7.7	155	8.8	118	7.0
180	98	7	135	10.1	163	12.8	107	8.3	137	9.7	103	7.6
200	83	8	114	10.8	136	13.4	89.4	8.8	117	10.6	87	8.2
220	67	8	91.6	11.5	109	14.0	71.4	9.2	95	11.4	71	8.7
240	50	9	68.0	12.1	80.2	14.6	52.6	9.5	71	12.3	53	9.2
260	32	9	43 3	12.7	50.6	15.0	33.2	9.8	46	13.1	34	9.7
273	20	10	26.6	13.0	30.9	15.3	20.3	10.0	28	13.7	21	10.1
280	13	10	17.4	13.2	20.2	15.4	13.2	10.1	19	14.0	14	10.2
293	0	10	0.0	13.6	0.0	15.6	0.0	10.3	0	14.5	0	10.5
300	−7	10	−9.6	13.8	−11.0	15.7	−7.2	10.4	−10	14.8	−7	10.7
Sources of above data	Fontana 1948		Furman 1950		Furman 1950		Altman, Rubin, and Johnston 1952		Bishop, Spretnak, and Fontana 1953 [h]		Bishop, Spretnak, and Fontana 1953 [h]	
Other refs.					Lucks and Deem 1958							

[a] Estimated.

[b] 0.07 C, 0.43 Mn, 0.53 Si, 17.0 Cr, 6.5 Ni, 0.12 Al, 0.37 Ti, bal. Fe. "Air cooled from 1900 °F and aged at 1000 °F for 40 min." These data are of a lower order of accuracy than the other data on steels in table 2.2.

[c] 0.05 C, 1.81 Mn, 0.62 Si, 0.006 S, 0.006 P, 15.3 Cr, 35.2 Ni, bal. Fe. Annealed 30 min at 1950 °F and water quenched.

[d] 0.07 C, 1.74 Mn, 0.56 Si, 0.006 S, 0.019 P, 18.65 Cr, 11.3 Ni, 0.77 Nb, bal. Fe. Annealed 30 min at 1950 °F and water quenched.

[e] 0.09 C, 0.32 Mn, 0.36 Si, 0.01 S, 0.01 P, 12.6 Cr, 0.12 Ni, 0.06 Cu, 0.03 N, bal. Fe.

[f] 0.24 C, 3.8 Mn, 3.8 Al, bal. Ti. Annealed one hr at 1300 °F and air cooled.

[g] 0.05 (max.) C, 2.7 Cr, 1.3 Fe, 0.08 (max.) N, bal. Ti. Annealed 6 hr at 1200 °F.

[h] Comparison of measurements in this paper on a commercially pure titanium with data from other sources (see Ti, table 2.1) suggests that the above data on titanium alloys may be grossly inaccurate.

TABLE 2.3. *Linear thermal contractions and coefficients of linear thermal expansion*

Other inorganic substances [e]

