DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
George K. Burgess, Director

LIGHT METALS AND ALLOYS
ALUMINUM
MAGNESIUM

CIRCULAR OF THE BUREAU OF STANDARDS, No. 346

B. S. Circular 346 - Please correct text as follows:

Fig.	Page	Should read
38	103	"Corson 2a" (not "Tammann, 52b, Bornemann, 62a"
42	105	omit "Corson"
44	107	"57cc" (not "57c")
47	109	"60d" (not "61d")
48	111	"Guillet, Rev. de Met. 18,1921,p.500" (not "Guillet, 61a,Curry,61v,Dix and Richardson 61a")
55	117	"68k" and "68a" (not "68k")
59	121	"Guillet, Rev. de Met. 18, 1921, p.500" (not "Guillet, 681")
61	123	"Fraenkel 76 (1908 ref.)" (not "Fraenkel 76")
68	128	"Guillet, Ref.de Met. 18, 1921, p. 511" (not "Guillet, 681")
70	130	"Gwyer (1906 ref.) p. 381 this circ." (not "Gwyer 82b")
74	162	"test" (not "text")
Table 39	141	line 1 - "Corbin" (not "Cobin") line 2 - "Belgian" (not "Began")
Sec.71	378	"Niobium" (not "Niobrium").

DEPARTMENT OF COMMERCE
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CIRCULAR OF THE BUREAU OF STANDARDS, No. 346
[Supersedes Circular No. 76]

LIGHT METALS AND ALLOYS

ALUMINUM
MAGNESIUM

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and by the chapter on aluminum in volume 5 of Mellor's treatise on inorganic chemistry (2i). Each of these deals with the subject from a somewhat different point of view than does this circular. These books will be found of value in a study of the subject, and they should be available to every student of the subject.

Matters fully dealt with in these books have therefore been given more brief reference than would otherwise have been required. The scope of the subject has become so great that it is not possible to go into detail on all phases. The effort has been to give briefly the most important and fundamental properties of the metal and its alloys and to make clear through the bibliography and the references to it the sources of more detailed information. Since the bibliography has been classified the sections of it pertinent to the particular phase being looked up should be consulted, since reference can not be made in the text to all or even the most important publications dealing with it. Extensive bibliographies are given by Anderson and by Mellor.

Much of the most valuable recent information on aluminum alloys has resulted from systematic research by the McCook Field Station of the United States Army Air Corps, by the Naval Aircraft Factory, by the United States Bureau of Mines, by the research staff of the Aluminum Co. of America, and by the National Physical Laboratory, of England, as well as by individual investigators in this and other countries, all reported in periodical technical literature. Such data, together with that collected in the previous edition of this circular, as well as the published and unpublished investigations of the Bureau of Standards itself, form the basis for this compilation.

The first edition was compiled by P. D. Merica, with the collaboration of many others of the bureau staff. This edition has been compiled by Miss M. G. Lorentz, with the aid of many others in the bureau, each of whom has aided in the phases upon which his experience best fitted him to pass.[2] Most of the sections have been read by members of the technical staff of the Aluminum Co. of America,[3] and that on duralumin by representatives of the Baush Machine Tool Co. as well. The section on magnesium has been read by the technical staff of the American Magnesium Corporation [3] and by that of the Dow Chemical Co. Many useful suggestions have been received from these readers, to whom grateful acknowledgment is made

The section on silicon and beryllium has been read by representatives of the Carborundum Co., the Electro-Metallurgical Corporation, and the Beryllium Corporation of America.

---

[2] Among those who have thus aided materially are W. Blum, H. C. Dickinson, J. R. Freeman, jr., H. J. French, H. W. Gillett, G. E. F. Lundell, W. F. Meggers, S. N. Petrenko, P. Hidnert, G. W. Quick, H. S. Rawdon, J. A. Scherrer, F. Sillers, jr., H. N. Solakian, W. Souder, M. R. Thompson, L. B. Tuckerman, H. C. Vacher, G. W. Vinal, M. Van Dusen, and F. Wenner.

[3] Especial thanks are due for much information and for constructive criticism from J. D. Edwards, of the Aluminum Co. of America; S. K. Colby, of the American Magnesium Corporation; R. W. Daniels, of the Baush Machine Tool Co.; and J. A. Gann, of the Dow Chemical Co.

LIGHT METALS AND ALLOYS—ALUMINUM, MAGNESIUM[1]

ABSTRACT

The physical and mechanical properties of aluminum and magnesium and of their light alloys, and the variation in properties caused by changing the composition of the alloy, by the presence of impurities, by mechanical working, by changes in conditions of manufacturing operations, and by heat treatment are given. The selection of the data available has been made and the data have been checked by representatives of the light-alloy industries in order to present reliable data. Equilibrium diagrams for the important alloy systems are given. The metallography, corrosion resistance, and methods of protection against corrosion, the theory of heat treatment, and the application of the alloys to industry are discussed. A selected and classified bibliography is appended.

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[1] Of this series, Circular No. 58 (2d ed. revised) on Invar and Related Nickel Steels, Circular No. 73 on Copper, and Circular No. 100 on Nickel, have already been issued.

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A. ALUMINUM

I. COMMERCIAL ALUMINUM

1. SOURCES, METALLURGY

Although the element aluminum constitutes approximately 8 per cent of the earth's crust, mainly in the form of clay, feldspar, and other double or complex silicates, it is from a less common but rather widespread ore that commercial aluminum is manufactured. This ore is bauxite, which is a hydrated oxide of aluminum with minor amounts of iron oxide, silica, and titanium oxide. It takes its name from the town of Baux, France, where it is found. Commercial deposits are located in France, Dalmatia, Istria, Yugoslavia, India, British Guiana, Surinam, and in the States of Arkansas, Georgia, Alabama, and Tennessee, to name only a few of its places of occurrence. Cryolite (Na_3AlF_6) is a relatively rare mineral used in the manufacture of aluminum; the only commercial deposit is found at Ivigtut, Greenland. A considerable amount of the cryolite used in the manufacture of aluminum is made artificially.

The distribution of the ores is discussed by Spurr (2b).[2]

The first preparation of metallic aluminum by reduction of aluminum chloride with potassium amalgam was described by Oersted in 1825 (4b). Wöhler reduced aluminum chloride with potassium in 1827. Thus, the metal has been isolated for over a century, though it was merely a laboratory curiosity for the first 25 or 30 years.

Production by reduction with sodium, the Deville method, was taken up, and by 1855 bars of the metal were available in such size that the physical properties could be studied.

The sodium-reduction method was expensive and the product likely to be contaminated with sodium. Not until Hall and Heroult invented the present electrolytic method of manufacture, about 1886, did the commercial possibilities for the use of aluminum become apparent.

The present-day metallurgy of aluminum is based on the experience of the last 40 years, in which period a huge industry has been developed and the metal has been applied to a myriad of engineering and household uses.

The manufacture of metallic aluminum consists properly of two operations: (*a*) The preparation of pure raw materials, aluminum oxide (Al_2O_3) and cryolite (Na_3AlF_6), and (*b*) the electrolysis of the aluminum oxide dissolved in a fused mixture of cryolite, with or without other fluoride compounds.

---

[2] The figures given in parentheses here and throughout the text relate to the reference numbers in the bibliography given at the end of this paper.

Bauxite as mined contains from 1 to 30 per cent of both iron oxide (Fe_2O_3) and silica, from which it must be freed before its addition to the electrolytic bath, since otherwise these metals would pass into the cathode metal in large quantities, being more readily separated from their oxides than aluminum. Two processes for doing this are in use. The older process, due to Le Chatelier and Morin, commonly known as the Deville process, consisted in roasting the powdered bauxite with soda, whereby sodium aluminate ($NaAlO_2$), silica (SiO_2), and iron oxide (Fe_2O_3) are formed. The sodium aluminate is then dissolved in water, leaving undissolved iron oxide and silica. From this solution aluminum hydroxide ($Al(OH)_3$) is obtained by passing carbon dioxide (CO_2) through it, by which aluminum hydrate is precipitated, forming soda (Na_2CO_3) anew. The aluminum hydrate is calcined to oxide. The Bayer method produces the sodium aluminate by treatment of bauxite with sodium hydroxide solution under pressure (five atmospheres of steam pressure). From this solution the greater part of the aluminum hydrate is precipitated by stirring with pure aluminum hydrate.

The natural cryolite is generally used in this country, but some artificial salt is produced, particularly abroad.

The electrolysis is carried out in carbon-lined pots, say, 3 by 4 by 7 feet long, using a bath of oxide and cryolite (with or without other fluoride additions, such as aluminum fluoride, fluorspar, etc.) containing not more than 20 per cent of oxide. The carbon lining serves as the cathode and carbon blocks as anodes.

Since 0.75 to 1 pound of anode carbon is consumed in the production of 1 pound of aluminum, the manufacture of the anodes is an important part of the process. In order to secure sufficiently pure metal the anodes must be of very pure carbon—petroleum coke, for example. Since such metallic oxides as those of iron and silicon are reduced in the electrolysis more readily than is aluminum oxide, their presence in any but very small amounts must be rigorously avoided both in the anodes and in the aluminum oxide. The purification of the ore and the need for pure carbon account for a considerable proportion of the total cost of production.

Molten aluminum has a lower specific gravity than the solid metal, and the specific gravity of the molten bath is scarcely 10 per cent less than that of the molten metal. The composition of the bath has to be chosen and kept adjusted so that the deposited metal will sink to the bottom of the bath. The concentration of Al_2O_3 in the bath must not be allowed to drop below that at which the "anode effect," the formation of a gas film about the anode, appears. The first sign of the anode effect (shown by an increase in the voltage of the cell) is a signal for the stirring into the bath of more Al_2O_3 which has been resting on the surface crust of the bath to be preheated.

The electrolysis is usually carried out at a temperature of from 900 to 1,000° C., using a current density of about 700 amperes per square foot and a bath potential of 6 to 8.5 volts. The heating is accomplished by this current, the theoretical decomposition voltage being about 2.1 volts (2c). Approximately 12.5 kilowatt-hours are required for the production of 1 pound of metal.

As the electrolysis proceeds aluminum oxide is added to replace that decomposed by the electrolysis. The molten aluminum is tapped from the reduction pots every one to four days into small ladles and from this into a large ladle. From this mixing ladle it is poured into ingot molds, furnishing commercial aluminum, which is usually remelted with other lots for further mixing.

The details of the electrolytic method of production as to purification processes, size of reduction pots, bath composition, etc., vary considerably in different plants and are less fully described in the literature than is the case in regard to the smelting of any other metal of major importance. A general but not detailed picture of commercial practice may be gained from references (2c) and (4a).

While much has been said about making aluminum from clay, bauxite continues to be used as the only ore. Lower-grade bauxites are continually being used, but when the cost of purification plus freight on near-by lower-grade ore exceeds those costs upon a more remotely located higher-grade ore a plant controlling sources of both grades of ore will naturally use the latter. Various processes for production of pure alumina suitable for reduction to metal as a by-product in production of other materials, such as fixed nitrogen through the aluminum-nitride process, have been suggested or tried, but none seems to be on a commercial basis.