T	Carbon dioxide		Pyrex	Silica glass [b]	Ice [c]		Indium antimonide		Quartz (crystalline, ‖) [d]		Magnesium oxide	
	$10^4 \frac{L_{190}-L_T}{L_{190}}$	$\frac{10^6}{L^{190}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$10^5 \frac{L_{273}-L_T}{L_{273}}$	$\frac{10^6}{L_{273}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$	$10^5 \frac{L_{293}-L_T}{L_{293}}$	$\frac{10^6}{L_{293}} \frac{dL}{dT}$
deg K		*deg*$^{-1}$ *K*				*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*		*deg*$^{-1}$ *K*
0			[a] 54.7	[a] −8							[f] 139	0
10							83.7	−0.06			[f] 139	
20	266	32	55.7	−6.60			84.4	−0.10			[f] 139	[f] 0.02
30	262	49					86.2	−1.72			[f] 139	[f] .06
40	256	67	56.7	−4.90			87.2	−0.82			[f] 139	[f] .14
50	249	83					88.0	−0.33			[f] 139	[f] .27
60	240	98	56.2	−3.02			88.2	+0.28			[f] 138	[f] .45
70	229	116					87.6	0.89			[f] 138	[f] .8
80	216	132	53.7	−1.41	612	7.7	86.4	1.50			[f] 137	[f] 1.2
90	203	147			603	10.2	84.6	2.18	107	2.7	135	[f] 1.7
100	187	160	50.2	−0.12	592	12.7	82.2	2.76	104	3.1	[f] 133	[f] 2.3
110	171	·170										
120	153	177	46.2	+0.87	562	17.7	75.7	3.48	97.7	3.7	[f] 127	[f] 3.4
130	135	184										
140	117	190	41.7	1.61	522	22.7	68.6	3.83	89.8	4.2	[f] 119	[f] 4.6
150	97	197										
160	77	207	37.2	2.08	471	27.7	60.8	4.08	80.9	4.7	109	5.6
170	56	230										
180	31	272	32.2	2.32	411	32.7	52.6	4.27	71.2	5.1	97	6.6
190	0	351										
200			27.2	2.36	341	37.6	43.9	4.43	60.5	5.5	83	7.4
220			21.7	2.18	261	42.6	34.8	4.58	49.1	5.9	67	8.1
240			15.7	1.81	171	47.6	25.6	4.71	36.7	6.4	51	8.8
260			10.2	1.26	70	52.6	16.2	4.83	23.6	6.8	33	9.4
273			6.2	0.81	0	55.8	9.8	4.91	14.6	7.1	20	9.7
280			4.2	0.54			6.5	4.95	9.6	7.2	13	9.9
293			0.0	0.0			0.0	5.01	0.0	7.5	0	10.2
300			−2.3	−0.29			−3.5	5.04	−5.3	7.6	−7	10.3
Sources of above data	Keesom and Kohler 1933-4; Maass and Barnes 1926		Head and Laquer 1952	Keesom and Doborzynski 1934; Scheel and Heuse 1914	Powell 1958		Gibbons 1958		Buffington and Latimer 1926		Durand 1936	
Other refs.	Keesom and Kohler 1933		Buffington and Latimer 1926; Tool and Saunders 1948; Winter-Klein 1950	Beattie et al. 1941; Dorsey 1907; Head and Laquer 1952; Henning 1907; Scheel 1907; Scott 1933; Sosman 1927; Souder and Hidnert 1926; Valentiner and Wallot 1915	Dennison 1921; Dewar 1902; Jakob and Erk 1928; Konig 1944; Lisgarten and Blackman 1956; Lonsdale 1958; Shallcross and Carpenter 1957		Potter 1956		Dorsey 1908; Lindemann 1912; Nix and MacNair 1941; Scheel 1907; Sosman 1927			

[a] Estimated.

[b] The thermal expansion of silica glass (fused silica, vitreous silica, quartz glass), though small, is variable from sample to sample. The above values are thought to be fairly representative of average behavior. The temperature of minimum length can vary from 180 to 230° K. Variations from the above values as large as 2×10^{-5} below 180 °K and 50% from 180 to 300 °K are possible.

[c] According to Powell, ice is slightly anisotropic, the expansion coefficients parallel and normal to the optic axis differing by about 1×10^{-6} deg^{-1} K. The above values are an average over all directions. The only other extended investigation [Jakob and Erk] is not in good agreement with Powell and found negative expansion coefficients below about 70 °K.

[d] Measured parallel to the optic axis. Nix and MacNair measured expansions perpendicular to the optic axis but presented only a coarse graph of the results, from which the following values of $10^6(dL/LdT)$ were taken: 7 at 100 °K, 10 at 150°, 12 at 200°, 13 at 250°, 14 at 300 °K.

[e] Ebert [1928] has given two isolated data for ruby *mica* measured in the lamination plane. These are as follows: $10^5(L_{273}-L_{83})/L_{273}=120$ and $10^5(L_{273}-L_{20})/L_{273}=135$.

[f] Extrapolated using Gruneisen correlation as explained in Introduction.

Table 2.4. *Linear thermal contractions*

Plastics and elastomers [a]

T	$10^5(L_{293}-L_T)/L_{293}$									
	Araldite [b] 501	Catalin [c]	Dynakon [d] rod F	Dynakon [e] sheet A3A	Fluorothene [f] or Kel-F	Laminac [g] 4129	Lucite [h]	Nylon [i]	Panelyte ∥ [j] 942	Panelyte ⊥ [k] 942
deg K										
0	1061	849	282	428	1135	1202	1134	1389	364	836
20	1051	835	279	422	1114	1188	1123	1379	362	824
40	1022	811	271	407	1070	1154	1092	1352	355	801
60	983	779	261	388	1019	1104	1048	1308	344	770
80	935	740	248	366	962	1042	995	1247	329	733
100	880	695	233	342	900	971	936	1172	310	689
120	819	644	215	315	834	893	869	1088	288	639
140	751	588	194	286	763	811	796	996	263	584
160	676	528	172	255	686	724	717	896	236	524
180	594	464	148	222	604	632	632	789	207	459
200	505	397	123	187	517	535	540	673	176	389
220	410	325	98	150	424	432	441	548	143	314
240	308	247	72	111	324	323	335	412	108	235
260	199	161	45	70	214	207	220	265	70	151
273	122	100	27	42	134	126	136	161	43	93
280	81	67	18	28	90	84	91	107	29	62
293	0	0	0	0	0	0	0	0	0	0
300	−46	−40	−9	−15	−52	−47	−53	−61	−15	−32

[a] Data from Laquer and Head [1952].
[b] Epoxy casting resin made by Ciba Co. 40 g of the material was catalyzed with 2 ml triethanolamine. Cured 8 hr at 120 ° C and then 24 hr at 180 ° C.
[c] Phenolic plastic made by Catalin Corp. of Am. ⅜ in. diameter rod.
[d] Glass fiber reinforced, molded polyester rod, 0.146 in. diameter, made by Dynakon Corp., Cleveland, Ohio.
[e] Same except ⅛ in. thick sheet.
[f] Polychlorotrifluoroethylene. The samples were, respectively, from a 5 in. diameter rod of Fluorothene made by Union Carbon and Carbide and from a 1⁄16 in. thick sheet of Kel-F made by M. W. Kellog and Co.
[g] An unsaturated polyester made by American Cyanamide Co. Catalyzed with 0.5 wt. % of tert. butyl hydroperoxide. Cured 48 hr at room temperature followed by 1 hr at 100 ° C.
[h] Polymethylmethacrylate. "Probably Du Pont Lucite". Average of two samples from rod stock.
[i] From ¾ in. diameter rod. "Probably E. I. Du Pont de Nemours and Co., grade FM-1".
[j] From a 1 in. diameter rod, grade 942. This is a molded, cloth-base, laminated phenolic made by Panelyte Div., St. Regis Paper Co. Measured parallel to the lamination and normal to the rod axis.
[k] Same except measured normal to both the lamination and the rod axis.

Plastics and elastomers [a]

T	$10^5(L_{293}-L_T)/L_{293}$									
	Plexiglas [b]	Polystyrene [c]	Polythene [d]	Rubber, [e] hard	Rubber, [f] Silastic 160	Seleetron [g] 5026	Teflon [h]	Tenite I [i]	Tenite II [j]	Vinylite [k]
deg K										
0	1220	1550	2449	1272	2301	1319	2140	1850	2304	1303
20	1210	1522	2439	1263	2296	1305	2110	1830	2284	1288
40	1160	1466	2404	1240	2276	1270	2060	1785	2244	1249
60	1110	1394	2349	1213	2231	1217	2000	1730	2189	1193
80	1050	1308	2279	1174	2161	1150	1930	1670	2114	1125
100	990	1211	2194	1128	2066	1075	1850	1600	2019	1050
120	930	1105	2089	1069	1951	994	1760	1520	1904	969
140	860	992	1964	1001	1816	907	1660	1425	1764	882
160	780	874	1814	942	1656	815	1540	1315	1604	789
180	690	752	1639	834	1466	718	1400	1190	1424	691
200	590	626	1439	736	1246	615	1240	1045	1219	587
220	490	499	1199	625	996	505	1050	880	994	475
240	370	368	919	501	721	386	855	690	749	354
260	240	232	594	364	441	256	645	465	484	225
273	150	141	359	256	256	164	500	290	299	136
280	99	93	239	181	165	112		195	199	90
293	0	0	0	0	0	0		0	0	0
298							0			
300	−55	−51	−131	−117	−119	−69		−115	−111	−50