Purification of aluminum oxide by other means than in the wet way, through sodium aluminate, is still in the development stage. The Al_2O_3 must be in such a condition that it is readily soluble in the cryolite bath. The only variation in the usual procedure receiving much publicity at present appears to be the Haglund process (4c), involving electrothermal purification of bauxite to produce a relatively pure mixture of aluminum oxide and sulphide, which is said to be undergoing commercial trial by the German Government (96g).

Those who were mainly instrumental in developing the present type of electrochemical reduction process for aluminum were Hall (1886), Heroult (1886), Kiliani (1889), and Hoopes (1900) (4e).

2. COMMERCIAL GRADES, SPECIFICATIONS

In this country three commercial grades of aluminum are produced: (*a*) Grade A, containing 99 per cent or more aluminum, and (*b*) grade B, containing from 98 to 99 per cent aluminum, the third grade containing 94 to 98 per cent aluminum. The first grade is largely used for wrought aluminum ware and for the preparation of light alloys for rolling and castings. The second grade is used in the steel industry, and sometimes for casting alloys, and the third grade is used entirely in the steel industry.

Within grade A the purest metal is generally reserved for manufacture of electrical conductors on account of its lower electrical resistivity. "Conductor grade" is therefore the purest metal now available in large quantity, being exceeded in purity only by the special electrically refined grade.

Metal next lower in purity is employed for uses involving severe deformation, as in "deep-drawn" stamped products and much wrought aluminum ware. For some cases where extreme deformation is required, as in collapsible tubes for ointments and creams, for example, the desired deformation can be obtained only in the special refined grade. The least pure of the grade A metal finds use in castings, but unless the metal has been specially selected it is rare that metal much above 99.4 per cent aluminum is available for casting purposes.

The impurities in commercial aluminum are chiefly iron and silicon, although minor amounts of copper are sometimes found. In the A grade the aluminum content will normally average about 99.2 per cent, with silicon varying from 0.15 to 0.40 per cent and iron varying from 0.25 to 0.70 per cent. The iron content is usually greater than the silicon content. Copper will vary from a trace only to over 0.05 per cent. Sodium is in recent years found only in traces if present at all. The B grade is characterized by the presence of more iron and a somewhat greater silicon content.

In commercial operation the metal is graded only on the basis of the minimum aluminum content, no guaranty being given on the maximum percentages of individual impurities in any of the commercial grades.

Aluminum containing 99.983 per cent aluminum (by difference) with 0.005 Si, 0.005 Fe, 0.007 Cu has been made by the Aluminum Co. of America by the special refining process described under the heading "Electrolytically refined aluminum." Metal made by this process is commercially available in several grades with a purity of 99.8 per cent aluminum and higher.

Aluminum comes on the market in several forms:

Ingots for remelting.—Either "waffle" ingots, consisting of series of square plaques 3 by 3 by ¾ inches, connected by a thin web, or notched-bar ingots about 14 inches long by 1¼ inches wide as well as a variety of other sizes and shapes.

Rolling ingots of different sizes.—3½ by 12 by 24 inches; 3 by 12 by 32 inches; 2 by 12 by 20 inches; 1⅜ by 12 by 18 inches.

Rolling slabs.—Ingots broken down to about ⅜ inch in thickness.

In Table 1 are given the compositions of aluminum ingots for remelting as given by specifications from various sources.

Table 1.—*Specifications for aluminum ingot for remelting*

Specification	Designation	Grade	Aluminum (minimum)	Copper (maximum)	Si plus Fe (maximum)	Mn, Cu, and other impurities	Cu and Zn	Mn, Mg, Zn, Cd, etc.	Total impurities (maximum)
			Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
F. S. B.[1]	134	A	99.0	--------	0.80	0.25	--------	--------	--------
		B	98.0	--------	1.50	.50	--------	--------	--------
A. S. T. M.[2]	B24-26T	99.5	99.5	0.10	Allowable	--------	--------	Not admissible.	0.5
		99.0	99.0	.25	do	--------	--------	do	1.0
		98	98.0	.45	do	--------	--------	do	2.0
ÖNIG[3]	Virgin aluminum.[4]	99.5	99.5	--------	0.5	--------	0.05	--------	--------
		99	99	--------	1.0	--------	.10	--------	--------
		98-99	98-99	--------	2.0	--------	.10	--------	--------
ÖNORM, M3426.	Remelted[4]	99	99	--------	--------	--------	--------	--------	--------
		98	98	--------	--------	--------	--------	--------	--------
		97	97	--------	--------	--------	--------	--------	--------

[1] F. S. B.=Federal Specifications Board, Bureau of Standards, Washington, D. C.

[2] A. S. T. M.=American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa.

[3] ÖNIG=Österreichischer Normenausschuss für Industrie und Gewerbe, Wien 111, Lothringerstrasse 12.

[4] Specific gravity, 2.7.

ÖNORM=Austrian standard.

3. ELECTROLYTICALLY REFINED ALUMINUM

In the previous edition of this circular the purest samples of aluminum mentioned as obtained up to 1919 were one of 99.66 per cent described by Richards and Thomson in 1897, and one of 99.67 per cent used by Northrup in 1917. The Bureau of Standards standard melting point sample prepared in 1923 has a purity of 99.66 per cent. Only rarely had metal of 99.7 per cent been produced up to that time. The most carefully selected metal used for scientific investigations of the properties of the metal and its alloys has in the past seldom been better than 99.6 per cent, and much such work has been done with 99.4 to 99.5 per cent metal as the best available to the particular worker at the time the work was done.

Since 1924, however, aluminum refined by the Hoopes process has been prepared as pure as 99.983 per cent. Substantial quantities have been produced with a purity above 99.95 per cent, with a still larger amount running over 99.9 per cent.

This great advance in purity has been obtained by subjecting to a second electrolysis aluminum that has first been prepared by the usual method and has been alloyed with copper to raise the specific gravity. This heavy alloy lies molten at the bottom of a cell and forms the anode layer from which aluminum is to be dissolved into the electrolyte and redeposited. The second layer is the electrolyte, a molten cryolite, aluminum fluoride, barium fluoride mixture. The top layer, the cathode, consists of purified aluminum. All three layers are molten and are kept separated by gravity.

When impurities, such as iron, silicon, and copper, are dissolved in the cryolite bath in the usual or primary electrolysis of Al_2O_3 with an insoluble anode, they tend to be deposited at the cathode before the aluminum. When the impurities are in the anode, however, they are the last to dissolve in the electrolyte. Thus, practically aluminum alone, with only minor traces of impurities, goes into the electrolyte for deposition at the cathode.

The process was described by Frary (4e) in 1925, and at the same time Edwards (33b) reported on some of the properties of the pure metal. The ductility of the pure material is much above that of the purest unrefined metal, the tensile strength lower, the electrical conductivity higher, the resistance to atmospheric corrosion and to attack by some chemicals higher, and, in general, all its properties vary from those of the purest material formerly available in the direction that would be expected. Hence an entirely new set of physical constants for the purest obtainable aluminum, in so far as those constants have been determined, is available for inclusion in this revision of this circular.

Similar revision of the properties of the alloys of aluminum will ultimately be available when scientific study of the various binary, ternary, and more complex systems has been made. Such studies are under way, and since most scientists will use the purest materials for study of aluminum alloys the properties of the alloys made with refined aluminum will in time be put on record.

One case of a notable increase in properties through the use of very pure aluminum has already been recorded. Archer and Jeffries (35a) have obtained a tensile strength of 50,000 lbs./in.^{2} with an elongation of 10 per cent, and in some cases even better figures on heat-treated sand-cast aluminum-copper alloys made from high-purity aluminum, while alloys of similar composition and treatment made from commercial aluminum show 31,000 lbs./in.^{2} and 8 per cent. Even these latter figures are decidedly in advance of those shown by unheat-treated alloys of similar composition, in which 20,000 lbs./in.^{2} and 2 per cent elongation would be considered satisfactory figures.

However, while it is probable that in other cases alloys with new or markedly improved properties may be developed, it is unlikely that the difference in properties between the old and the new alloys will, in general, be as marked as in this case or between the old and the new metal itself. Alloying aluminum with another metal generally produces a harder alloy, and for most purposes this increased hardness and the increase in other properties that accompanies it, are what is desired. Since the hardening produced by the amounts of alloying elements normally used in the alloys is far greater than that produced by the 0.3 to 0.5 per cent of iron, silicon, and copper found as impurities in the best commercial unrefined aluminum, it is not to be expected that any very great difference would be found in the properties of most alloys of commercial compositions, whether 99.5 or 99.9 per cent aluminum were used in their preparation. An increase of 0.5 per cent in the amount of intentionally added alloying element would very often bring to the alloy made with 99.9 per cent aluminum properties quite similar to those made from 99.5 per cent aluminum.

A much better understanding of the effect of iron and silicon as impurities in alloys with other metals will be obtainable when the alloys may be made up free from iron and silicon, and with this better theoretical understanding commercial advances will be made that will be well worth having. Alloys that are now considered as binary, being made up of commercial aluminum, with a little iron and silicon, plus an intentional alloying element, will come to be considered as quaternary. But from the engineering and commercial point of view greater advances are in sight in respect to the unalloyed metal for such uses as electrical conductors and for deep-drawing and forming under extreme distortion than in the alloy field as a whole.

Thus, while for a great many present uses of pure aluminum and for those new ones which will appear as a result of acquaintance with the properties of the refined metal, considerable commercial changes will be wrought when refined metal is available in any quantity desired, the probable lack of material differences in the properties of most common alloys of aluminum and the extra cost of the metal due to the added refining process do not presage many immediate commercial changes in the alloy field.

The data given herein for the properties of alloys made from commercial, unrefined metal may therefore be expected to be applicable for most commercial purposes for some time to come.

Since the refining process uses a copper aluminum alloy as anode, there is a possibility that the old Cowles process for the reduction of Al_2O_3 with carbon by the electrothermal method in the presence of copper to form an aluminum copper alloy might to some extent serve as a primary smelting process instead of the present electrolytic method. Since the Cowles process is adapted only to alloys rather rich in copper, such a method could hardly be relied upon to produce direct an alloy suitable for refining without addition of more aluminum made by the electrolytic method.

Von Göler and Sachs (33a) have compared aluminum of 99.93 per cent purity (American electrolytically refined) with commercial aluminum of 99.09 and of 98.70 per cent purity. The 99.09 per cent grade contained about 0.5 per cent Si and 0.4 per cent Fe with traces of Cu and Zn while the 98.70 per cent grade contained, besides Fe and Si, about 0.25 per cent Cu and 0.10 per cent Zn. Sheet cold-rolled from 5 to 1 mm (96 per cent reduction) was annealed for one-half hour at various temperatures. Complete annealing was obtained in all specimens at about 250° C. Grain growth and consequent decrease of elongation in the tensile test was much more marked at temperatures above 375° C. in the purest material than in the impure ones. X-ray studies by the pinhole method helped to establish the facts as to grain growth.