[a] Data from Laquer and Head [1952] except as otherwise noted. (In addition to the substances listed in the table, data have been given for 16 specially compounded rubbers by Dunsmoor et al. [1958] and Trepus et al. [1959]. These data consist mainly of values of $(L_{293}-L_{78})/L_{293}$. See also Wood, Bekkedahl, and Peters [1939].)
[b] Polymethylmethacrylate made by Rohm and Haas Co. Data from Giauque, Geballe, Lyon, and Fritz [1952].
[c] Average of two samples from rod stock, both "probably American Phenolic Corp. grade 912A".
[d] Polyethylene made by E. I. Du Pont de Nemours and Co. Molded under 2000 psi pressure at 150 °C for 10 min. Directional variations were negligible. See also Hunter and Oakes [1945]. Five filled polythenes were measured by Head and Laquer [1952].
[e] Measured normal to a 1 in. thick slab made by W. H. Salisbury and Co. Shore hardness was 90 on the A2 scale. See also Dorsey [1908].
[f] A silicone rubber, hardness 77, made by Dow Corning Corp. Molded under 200 psi at 120 °C for 10 min. Cured 15 hr at 150 °C, 7 hr at 200 °C, and 17 hr at 250 °C. A similar sample that was uncured had a hardness of 48 on the Shore A2 scale. It was too soft to measure closer than ±25%. Within these limits it was the same as the harder sample.
[g] An unsaturated polyester made by Columbia Resins Div., Pittsburgh Plate Glass Co. Catalyzed with 0.5 wt % tert. butyl hydroperoxide. Cured 48 hr at room temperature, then 1 hr at 100 °C.
[h] Polytetrafluoroethylene. Extruded and annealed sample measured by Kirby [1956]. He found that strained samples could have expansions larger or smaller than those of annealed Teflon, the differences being as large as 20%. Laquer and Head [1952] measured two samples of Du Pont Teflon rod taken normal and parallel to the extrusion direction. The expansions parallel were roughly 15% larger than those normal, and the average is 10 to 15% larger than the above data by Kirby. The data of Laquer and Head were used only to guide the extrapolation of Kirby's values below 80 °K. Teflon has a first order transition at 20 °C. Therefore we use 25 °C as a reference temperature and tabulate $10^5(L_{298}-L_T)/L_{298}$ above.
[i] Formula 0072-MS. A cellulose acetate made by Tennessee Eastman Corp. Molded under 5000 psi pressure at 150 °C for 20 min.
[j] Formula 205A-MS. Otherwise same as above.
[k] Average of two types with nearly identical expansions made by Bakelite Corp.: (1) VYDR. 95% vinyl chloride, 5% vinyl acetate. Stabilized with 5 wt % dibutyl tin maleate and molded under 6500 psi pressure at 150 °C for 5 min. (2) VMCH. 86% vinyl chloride, 13% vinyl acetate, ¾% dicarboxylic acid. Stabilized with 5 wt % dibutyl tin maleate and molded under 5000 psi pressure at 130 °C for 30 min.

Table 3. *Miscellaneous substances*

3.1. Mostly alloys. Data from Gregg [1954]

Substance	Rockwell Hardness	$10^4(L_{294}-L_T)/L_{294}$		
		T=194 °K	T=166 °K	T=77 °K
High speed steel (18 W, 4 Cr, 1 V)	C 63	11	14	20
High speed steel (6 W, 5 Mo, 4 Cr, 2 V)	C 64	11	13	20
High speed steel (18 W, 4 Cr, 2 V, 9 Co)	C 65	10	13	18
High speed steel (5 W, 4 Cr, 4 V, 4 Mo)	C 64	13	16	23
High speed steel (4 W, 5 Mo, 4 Cr, 1 V, 12 Co)	C 67	10	12	16
Tool steel (1.10 C)	C 66	12	14	20
Tool steel (0.90 C, 1.20 Mn, 0.50 Cr, 0.50 W)	C 63	12	14	20
Tool steel (0.50 C, 0.90 Cr, 1.25 W)	C 66	12	15	18
Tool steel (2.25 C, 12.00 Cr, 1.00 Mo)	C 64	13	14	20
Chrome vanadium steel (SAE 6150)	C 58	13	15	22
Aluminum (25)	H 64	22	28	31
Cast alloy (20 Co, 8 W, 7 Mo, 5 Cr, 2 V, 0.7 C, .7 B, bal. Fe)	C 69	9	11	15
Cast alloy (44 Co, 17 W, 33 Cr, 2.25 C, 2 Fe)	C 58	10	13	18
Carboloy (Grade 44 A)	A 91	2	3	8
Bronze [a] (SAE 660)	F 78	19	22	33
Cast iron [b]	B 85	11	13	19

[a] See also Henning [1907].

[b] See also Beenakker and Swenson [1955], Chevenard [1926].

3.2. Various alloys. Data from Lucks and Deem [1958]

Substance [d]	Condition	$10^5(L_{293}-L_T)/L_{293}$		
		T=200 °K	T=144 °K	T=116 °K
Aluminum, 2024 [a] (4.5 Cu, 1.5 Mg, 0.6 Mn)	T 4 [e]	194	294	345
Aluminum, 7075 [a] (5.5 Zn, 2.5 Mg, 1.5 Cu, 0.3 Cr, 0.2 Mn).	T 6 [e]	185	276	314
Inconel-X (73 Ni, 15 Cr, 7 Fe, 2.5 Ti, 1 Cb, 0.7 Al, 0.4 Si, 0.5 Mn).	Hot rolled. Solution treated 3 hr at 2100 °F, air cooled. Double aged 24 hr at 1550 °F, air cooled; 20 hr at 1300 °F, air cooled.	113	176	206
Magnesium, AN–M–29 (3 Al, 1 Zn, 0.3 Mn)	Hot rolled. Annealed 1 hr at 600 °F. Furnace cooled	[b] 231	[b] 353	[b] 408
"K" Monel [c] (66 Ni, 29 Cu, 2.75 Al, 0.9 Fe, 0.75 Mn, 0.5 Si, 0.15 C, 0.005 S).	Hot rolled. Annealed 1 hr at 1650 °F. Water quenched	115	176	206
Steel, SAE 1010 (0.10 C, 0.5 Mn)	Hot rolled	98	148	172

[a] See also Fontana [1948, 1953].

[b] Average of three mutually perpendicular orientations. Values in the rolling direction were 2% lower; values in the rolling plane but transverse to the rolling direction were 5% lower; values normal to the rolling plane were 7% higher.

[c] K-Monel has a Curie point at about 160 °K. The above data are too sparse to indicate if there is an appreciable anomaly in the expansion at the Curie point.

[d] The compositions given are nominal or average ones for these alloys. They were taken from the ASM Metals Handbook, 1948 edition, in which alloy 2024 is listed as alloy 24S, alloy 7075 is listed as alloy 75S and magnesium AN–M–29 is listed as alloy AZ31X.

[e] Solution treatment and precipitation. See ASM Metals Handbook for details.

3.3. Optical glasses. Data from Molby [1949] [c]

T	$10^5\frac{L_{293}-L_T}{L_{293}}$													
	Crown C–1 [a]	Borosilicate crown BSC–1 [a]	Borosilicate crown BSC–2 [a]	Light barium crown LBC–2 [a]	Dense barium crown DBC–1 [a]	Dense barium crown DBC–3 [a]	Dense flint DF2 [a]	Extra dense flint EDF–3 [a]	Barium flint BF–1 [a]	Crown flint CF–1 [a]	Glass #11 [b]	Glass #32 [b]	Glass #33 [b]	Glass #45 [b]
deg K														
80	134	133	112	137	110	105	136	139	142	110	100	102	92	96
90	130	128	109	132	107	101	131	135	137	107	97	99	90	94
100	126	124	105	128	104	98	126	130	133	104	94	96	87	91
120	116	114	97	117	95	90	115	118	122	95	88	89	83	85
140	106	104	88	106	87	82	104	106	111	87	80	81	74	78
160	95	92	77	95	77	73	92	94	98	77	72	72	66	70
180	82	80	66	82	67	63	79	81	85	67	63	63	58	62
200	69	67	57	68	56	53	66	67	71	56	53	53	49	52
220	55	53	45	54	44	42	52	53	56	44	42	42	39	42
240	41	39	33	40	33	31	38	39	41	33	31	31	29	31
260	26	25	21	25	21	20	24	25	26	21	20	20	18	20
273	16	15	13	15	13	12	15	15	16	13	12	12	11	12
280	10	10	8	10	8	8	9	10	10	8	8	8	7	8
293	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	−6	−6	−5	−5	−5	−4	−5	−5	−5	−5	−4	−4	−4	−4

[a] Bausch and Lomb Co. designation. Composition was not given.