On the basis of a very small increase in tensile strength of the 99.93 per cent material on quenching after heating at 500°, over that of the fully annealed material, Von Göler and Sachs conclude that the 0.010 per cent Si and 0.024 per cent Fe present are not in stable solid solution at room temperature.

4. PRODUCTION, PRICE

Table 2 gives a general idea of the world's production and consumption of aluminum. Both production and consumption have increased within the past 20 years at a remarkable rate. The United States leads the world in production.

Table 3 gives the average yearly prices for ingot aluminum from the beginning of its manufacture on a commercial scale, and Table 4, the value of domestic production, imports, and exports from 1913 to 1925, inclusive.

TABLE 2.—*World's production of aluminum (in metric tons)* [1]

Year	Austria	Canada	France	Germany	Great Britain	Italy	Norway	Switzerland	United States [2]	Total
1902	--------	--------	1,500	[3] 2,700	650	--------	--------	--------	3,650	--------
1903	--------	--------	1,800	[3] 2,700	760	--------	--------	--------	--------	--------
1904	--------	--------	1,900	[3] 3,300	760	--------	--------	--------	--------	--------
1905	--------	--------	3,300	[3] 3,300	1,100	--------	--------	--------	--------	--------
1906	--------	--------	4,400	[3] 3,850	1,100	--------	--------	--------	--------	--------
1907	--------	--------	6,600	[3] 4,400	1,980	--------	--------	--------	--------	--------
1908	--------	--------	6,600	[3] 4,400	2,200	660	--------	--------	--------	--------
1909	--------	--------	6,600	[3] 5,500	3,100	880	660	--------	14,550	--------
1910	--------	--------	10,500	[3] 8,800	5,500	880	990	--------	17,750	--------
1911	--------	--------	11,000	[3] 8,800	5,500	880	990	--------	19,850	--------
1912	--------	--------	14,300	[3] 13,200	8,300	880	1,650	--------	19,850	--------
1913 [4]	5,000	5,916	[5] 13,503	800	10,000	[5] 874	2,500	10,000	29,500	78,093
1914	4,000	6,820	[5] 9,967	800	8,000	[5] 937	2,500	10,000	40,600	82,924
1915	2,500	8,490	[5] 6,020	2,000	6,000	[5] 904	3,500	12,500	45,000	86,914
1916	5,000	8,800	[5] 9,604	8,000	4,000	[5] 1,126	6,000	15,000	63,000	120,233
1917	5,000	11,800	[5] 11,066	15,000	6,000	[5] 1,740	8,000	15,000	90,700	164,306
1918	8,000	15,000	[5] 12,023	25,000	14,000	[5] 1,715	7,500	15,000	102,000	200,328
1919	5,000	15,000	[5] 10,255	15,000	10,000	[5] 1,673	4,000	15,000	90,000	165,929
1920	2,000	10,000	[5] 12,304	10,000	8,000	[5] 1,238	5,000	12,000	90,000	150,542
1921	2,000	6,000	[5] 8,380	10,000	5,000	[5] 744	4,000	10,000	28,750	74,874
1922	4,000	9,000	[5] 7,494	12,000	9,500	[5] 810	6,000	12,000	52,000	112,804
1923	4,000	16,500	[5] 14,343	15,900	9,000	[5] 1,473	[5] 13,319	12,000	95,000	181,535
1924	3,000	16,000	18,500	18,400	7,000	[5] 2,058	[5] 19,948	19,000	85,000	188,006
1925	4,000	17,000	20,500	25,000	9,000	[5] 1,830	23,000	20,000	93,000	213,330
Capacity	10,000	[6] 20,000	33,000	40,000	15,000	8,000	30,000	30,000	125,000	311,000

[1] All of these values except those marked [1, 2, 3, 5] are taken from an assembly of statistics by Krause (21) which he states are in many cases only estimates, and are from reports of the Metallhandelgesellschaft Frankfurt A. M., and from reports appearing in Zeit. f. Elektrochemie. Further import and export statistics are given there also.

[2] From Geological Survey data (2k) (4h).

[3] Including Austria and Switzerland.

[4] 1913–1923 estimated figures taken from (3e).

[5] Official figures.

[6] According to McBride (4a), the estimated world production of primary aluminum was 150,000 tons in 1925 and the present construction in the new Canadian plant of the Aluminum Co. of Canada (affiliated with the Aluminum Co. of America) will add capacity for production of perhaps 25,000 tons, while projected future construction, to utilize the full power that will be available, would increase this to 300,000 tons at this one plant.

TABLE 3.—*Price of aluminum* [1]

Year	Price per pound	Year	Price per pound	Year	Price per pound
1852	$545.00	1897	$0.283	1912	$0.198
1854	272.20	1898	.249	1913	[2] .236
1855	113.30	1899	.249	1914	[2] .186
1856	34.00	1900	.227	1915	[2] .340
1857	27.20	1901	.227	1916	[2] .607
1857–1886	11.33	1902	.269	1917	[2] .516
1886	7.94	1903	.269	1918	[2] .334
1888	5.39	1904	.269	1919	[3] .333
1890	2.43	1905	.396	1920	[3] .360
1891	.87	1906	.396	1921	[2] .212
1892	.566	1907	.412	1922	[4] .20
1893	.566	1908	.187	1923	[3] .258
1894	.453	1909	.156	1924	[3] .275
1895	.34	1910	.164	1925	[5] .28
1896	.295	1911	.131	1926	[3] .275

[1] Figures from 1852 to 1912, inclusive, refer to general market price (Krause 21).

[2] From Eng. and Min. J. (4i). These apply to the United States only.

[3] From Chem. and Met.

[4] From Geological Survey. Figures for 1913 to 1926 apply to the United States only.

[5] Bureau of Mines.

TABLE 4.—*Value of aluminum produced and consumed in the United States, 1913 to 1925, inclusive, in $1,000, to the nearest $1,000*

Year	Domestic production		Imports [2]	Exports [3]	Apparent consumption
	Primary metal	Secondary metal [1]			
1913	$9,450	$2,199	$3,846	$966	$14,529
1914	10,080	1,673	2,801	1,547	13,008
1915	16,280	5,802	1,808	3,682	20,208
1916	33,900	23,430	1,786	15,417	43,699
1917	45,882	([4])	57	14,586	[5] 31,352
1918	41,159	10,114	555	10,869	40,958
1919	38,558	12,015	4,569	3,890	51,310
1920	41,375	9,489	13,077	5,631	58,310
1921	10,906	3,775	8,890	3,109	20,462
1922	13,622	6,086	9,695	2,836	26,567
1923	28,305	10,825	8,743	3,572	----------
1924	37,607	14,596	7,145	4,172	----------
1925	36,430	[6] 24,816	10,107	6,057	----------

[1] Value based on average open-market price, as quoted by Eng. and Min. J. for 1913 to 1917, and by Am. Metal Market for 1917 to 1922.

[2] Imports for consumption, figures for 1913 to 1917 from Department of Commerce reports. All figures include aluminum in crude form, leaf, sheets, plates, bars, strips, wire, rods, and all manufactures of; table, kitchen, and hospital ware.

[3] Exports 1913 to 1917 from Department of Commerce reports. Include ingots, metal and alloy, plates and sheets, and all manufactures of (1918 to 1922).

[4] No statistics available.

[5] This includes primary metal alone in 1917.

[6] The seemingly large increases in the recovery of secondary aluminum are attributed to the fact that statistics are more complete in recent years, and because the use of aluminum and its alloys for castings has expanded in recent years, the reuse in this field being more rapid than with respect to the use of aluminum for all other purposes. Imports contribute in equal proportion with material of domestic origin. Anderson (5b) states that the production of secondary metal now amounts to 29 per cent of the total aluminum supply in the United States.

NOTE.—Taken from Mineral Resources of the United States, 1917, 1922, and 1925.

5. APPLICATIONS OF ALUMINUM

The story of the uses and applications of aluminum is a long one. As might be expected, it has made a place for itself everywhere where lightness, malleability, high electrical conductivity, and its resistance to corrosion are service features, and where the low modulus of elasticity is not a drawback. There is large use of aluminum alloys in the automobile and aircraft industries.

The major uses of the commercially pure metal are for cooking utensils and vessels of all kinds, for electrical conductors to replace copper, for rectifiers, and lightning arresters. Aluminum is also used as a deoxidizing agent in the manufacture of iron and steel, the 94 to 98 per cent Al grade being used exclusively in the steel industry. Large amounts of 98 to 99 per cent are used in castings when the impurities are not objectionable, and to a limited extent in certain fabricated material and in the Goldschmidt thermit process. Aluminum is used as a substitute for stone in lithographic work, as wrapping foil, as paint powder, as a constituent of the explosive ammonal. It is manufactured in every commercial form—bars, tubes, sheets, powder, foil, sections, and ingots. A large tonnage of metal is also supplied to the trade in the form of casting alloys. Different shapes and sizes of ingots are used to distinguish the different grades and alloys, such as notched ingots.

Richards (6d) listed about 200 commercial and technical uses of aluminum in 1915, and over 400 uses for aluminum and its alloys were listed by Anderson (2d) in 1919. Among the varied articles for which aluminum and its alloys are used may be mentioned automobile and bus bodies, crank cases, oil pans, pistons, oil pumps, carburetor bodies, cam-shaft housings, camera parts, etc.; dirigible framework; sheathing for railway cars, metal furniture, wire, cable, powder, paint, etc. Only a few of these uses will be considered here. The reader is referred to Anderson's book (2d) and to the bibliography for more detailed accounts of the uses of aluminum.

As Ralston (4f) and Jacobson (4d) point out, scrap aluminum and dross obtained from skimmings in melting aluminum or reclaiming scrap and which contains tiny metallic globules may be combined with chlorine to form aluminum chloride, a compound of major importance in petroleum refining and cracking.

6. ALUMINUM AS SUBSTITUTE FOR OTHER METALS

It may be worth while to point out that aluminum may be used as a substitute in many cases for metals which are either more expensive or are difficult or impossible to obtain. Aluminum foil has been in use for some time and can be used to replace tin and tin-lead alloy foil. In view of the probable continued high price of tin this use for aluminum will doubtless increase. Aluminum bronze castings may sometimes be used to replace tin bronzes. The greater cost per pound of aluminum over metals, such as lead and zinc, should not be allowed to give a false impression of its cost. In many cases, such as that of foil, of small manufactured articles, and of many castings, the size and shape of the article is determined by its use, so that it is the cost per unit of volume of the material, not that per unit of weight, which must be considered.

The metal screw caps used on glass jars for household canning, for example, have been usually made of a very pure grade of zinc, the purity being necessary for sufficient ductility to allow the large distortion of the metal in forming the piece. When the war need of pure zinc for cartridge cases made it necessary to find substitutes for other uses of such zinc, wherever possible aluminum caps were substituted at a saving in cost at the prices then obtaining.

II. METALLOGRAPHY

1. SPECTRUM LINES

The ultimate ray for neutral atoms of aluminum (excited in flame or arc spectra) has a wave length of 2961.54 A, and lines of slightly less sensitiveness are represented by 3944.03, 3082.16, 3092.72, and 3092.84 A. The sensitive lines for ionized atoms of aluminum (excited in condensed spark spectra) lie still further out in the ultra-violet; the ultimate ray has wave length 1670.98 A and other sensitive lines occur at 1856.00, 1858.13, and 1862.48 A. On account of the difficulty of making observations so far in the ultra-violet, the lines first named are, in practice, relied upon to reveal the presence of aluminum in spark as well as in arc sources. The spectral test for aluminum is very sensitive, amounts of the order of 0.01 per cent being detected with ease. Observations must be made photographically since all the sensitive lines lie in the ultra-violet.

2. CRYSTAL STRUCTURE OF ALUMINUM AND MAGNESIUM, THEIR ALLOYS AND COMPOUNDS

Aluminum crystallizes in the cubic system. The length of the unit cube (lattice constant) is 4.043 Angstrom units. The density calculated on this basis is 2.692 g/cm^3. The closest approach of atoms was calculated as 2.859 A.

The crystal structures of aluminum, magnesium, and compounds of these metals as determined from X-ray data are summarized in Table 5. The crystal structures of some alloys are given in Table 6. Data for both tables were obtained from the International Critical Tables, vol. 1, pp. 338 to 353; 1926.

TABLE 5.—*Crystal structure of compounds of aluminum and of magnesium*

Chemical symbol	Crystal system	Unit cell, A			Calculated density	Reference
		a_0	c_0	Molecules		
Al	*c*	4.043		4		13–a, f, g, h, i, j; 31–1; 42–e, j, k, m.
AlSb	*c*	6.13		4	4.26	13–k.
CuAl	*h*	3.89(94° 36′)		4		13–a, b, l.
Cu_3Al	*c*	3.47		4		31–m, l.
$CuAl_2$	*t*	6.05	4.88	4	4.35	13–a, b.
NiAl	*c*	2.82		1	6.25	31–m.
Mg	*h*	3.22	5.23	2	1.709	42–k, n, o; 31–l.
Mg_2Si	*c*	6.39		4	1.94	13–k.
Mg_2Sn	*c*	6.78		4	3.54	31–n; 13–l.
Mg_2Pb	*c*	6.75		4	5.47	13–m.
Al_3Mg_4	*c*	4.80			2.62	31–m.

c=cubic. *h*=hexagonal. *t*=tetragonal.

TABLE 6.—*Crystal structure of alloys of aluminum and of magnesium*

Alloy	Percentage composition	Crystal type	Unit cell, A	Reference
Al-Zn	0–20 Zn	f. c. c	4.043–4.034	13–g.
	20–95 Zn	f. c. c.+h. c. p		
	95–100 Zn	h. c. p		
	Al Mn Cu			
Al-Mn-Cu	15.9 23.9 60.3	f. c. c	3.70	31–o, p.
	14.3 28.6 57.1	f. c. c.+b. c. c	2.98	
Mg-Sn	0–67 Mg	Sn+Mg_2Sn		13–l.
	67–100 Mg	Mg_2Sn+Mg		
Mg-Pb	0–67 Mg	Pb		13–l.
		$PbMg_2$		
	67–100 Mg	$PbMg_2$		
		Pb		
Mg-Al	91.2 Al	f. c .c	4.106	13–f.
	7.3	h. c. p	3.151 (A_0) 5.23 (C_0)	

f. c. c.=face centered cube. h. c. p =hexagonal close packing. b. c. c.=body centered cube.

Al–Cu alloys.—Data for these alloys from the same source are summarized in Figure 1 (13a, d 31k, e).

Al–Ag alloys.—When aluminum is dissolved in silver the volume of the latter is said (13f) to be increased, although the aluminum has a smaller atomic volume.

Duralumin.—Anderson (43tt) states that the crystal structure of duralumin is face-centered cubic with lattice parameter 4.046 ± 0.005 A "substantially identical with the aluminum lattice." Davey (13d) gave 4.046 ± 0.004 A as the value of aluminum. Clark and Brugmann (13e), however, found that the duralumin lattice is like that of aluminum, but with a lattice parameter of 4.052 A as contrasted with 4.046 A for aluminum. Lange (13j) stated that when duralumin is aged a new lattice structure with a slightly larger lattice parameter is observed.

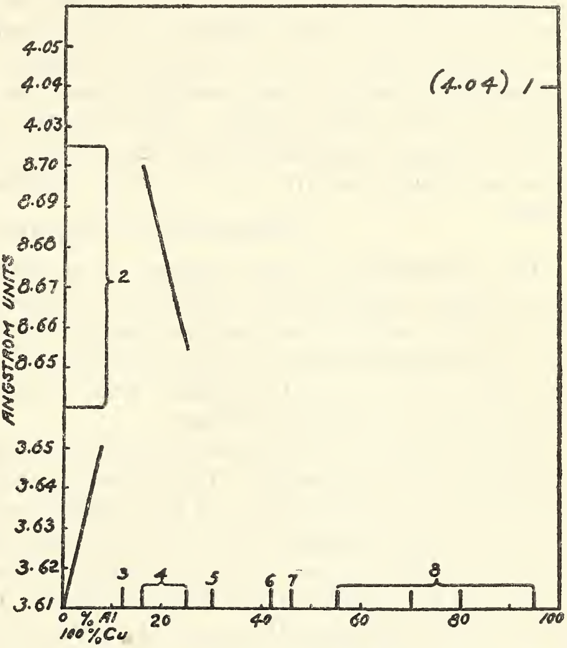

FIG. 1.—*Diffraction data for copper-aluminum alloys (International Critical Tables)*

1, Al pattern, face-centered cubic.

2, α phase. Copper structure with values of A_0 shown below. Face-centered cubic.

3, a fine-grained mixture of α and γ phases. Preliminary attempts to study phases stable at high temperatures are yet inconclusive.

4, pattern of γ phase. Cubic with A_0 values, as shown above. Composition of crystalline phase uncertain.

5, it has been considered that an alloy of this composition is the compound CuAl and a structure has been assigned to it. Probably incorrect.

6, a mixture of γ and η phases

7, Pure η phase. Compound $CuAl_2$.

8, mixtures of η phase ($CuAl_2$) and Al patterns in varying proportions.

Diffraction patterns were obtained at the bureau of duralumin which had been quenched from above the $CuAl_2$ solution line and material which had been furnace cooled from the same temperature. The pattern of the former was similar to that of aluminum while the latter showed in addition the pattern of the precipitated $CuAl_2$. The $CuAl_2$ pattern was identified by direct comparison of patterns of that compound. It was further noted that in the furnace cooled specimen the pattern was of the "dashed" type, indicative of coarser grain size.

3. MICROSTRUCTURE

Aluminum exists in only one solid phase or form so far as is known. Some of the earlier investigators (29c, e) interpreted the results of their calorimetric measurements on aluminum as indicating the existence of a thermal transformation at 560° C. (approximately). The absorption of heat at this temperature (about 5 calories per gram (29e)) can be accounted for, however, by the fusion of the eutectic of aluminum and silicon at this temperature. Thermal analyses made at the Bureau of Standards of aluminum (99.6 per cent) have shown heat evolutions or absorptions corresponding to the solidification or fusion of the two eutectics commonly present in commercial aluminum and resulting from the presence of a small amount of iron and of silicon. The eutectic of aluminum and the iron-aluminum compound, $FeAl_3$, fuses at 655° C. and that of aluminum and silicon at 576° C. No other thermal arrests have been found.

(a) PREPARATION OF SPECIMENS

The preparation of the surface of an aluminum specimen for microscopic examination is difficult. Precautions must be taken (*a*) that the surface shall not be distorted by the sawing, grinding, and polishing operations, (*b*) that particles of the abrasive shall not be forced into the metal surface, and (*c*) that the final polishing process shall not dull the surface.

Light pressures and the use of fine saws and files will aid in preventing the first difficulty. The microtome has also been used with success in the preparation of a flat, smooth surface suitable for the final polishing operation (11a). The second difficulty can be prevented, in large measure, by moistening the fine emery papers with a solution of paraffin in a suitable solvent. The use of alcohol or light oil for moistening the emery papers has also been found useful. For the final polishing, magnesia is very generally used, according to the recommendation of Hanson and Archbutt (11f), who followed an earlier suggestion of Rosenhain.

The following recommendation was prepared by Dix and Keith (11c) for the American Society for Testing Materials (11b) for the preparation of metallographic specimens of aluminum and aluminum alloys:

> It is recommended that, following the cut on the file, two coarse emery papers, No. 2 and No. 1, be used, preceding the use of the finer metallographic polishing papers. The papers should be prepared by applying a solution of paraffin in kerosene and working well into the surface. The polishing must be done by hand. The papers may be used as so prepared or moistened with additional solvent. It is not always necessary to use this solution on the coarse papers, No. 2 and No. 1. The hand polishing may be stopped at either No. 000 or No. 0000 paper and the polishing continued on a wheel revolving at approximately 200 r. p. m. For the first cut on the wheel a coarse grade of broadcloth is used with a grade of abrasive similar to 65–F alundum. The next cut is made using a softer broadcloth and "heavy magnesium oxide" applied as follows: The pad is moistened with distilled water and approximately one teaspoonful of powder applied evenly to the surface and thoroughly rubbed in, all hard and coarse

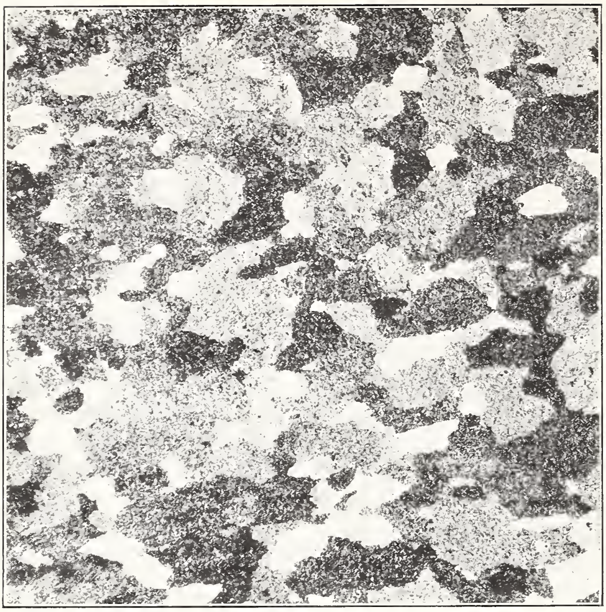

Fig. 2.—*Structure of annealed aluminum sheet.* × *10*

Etched in 8.7 per cent HF, 13 per cent HCl. (Flick, Aluminum Company of America)

Fig. 3.—*Structure of ingot aluminum.* × *500*

Etched in 1 per cent HF to which a few drops of HNO_3 were added. Illustrates the "Chinese script" formation of the iron constituent appearing in ingot aluminum of 99.14 per cent purity. Only one iron constituent appears in this specimen. (Aluminum Company of America) particles being brushed off with the hand. After the scratches left by the 65–F material have been removed the pad is washed clean and a smaller quantity of powder worked in as before. This time the cut is made at right angles to the first treatment. This procedure may be repeated several times until the specimen shows a brilliant reflecting surface and under the microscope the aluminum solid solution matrix appears clear white and the constituents stand out in even colors, free from tarnish. Only distilled water should be used during the polishing with the magnesia powder, otherwise there is danger of forming particles of carbonate, which are harsh and scratch the specimen. It is good practice to frequently raise the specimen from the pad and revolve it 180° before replacing. The pressure and quantity of water to be used can only be determined after considerable practice and varies with the nature of the alloy.