[b] Eastman Kodak Co. designation. Composition was not given.

[c] Dorsey [1907] also gives data on a crown glass. Composition not stated.

TABLE 4. *Anisotropy of single crystals*

4.1.[a] Antimony, beryllium, bismuth, tin (white)

T_2	T_1	$\frac{10^6}{L_{293}}\frac{L_2-L_1}{T_2-T_1}$							
		Antimony		Beryllium		Bismuth		Tin (white)	
		‖	⊥	‖	⊥	‖	⊥	‖	⊥
deg K	*deg K*	*deg⁻¹ K*	*deg⁻¹ K*	*deg⁻¹ K*	*deg⁻¹ K*	*deg⁻¹ K*	*deg⁻¹ K*	*deg⁻¹ K*	*deg⁻¹ K*
293	273	16.18	8.24	8.59	11.70	16.20	11.60	28.99	15.83
273	233	16.17	8.11	7.58	10.73	16.20	11.53	27.98	15.60
233	193	16.15	7.84	5.81	8.65	16.20	11.38	26.67	15.00
193	153	16.11	7.43	3.97	6.09	16.08	11.04	25.69	14.22
153	113	16.09	6.78	2.07	3.45	15.94	10.59	24.44	13.08
113	90	15.81	6.04	0.73	1.58	15.86	9.89	23.23	11.79
90	78	15.48	5.27	--------	0.79	15.55	9.25	22.45	10.66
90	57	--------	--------	0.13	--------	--------	--------	--------	--------
78	58	14.7	4.2	--------	--------	14.9	8.5	20.57	8.58
58	20	--------	--------	--------	--------	13.3	5.1	--------	--------

[a] The tabulated values are average expansion coefficients in the intervals, T_1 to T_2, measured parallel and normal, respectively, to the trigonal (antimony, bismuth), hexagonal (beryllium), or tetragonal (tin) axis. The data are from Erfling [1939].

4.2.[a] Cadmium, zinc

T_2	T_1	$\frac{10^6}{L_{293}}\frac{L_2-L_1}{T_2-T_1}$			
		Cadmium		Zinc	
		‖	⊥	‖	⊥
deg K	*deg K*	*deg⁻¹ K*	*deg⁻¹ K*	*deg⁻¹ K*	*deg⁻¹ K*
293	253	54.3	19.1	64.3	+12.5
253	213	55.4	17.8	65.1	11.3
213	173	56.7	16.4	65.4	10.1
173	133	58.0	14.6	65.6	8.3
133	93	58.9	11.7	64.4	+5.0
86	20	54.5	3.6	52.5	−2.1

[a]The tabulated values are average expansion coefficients in the intervals, T_1 to T_2, measured parallel and normal, respectively, to the hexagonal axis. The data are from Gruneisen and Goens [1924].

4.3.[a] Magnesium

T_2	T_1	$\frac{10^6}{L_{293}}\frac{L_2-L_1}{T_2-T_1}$	
		‖	⊥
deg K	*deg K*	*deg⁻¹ K*	*deg⁻¹ K*
293	193	25.7	24.3
193	90	20.3	18.8
90	78	13.8	13.0
78	20	5.8$_8$	5.3$_8$

[a]The tabulated values are average expansion coefficients in the intervals, T_1 to T_2, measured parallel and normal, respectively to the hexagonal axis. The data are from Goens and Schmid [1936].

4.4. Mercury

T	10⁶×Expansion coefficient[a]		Source
	‖	⊥	
deg K	*deg⁻¹ K*	*deg⁻¹ K*	
158	49.8	37.7	Hill [1935]
113	44.9	35.2	Hill [1935]
83 to 113	42.6	33.4	Hill [1935]
85 to 194	47.0	37.5	Gruneisen and Sckell [1934]

[a]The first two lines give instantaneous expansion coefficients, $10^6(dL/LdT)$, while the last two lines give average expansion coefficients, $(10^6/L)[(L_2-L_1)/(T_2-T_1)]$, in the indicated temperature intervals. The directions of measurement were parallel and normal, respectively, to the trigonal axis.

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