(b) ETCHING

In etching aluminum and its alloys for examination for macroscopic structure by the unaided eye or at low magnifications a combination of hydrofluoric acid and hydrochloric acid has been found to give excellent results. The etching may be done in two stages (11g), the concentrated hydrochloric acid being the second one and lasting for only a few seconds. A simpler method, however, consists in mixing the two acids in the proper proportions (11e), as shown in Table 7. Figure 2, macrograph of 99.2 per cent, annealed aluminum sheet etched in 8.7 per cent, HF–13 per cent HCl, × 10, as shown by Flick, was revealed by means of this reagent. A sodium hydroxide solution (10 per cent by weight) also is a satisfactory etching reagent for revealing the macrostructure. In Table 7 are listed the etching reagents which have been recommended as being most useful for use in the study of the microstructure of aluminum.

TABLE 7.—*Etching reagents for aluminum* [1]

No.	Reagent	Concentration	Specific use	Authority	Reference No.
1	HF and HCl [2]	10 to 20 per cent alcoholic HF and concentrated HCl.	Macroscopic	Czochralski	11g.
2	HF and HCl [2]	10 parts HF, 15 parts HCl, .90 parts H_2O.	do	Flick	11e.
3	HF	0.1 to 10 per cent	General	Various	11f, h, i, j, k, l, m, n, o, p.
4	NaOH	0.1 to 10 per cent	do	do	11f, h, i, k, l, m. n, o, p.
5	NaOH	0.1 per cent in 10 to 50 per cent of alcohol.	do	Merica	11o.
6	HNO_3	1 per cent in alcohol	Mg_2Al_3	Hanson	11f.
7	HNO_3	10 per cent in alcohol	Mg_2Al_3	do	11f.
8	HNO_3	20 per cent [3] quench	$CuAl_2$	do	11f.
9	HNO_3	25 per cent [3] quench	"X" Const. from $FeAl_3$.	Dix	11q.
10	Ferric sulphate	10 per cent	$CuAl_2$ from $FeAl_3$	Anderson	11j.
11	Picric acid	4 per cent in alcohol	$CuAl_2$	Meyer	11r.
12	H_2SO_4	10 per cent [3] at 60 to 70° C.	$FeAl^3$	do	11r.
13	HNO_3+HF in glycerol.	HNO_3 1 vol.; HF, 2 vols. glycerol, 3 vols.	Alternate polish and etch. Reveals residual coring.	Villela	11s.

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[1] Table 7 has been based largely upon the work of Dix and Keith (11c). The reference numbers have been changed to agree with the present bibliography and one additional reagent, No. 13, has been added.

[2] Czochralski originally etched for grain by using from 10 to 20 per cent of concentrated HF in 100 cc absolute alcohol, followed by dipping in concentrated HCl solution. Flick has very satisfactorily modified this etch by using a single solution prepared as follows: 10 cc of commercial HF and 90 cc of distilled water and 15 cc of concentrated HCl.

[3] By the 20 and 25 per cent nitric acid quench is meant the procedure of heating the solution to exactly 70° C. and immersing the specimen for a period from 2 or 3 seconds to 30 seconds and then immediately quenching the specimen in cold water. This same procedure may be used with the sulphuric acid etch although the quench is not essential.

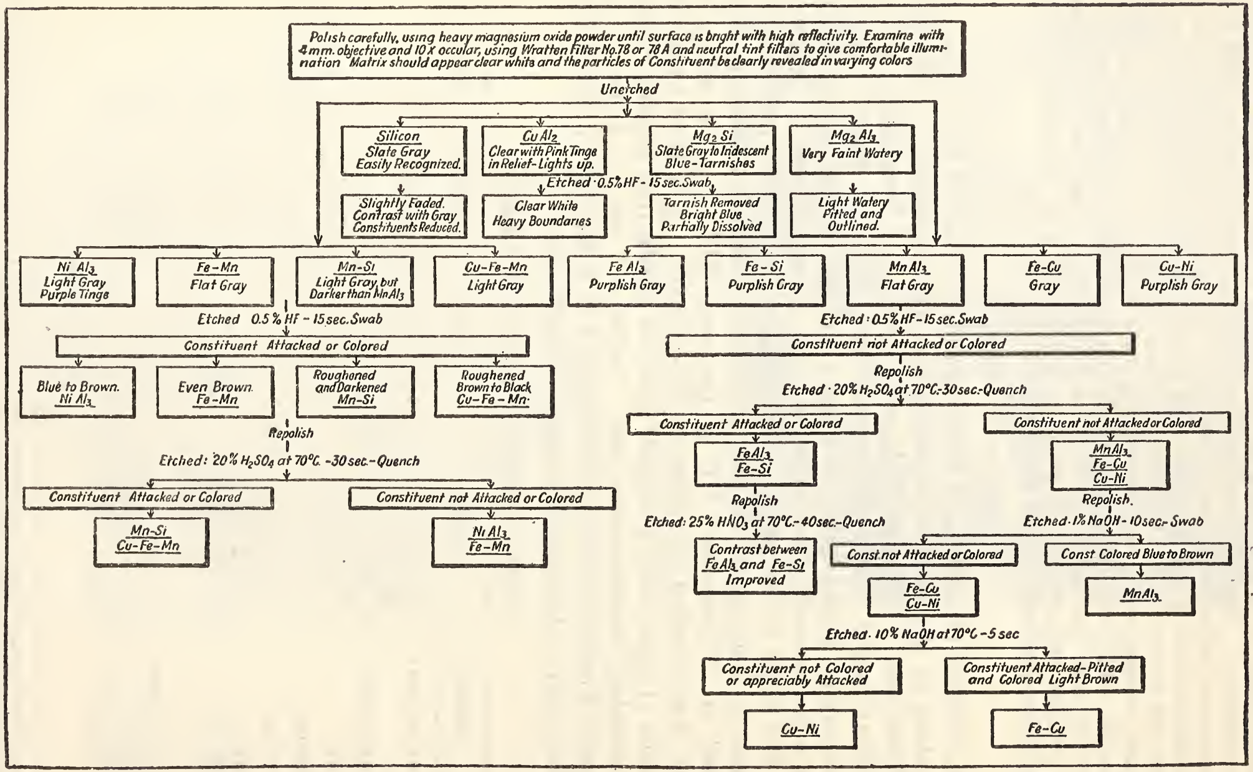

FIG. 4.—*Scheme for metallographic identification of constituents in aluminum and its alloys, after Dix*

FIG. 5.—*Average structure of No. 12 alloy (8 per cent Cu) in cast notch bar*

Showing network of iron constituent in halftone in the form of delicate "Chinese script" figures and $CuAl_2$ which appears as dark, rounded particles with black borders. (Aluminum Company of America)

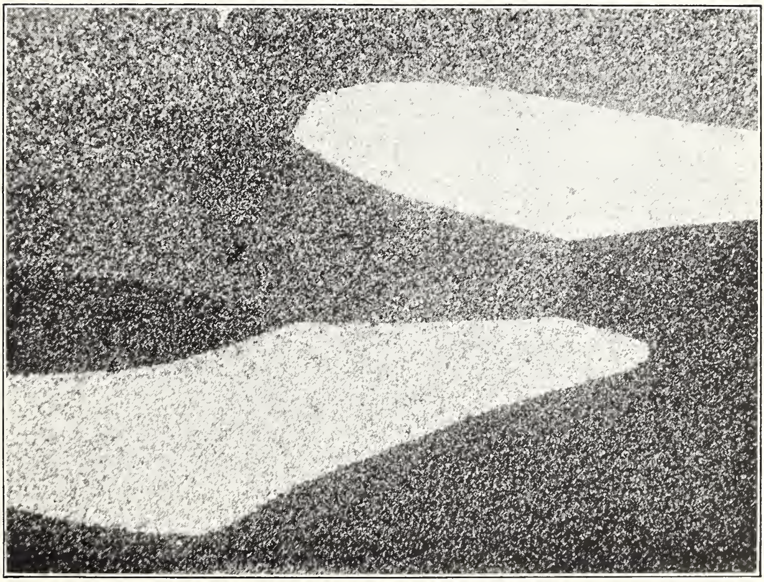

FIG. 6.—*Structure of cast aluminum of high purity (99.976 per cent).* × *50*

Etchant, dilute HF. Note the absence of any hardening constituent such as shown in Figure 2

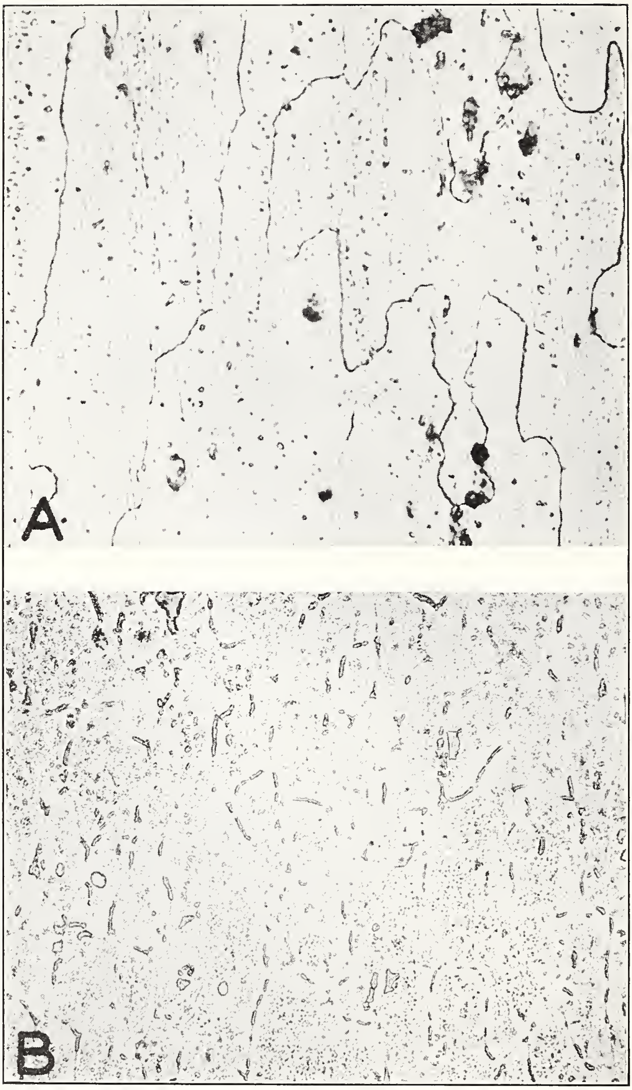

FIG. 7.—*Structure of duralumin sheet*

a. Quenched in ice water from 500° C. Etched in 1 per cent HF, for 20 seconds. × 250.
b. Furnace cooled from 500° C. Etched in 1 per cent HF for 20 seconds. × 250.

Dix (11c) has stated that the most useful etching method for aluminum is that of swabbing the polished surface with a 0.5 per cent solution of hydrofluoric acid. On the other hand, he has stated that, with proper polishing technique, the differences in color and shape of a number of constituents, especially in cast alloys, is pronounced enough, provided the polishing has been properly done, to serve as a means for their identification. However, for the more complicated constituents a means of differentiation by etching is required. Etching to remove the surface flow is also required for structures containing finely dispersed constitutents. Figure 4 from Dix is given as a guide for the identification of the constituents in commercial aluminum alloys based upon the appearance of these constituents as seen in the unetched condition and also after etching. This also serves as a list of the various constituents which may occur in such alloys. In many cases the exact composition of the constituent is unknown and it has been referred to simply by the principal elements known to be present. The microstructure of commercial aluminum (99.14 per cent) in the cast or ingot form is shown in Figure 3. This type of structure; that is, a soft matrix embedded in which is a more or less continuous skeleton of the harder constituents, and generally referred to as the "cast structure" is characteristic of the cast alloys, in general. This is illustrated by Figure 5, which shows the commercial copper-aluminum alloy known as "No. 12." The degree to which the skeleton framework of the harder constituents is developed depends upon the amount of the alloying elements used. Cast aluminum of very high purity (99.976 per cent), Figure 6, shows none of the "hardening" constituents.

The "cast structure" is more or less broken up during the mechanical working of the alloys and in material, such as sheet, which during the process of fabrication is subjected to very severe mechanical working, both hot and cold, as well as to various intermediate annealing treatments, no trace of it remains. The microstructure of sheet duralumin, as shown in Figure 7 (*a*) and (*b*), is typical of such material.

III. CHEMICAL PROPERTIES

The atomic weight of aluminum is 26.97. Aluminum is a very active element and under proper conditions reacts readily with other elements and substances, such as chlorine, sulphur, oxygen. Its molecular heat of combustion is (for $Al_2O_3 = 101.9$ g), 391,350 calories.

The ease, however, with which aluminum reacts with oxygen, water, etc., is very dependent upon the physical state of the metal. As an amalgam, for example, it reacts very readily at ordinary temperature with air, water, and other substances, as one would expect from its high heat of reaction. As a solid mass, however, its rate of reaction with the same substances is very much slower, often unnoticeable. Commercial aluminum powder does not react visibly with moist air or water at room temperature. Such cases of the "chemical stability" of aluminum are undoubtedly due to its protection by a thin coating of reaction product, be it oxide, hydrate, or other material which readily forms on the fresh surface when first exposed. An important corollary of this fact is that the rate of corrosion of aluminum and of its light alloys depends on whether this protective coating of oxide once formed remains in place, protecting the remainder of the metal, or whether it is removed as it is formed. Thus, the corrosion of the metal and its alloys is much more rapid in running water, and under conditions in which air and water erosion also play a part, than in still water. This phase will be considered in more detail in the section on "corrosion."

Aluminum in the solid form is corroded only slowly and superficially by pure water. In the air, damp or dry, it is also only superficially oxidized. When heated to 400° C. for 10 minutes in air, an incipient oxidation is noticed which increases slowly up to 800° C. and then increases rapidly. Very finely divided aluminum will decompose water very slowly, but noticeably at 100° C., until a protective film is formed.

Ammonium hydroxide attacks aluminum slowly, forming aluminum hydrate. Sodium and potassium hydroxides ($NaOH$ and KOH) dissolve it rapidly.

Sulphur, free or dissolved in carbon disulphide (CS_2), does not affect aluminum at ordinary temperatures.

A solution of a mercury salt attacks aluminum. The mercury liberated by the reduction of the salt amalgamates the aluminum. The aluminum in this amalgam is very active and from it aluminum oxide is very rapidly formed by the action of water. Aluminum articles must, therefore, be protected from the action of mercury salts.

Commercial aluminum, in general, is inactive in the presence of metallic mercury; the oxide film serves to protect the metal. In order to cause amalgamation it is necessary that the surface of the aluminum be abraded while immersed in the mercury. Aluminum higher in purity than approximately 99.5 per cent may amalgamate without abrasion. In general, the more alloying constituent added to aluminum, the less likely it is to amalgamate. It is not safe, however, to use any aluminum in contact with mercury where there is any acid present or the possibility of forming a salt of mercury which would amalgamate the aluminum.

Cold concentrated or dilute nitric acid (HNO_3) attacks aluminum only very slowly. The metal becomes "passive" under the action of this acid. Dilute and concentrated sulphuric acid (H_2SO_4) attacks aluminum but slowly when cold. When concentrated sulphuric acid is heated with aluminum the latter is attacked with formation of sulphur dioxide (SO_2). Dilute and concentrated hydrochloric acid (HCl) readily dissolve aluminum, as do other mineral acids in the presence of metal chlorides. The purity of the metal is an important factor influencing the rate of solution. Edwards (14g) has reported that a sample of 99.9 per cent aluminum sheet immersed in a solution of concentrated hydrochloric acid 5 parts (by volume) and water 95 parts was still bright and showed no appreciable corrosion after six weeks' exposure.

Seligman and Williams (14e, f) have carried out extensive tests of the resistance of aluminum to corrosion by acids, particularly nitric, sulphuric, and acetic acids, the results of which are of decided practical value in view of the extensive use of aluminum for kitchen utensils and for acid vats and condensers. Their conclusions follow:

The rate of attack of aluminum by cold acetic acid is small; it increases with increasing dilution of the acid. Aluminum vessels can be used for containing concentrated nitric acid when cold; with hot nitric acid of any concentration aluminum has but a limited life. Dilute cold nitric acid also can be handled in aluminum vessels, but the life of the latter is not as long as with the concentrated acid. In the discussion of a paper by Edwards (14g) it was stated that the use of aluminum for the transport of nitric acid in Germany is in connection with acid made from air nitrogen, whereas in this country the presence of small traces of chlorine in commercial nitric acid has made its use impossible for tank cars.

The corrosion of aluminum is greater in mixed sulphuric and nitric acids than in either alone (contrary to opinion previously held), and aluminum vessels should be used only with caution for handling such mixed acids.

Investigating the corrosion of aluminum by acids, bases, and water, Maass and Wiederholt (17e) concluded that when solutions of equal concentrations are used the bases attack aluminum the most strongly. The loss of weight of metals in acids and bases is in little relation to the concentration of the hydrogen and hydroxyl ions but is strongly influenced by other ions present in the solutions. A typical attack of the ions concerned is also noticeable in salt solutions. The influence of the cations is shown in that the potassium promotes the attack the most and sodium, ammonium, calcium, and magnesium the least. Of the anions, chlorine was the most dangerous, for it led to strongly local attack besides the uniform attack. The decomposition of aluminum was least vigorous in solutions in which sulphate and nitrate ions were present. In electrolytes containing carbonic acid the severe effect of the cations with the presence of potassium and sodium salts is shown and, because of the high degree of alkalinity of the solution, leads to severe corrosion. In acids the surface attack was uniform and proceeded without the formation of visible corrosion products, while the decomposition of the metal in bases and salt solutions proceeds with the formation of aluminum hydroxide. It has recently been shown (14a) that the rate of solution of aluminum by sulphuric acid is decidedly accelerated by the presence of small amounts of a chloride or fluoride. The presence of bromide or iodide, however, had no appreciable effect upon the rate of solution.

The bureau often receives inquiries relative to the toxic properties of aluminum, particularly in reference to its use as a cooking utensil. The following opinion was expressed by the Public Health Service concerning this matter:

> There is no evidence available which would indicate that aluminum cooking utensils represent a potential danger to health. There is no question that if strongly acid or alkaline foods are prepared in such containers a certain amount of the metal will be dissolved and will pass over into the food. It is very doubtful, however, whether a sufficient amount of metal will be found under such circumstances in food so as to produce a deleterious effect on the health of persons consuming this food. It should be remembered that certain widely used baking powders contain considerable quantities of aluminum salts and while certain objections have been raised to the use of these aluminum baking powders, the question of their injuriousness has not been definitely established. In the use of aluminum cooking utensils it may, perhaps, be advisable to avoid strongly acid foods. It may also be desirable not to let food stand for many hours in the aluminum cooking utensil.

1. CORROSION

No sharp distinction can be made between the "chemical resistance" of aluminum as illustrated by Table 8 and "corrosion resistance." The term "corrosion" as used in this section applies particularly to the chemical attack of the metal occurring as a result of the conditions encountered in ordinary service or usage, such as exposure to the weather, to water, etc.

Table 8 shows opinions as reported from a variety of sources of the attack on aluminum of various chemicals. In cases where the report was merely that a corrosive attack was obtained, without specifying the amount, the material has been listed under "slight attack." Some materials are listed under more than one heading, according to the condition of the material. The original sources should be consulted for more detail.

TABLE 8.—*Chemical attack upon aluminum*

Reported no attack

Acetic acid, 99 per cent, 17–h.
Acetic acid, glacial, 7–b; 17–r.
Acetylene, 17–r.
Alcohols, aromatic, 7–c.
Aliphatic acids, 7–b.
Alkaloids, 7–b.
Ammonium hydroxide (free from alkali salt impurities) 7–b, c; 17–h, r.
Ammonium nitrate, 7–c.
Ammonium sulphide, 7–b.
Beer, 7–b; 17–r.
Benzol, 7–b.
Butyric acid, boiling, 99 per cent, 17–r.
Calcium chlorate, 7–b.
Calcium nitrate, hot, 7–b.
Camphor, 7–b.
Chlorides of alkali metals and Mg, 17–h.
Chromic oxide, 7–b.
Citric acid, 17–r.
Copal, 7–b.
Cresol, not over 99 per cent, 7–b; 17–r.
Distilled water, 7–b.
Dyes, 7–a, b.
Ether, 7–b.
Ethereal oils, 7–b.
Ethyl acetate, anhydrous, 7–b.
Fatty acids, 7–b, 17–r.
Ferric chloride, concentrated or dilute, 20–a.
Ferrous sulphate, very dilute at room temperature, 7–a.
Formaldehyde, 7–a, 17–r.
Gallic acid, 17–r.
Gelatin, 17–r.
Glue, 7–b.
Glycerine, 7–b.
Glycerol, 17–r.
Glycol, 17–r.
Hot basic solutions, 7–b.
Hydrocyanic acid, 17–r.
Hydrogen sulphide, 17–r.
Lactic acid, 7–b, c; 17–r.
Ketones, 7–b.
Linseed oil varnish, 7–b.
Lead azide, 7–b.
Madder lake, 7–b.
Milk, 7–b.
Mustard, 7–a.
Naphthol, 7–b.
Nitrates of alkali metals, 17–h.
Nitric acid, 17–r; 90 per cent or over, 7–c.
Nitric acid, cold or boiling, 29.
Nitrocellulose, 7–b.
Paraffin, 7–b.
Paraldehyde, 7–b.
Pharmaceutical preparations, 7–a.
Phosphoric acid, below 1 per cent, 7–b.
Picric acid, 17–r.
Potassium ferrocyanide, 7–b.
Potassium nitrate, fused, 17–r.
Potassium solutions, 7–b.
Propronic acid, 99 per cent, 17–r.
Pyrogallol, 17–r.
Pyrotechnical inflammables, 7–b.
Quinol, 17–r.
Resorcinol, 17–r.
Rhodium salts, 7–b.
Rosin, 7–b.
Soap, 17–r.
Stearic acid, 17–r.
Sugar solutions, 7–b.
Sulphur, 17–r.
Sulphur dioxide, 17–r.
Sulphuric acid, cold, dilute, 17–k, r.
Tartaric acid, 17–r.
Trichlorethylene, 7–b.
Yeast, 17–r.

Reported slight attack

Acetic acid (over 1 per cent), 17–r, h, k.
Acetic acid, 1–10 per cent, 7–a, c.
Acetic anhydride, 17–r.
Amyl alcohol, anhydrous, at high temperature 17–r.
Boiling distilled water in presence of air, 17–l.
Boric acid, 17–r.
$Ca (OH)^2$, 17–k.
Ethereal oils, 7–a.
Fruit acids, 7–a.
Gunpowder, 17–j.
Hard industrial waters, 17–n.
Iodine, 17–r.
Magnesium sulphate, 17–r.
Methyl alcohol, 17–r.
Nitric acid, dilute, cold, 17–k.
Ozone, 17–r.
Potassium hydroxides, dilute or concentrated, 17–k.
Potassium nitrate, 17–l.
Potassium sulphate, 17–l.
Sodium bicarbonate, 17–r.
Sodium chloride, 17–l.
Sodium nitrate, 17–l.
Sulphuric acid dilute, cold, 17–r; warm, 17–k.
Tannin, 17–r.
Vinegar, 7–b.
Wine, 7–a.

Conflicting reports

Alcohols, 17–h, r.
Varnish, 7–a.
Pharmaceutical preparations, 7–b.
Calcium chloride, 17–r.
Calcium sulphate, 17–r.
Carbon dioxide in water, 7–a, b; 17–r.
Hydrogen peroxide, 17–r.
Sodium chloride, 17–r.

Reported severe attack

Acetic acid (up to 1 per cent), 17–r, h, k.
Alkalis, caustic, 17–r.
Ammonium alum, 7–b.
Aluminum sulphate, 7–b.
Amino-hydrocarbon, 7–c.
Aniline, near boiling point, 17–h, r; 7–c.
Azide, 17–r.
Barium chloride, 7–a.
BaO_2H_2, 17–k.
Benzaldehyde (in acid solutions), 17–r.
Bromine, 17–r.
Butyl alcohol, anhydrous at high temperature, 17–r.
Butyric acid, over 99 per cent, 17–r.
Calcium silicate, 7–b.
Chlorine, 17–r.
Cresol, above 99 per cent, 7–b.
Ethyl chloride, 7–b.
Ferrous sulphate, high temperatures 7–a.
Ferric acid solution, 17–f.
Formic acid, all concentrations, 7–a, c; 17–r.
Hydrochloric acid, almost all conditions, 7–b; 17–r.
Hydrofluoric acid, 7–b.
Mercury,[1] 7–b; 17–r.
Mercury salts, 7–b; 17–r.
Naphthols, anhydrous at high temperature, 17–r.
Naphthylamines, 17–r.
Nitric acid, dilute, hot, 7–a, 17–k.
Oxalic acid, 17–r.
Potassium lye, warm, 17–k.
Palmitic acid, anhydrous, 17–r.
Phenol, anhydrous, at high temperatures, 7–b; 17–r.
Phosphoric acid, 7–b; 17–r.
Picric acid, 7–b.
Pigments, 17–r.
Potassium carbonate, aqueous, 17–r.
Potassium hydroxide, aqueous, 17–r.
Propronic acid, over 99 per cent, 17–r.
Soda, 7–b; 17–r.
Sodium chloride, hydrous, 7–b.
Sodium hydrosulphite, 7–c.
Sodium hydroxide.
Sulphuric acid, hot, concentrated, 17–r; 15 per cent, 7–a, b.
Tar oil, 7–b.
Tin chloride, 7–b.
Toluidine, 17–r.

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[1] See also p. 24.

(a) SHEET METAL

Following an extensive "epidemic" of the deterioration of aluminum cooking vessels in storage, by exfoliation, cracking, and blistering, Heyn and Bauer (17q) made a rather thorough investigation of the corrodibility of sheet aluminum, the results of which have been widely accepted, and, in large measure, form the basis of our knowledge of the corrosion of aluminum. It should be pointed out, however, that the serious deterioration which prompted the investigation by Heyn and Bauer was in all probability characteristic of some of the metal as made at that time (about 1910) and does not occur to the same degree in present-day aluminum.

According to Heyn and Bauer, the corrosion of aluminum may be of two general types (*a*) a uniform surface attack in which a coating of oxide forms over the surface, and (*b*) a local attack resulting in the formation of pits, blisters, and exfoliation. They found the latter type of corrosion to be restricted almost exclusively to metal in the cold-rolled or work-hardened condition and to occur most readily in certain types of tap water or salt solutions, especially calcium salts. Distilled water did not cause corrosion of this type in the hard-rolled sheet. Annealed sheets even after several months' immersion, under the same conditions as resulted in pronounced localized attack of the cold-rolled sheets, showed only slight uniform surface attack.

For distilled water, with access of air, they report that the diminution in thickness (0.8 to 1.2 mm thick) in 207 days was 0.0045 mm for hard sheet, 0.0048 mm for medium sheet, and 0.0054 mm for soft sheet. Water, in the absence of air or oxygen, did not attack the metal. Medium hard sheet aluminum showed the following decrease in thickness after 61 days' immersion in sodium-chloride solution of the following concentrations: 0.34 N NaCl, 0.0015 mm; 0.86 N NaCl, 0.0024 mm; 3.42 N NaCl, 0.0029 mm.

According to Heyn cold-worked aluminum is electronegative (Heyn designated it "electropositive") with respect to the same metal in the annealed state, by about 0.03 volt when immersed in tap water. This will account, in part, for the greater susceptibility of the cold-worked metal toward corrosive attack, though not for the nonuniform attack. Initial stresses in the severely worked metal may possibly play a part in this also. Seligman and Williams (17n) concluded that the composition of the water and the mechanical imperfections in the metal account largely for the corrosion of aluminum, impurities and physical differences contributing also. They attributed the formation of blisters to the presence of water in cavities initially present in the metal. They reported that no corrosion occurred in water freed from oxygen by boiling or in water under an inert atmosphere, such as hydrogen or carbon dioxide.

The fact that the condition of the surface, especially of sheet material, has an important bearing on the corrosion resistance of aluminum is well established. A well-polished surface resists corrosion much longer than a rougher one does. Even after the corrosive attack has well advanced, material which initially lacked polish corrodes differently from well-polished material, usually at a somewhat higher rate. Scratches and surface imperfections, according to Maass (17a) continue to affect the corrodibility of aluminum long after the surface layer of metal has been removed, the attack of the metal along the scratches being noticeably greater than the average rate of attack of the metal.

(b) CAST ALLOYS

Concerning the relative corrodibility of cast and worked aluminum diametrically opposite statements have been made (14c, 17g). The fact that cast material is always more or less porous renders an accurate determination of the rate of corrosion very uncertain. The matter is of but little practical importance, however, since the two types of material are seldom used for the same purpose.

Sayre and Basch (17i) have investigated the resistance of cast aluminum alloys to salt water corrosion by determining the tensile properties before and after corrosion. They concluded that initial high tensile strength is no criterion of corrosion resistance. According to their results the manganese-aluminum and the silicon-aluminum alloys of relatively low tensile strength showed the greatest resistance to corrosion in salt water. They also reported that the heat-treated aluminum-copper alloy showed a considerably greater resistance to corrosion than did the ordinary copper-aluminum casting alloys.

(c) WROUGHT ALLOYS

Where somewhat greater strength than can be obtained with pure aluminum, combined with good resistance to corrosion, is desired, the alloy with 1 to 1½ per cent manganese is used, since manganese appears to be the least harmful of the available strengthening elements. Such alloys under some conditions of exposure are practically as free from corrosion as aluminum itself.

Duralumin is somewhat less resistant, but for ordinary exposure to the weather its resistance is better than that of iron or steel when both are exposed in equal thickness and both are bare.

Figure 8 shows an airship member made up of duralumin and steel which was exposed to the weather on the roof of one of the buildings at the Bureau of Standards for approximately three years. Rusting and scaling of the steel is apparent, while the duralumin is relatively free from surface corrosion.

Unprotected wrought heat-treated aluminum-copper alloy (25S, see p. 242) is being used for the radiator shell of one automobile which is in large production, and seems to have given little trouble from corrosion.

Care must be taken in the use of aluminum and its alloys to avoid conditions under which rain or condensed moisture will be held in contact with the aluminum. Thus, in aircraft construction the placing of wood or canvas in contact with aluminum alloys is avoided on account of the danger of retention of moisture at the junction, which would cause rapid corrosion. When protective coatings are inapplicable, frequent rubbing over with an oily rag is advisable to keep the surface water repellant.

(d) IMPURITIES

It is generally recognized that the purer grades of aluminum do not corrode so readily as the impure material. In any discussion of the effect of impurities upon the "natural" corrosion of aluminum, the previous thermal treatment, as a result of which the form in which such impurities occur and the uniformity of their distribution are effected, must be considered. As a general rule, wrought-aluminum alloys in which the alloying elements are held in solid solution, as a result of quenching from a relatively high temperature, are more resistant to corrosion than the same alloys after an aging treatment that results in the precipitation from solid solution of the alloying elements, usually in the form of a compound with aluminum. If the aging is carried out at a temperature considerably above room temperature, the resistance of the alloy to corrosion is less than if aged at room temperature.

In discussing the effect of silicon upon the corrosion resistance of aluminum, Wiederholt (18f) states that material heated to 300° C. has very low resistance to corrosion as compared with that of the same material heated at temperatures above 300° C., and then quenched so as to retain the silicon in solid solution.

Czochralski (20a) recently investigated the "blackening" of aluminum cooking utensils and concluded that the alkalinity of the water used was largely responsible for this behavior of aluminum. The purity of the metal, however, is also a factor. If iron is present in the metal, the iron bearing constituent, that is, the compound $FeAl_3$ is dissolved in preference to the aluminum matrix and the iron may then be precipitated from solution on the surface of the metal as a black film. Both copper and sodium, according to Bailey (17o), lower the corrosion resistance of aluminum. The presence of copper as an alloying element appears to be intimately related to the susceptibility of certain of the aluminum alloys to embrittlement by intercrystalline corrosion. Isgarischew and Jordansky (14a) have

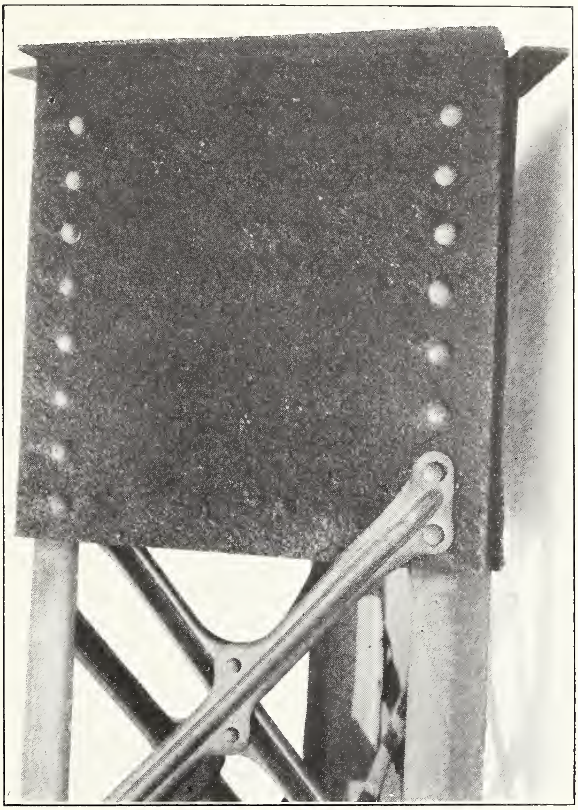

FIG. 8.—*End of experimental duralumin girder showing steel plates after atmospheric exposure of approximately three years at the Bureau of Standards*

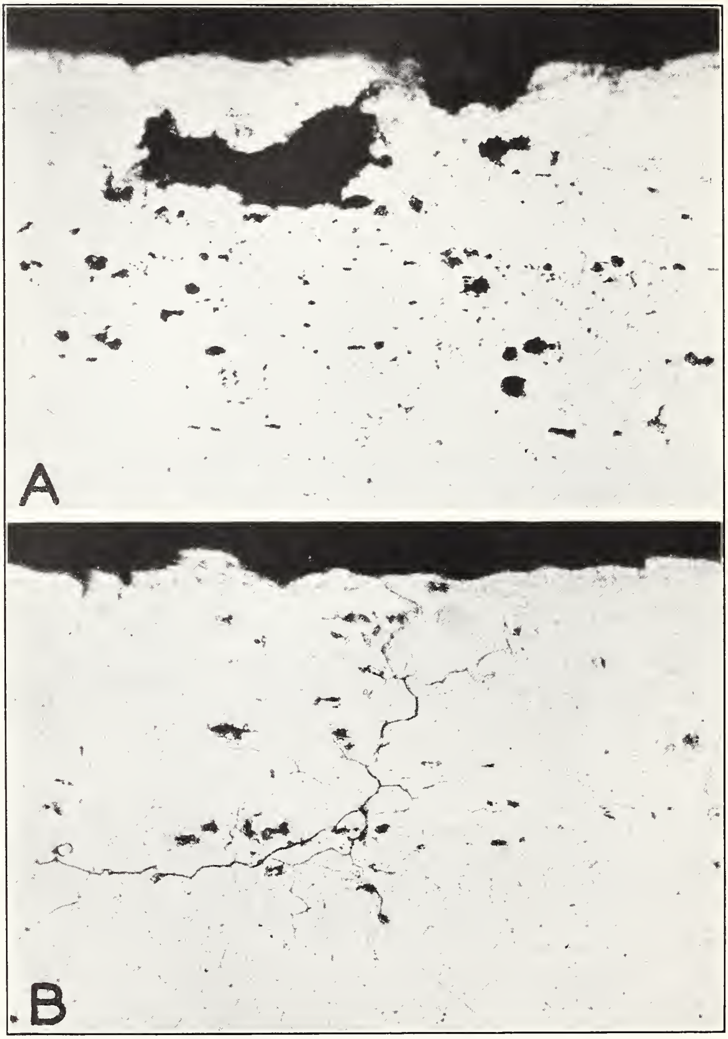

Fig. 9.—*Effect of corrosion on sheet duralumin. In each case the micrograph shows a section perpendicular to the corroded surface, unetched.* × *500*

a. Sheet duralumin, corroded with a calcium chloride solution, showing a roughened and pitted surface. This is the more common type of corrosive attack.

b. Sheet duralumin in which an intercrystalline corrosive attack occurred under atmospheric exposure conditions.

determined the effect of addition of copper, nickel, and magnesium upon the rate of solution of aluminum in hydrochloric acid and in potassium hydroxide. They reported that the accelerating effect of copper is decidedly greater than that of nickel. The results obtained with the magnesium alloys were inconclusive.

2. INTERCRYSTALLINE CORROSION

The usual effect of corrosion on aluminum and its alloys is a roughening of the surface which may often take the form of pitting or other localized attack. In addition to a corrosive attack of this kind, duralumin, and some of the other high-strength (heat treatable) wrought alloys occasionally are subject to intercrystalline corrosion, the surface evidence of the attack being very slight. (Fig. 9.) Although the two forms of corrosion may occur simultaneously on the same material, usually one or the other predominates. Wrought alloys containing copper appear to be more susceptible to the intercrystalline form of corrosive attack, as developed by laboratory corrosion tests, than those free from copper but alloyed with Mg_2Si. This does not apply, however, to the other and more common form of corrosion attack.

As a result of intercrystalline corrosion, the tensile properties may be very materially affected, the greatest change being a pronounced lowering of the elongation. If the material is in the form of sheet or wire, it may be very decidedly embrittled, according to the severity of the attack. Chloride solutions are most active in producing a corrosive attack of this kind. The different susceptibility of various lots of duralumin to intercrystalline corrosion depends upon several factors, chief among which are the heat treatment which the material has received and the mechanical treatment (cold-working) after heat treatment. Knerr (17m) has shown that the corrodibility of duralumin, in general, is affected by the method of quenching used in the heat treatment, being less for cold water than for hot water. This point has been investigated further at the Bureau of Standards and it has been shown that cold-water quenching renders sheet duralumin much less susceptible to intercrystalline corrosive attack than does oil quenching or hot-water quenching although the mechanical properties, in general, are scarcely affected by these variations in the quenching media. Intercrystalline corrosion is a matter for serious consideration in the case of sheet materials. In the case of forgings and other pieces of relatively large cross section, however, nothing has ever been observed to indicate that it need be regarded very seriously in relation to such materials. In contrast to sheet duralumin, sheet aluminum does not appear to be susceptible to intercrystalline corrosion to any extent.

LeChatelier (17p) has described a case of the disintegration of aluminum very suggestive of an intercrystalline attack. The metal, which was designated as "impure," can not be considered as representative of aluminum as made at the present time, however.

The subject of the deterioration of aluminum alloys by reason of intercrystalline corrosion has only comparatively recently received serious consideration. Much more information is needed, for example, such as that obtained from carefully supervised exposure tests before very definite conclusions can be reached concerning the rate at which such a corrosive attack progresses or the factors which promote it.

3. CORROSION TESTS

The corrosion resistance of aluminum and its alloys in the past has practically always been determined by carrying out a "small-scale" experiment in which the essential features of the service for which the material was intended were reproduced. Usually such tests consisted simply of immersion in a chosen liquid and the change of weight per unit area was determined. Most of the data in Table 5 were obtained by such tests.

Mylius (14d) has proposed a thermal-hydrochloric acid test as a means for determining the relative resistance of sheet aluminum specimens against attack by chemicals, the maximum temperature attained in the reacting acid being used as measure of the speed of reaction. A piece of the sheet material of 20 cm² area rolled into a cylinder is immersed in 5 cm³ of hydrochloric acid (4 per cent solution). The maximum temperature (t) attained is noted as well as the time in minutes (m) for attaining this temperature. The quotient, $\frac{t-20}{m}$, is termed the reaction figure and is stated to be a measure of the corrosion resistance of the material. For iron-free aluminum, it was found to vary from 0 to 4; for technically pure aluminum, 4 to 10; and soft aluminum alloys are in classes varying from 0 to 20. The protective action of an initial surface film of aluminum oxide can readily be shown by the lower reaction figure for such a material.

Mylius (14b) has also used a hydrogen peroxide solution (3 per cent), to which sodium chloride (1 per cent) has been added as a means for demonstrating the relative resistance of specimens of worked aluminum to sea-water corrosion. The loss of weight of the specimen and the amount of alumina on the surface were used as a measure of the attack. Mylius states that a secondary surface oxide layer limits the attack and concludes that technically pure aluminum can not be designated as resistant to salt water, but that carefully rolled thin sheets can be rendered highly passive to salt-water attack by heating them to 300 to 400° C. in the air.

A critical study of the "oxidizing sodium chloride" test has been made by Rackwitz and Schmidt (17b). They showed that light has an effect upon the rate of corrosion by affecting the stability of the reagent; hence, in carrying out the test, the specimens and solution should be protected from bright light. Heat also affects the test results and a temperature of 15 to 20° C. was recommended. Rackwitz and Schmidt also concluded that a relatively large solution of a concentration considerably less than that recommended by Mylius, with frequent renewal of the solution, was necessary in order to obtain reproducible results.

This sodium chloride-hydrogen peroxide solution has been used extensively at the Bureau of Standards in the study of the susceptibility of sheet duralumin and similar aluminum alloys to intercrystalline corrosion. The degree of the intercrystalline corrosive attack by this solution as well as by ammonium chloride, varies decidedly for different materials, and appears, on the whole, to be a suitable means for the laboratory study of the service deterioration of aluminum alloys by intercrystalline embrittlement. The change in the tensile properties resulting from the corrosive attack is a very much better criterion to use, however, than is the loss of weight in the case of sheet material. The corrosion specimens are made in the form of tension specimens, and the tensile properties are determined after corrosion, for comparison with the initial properties of the material, according to the method described by Blough (17d).

The results of corrosion tests reported by Rackwitz and Schmidt (17b) for a series of light alloys, each of which was subjected to several different corrosion tests, have strikingly corroborated this fact, that the drop in tensile properties resulting from a corrosive attack can not be estimated with any degree of assurance whatever from the results of "loss of weight" corrosion tests.

4. PROTECTION OF ALUMINUM AGAINST CORROSION

Both aluminum and its light alloys are attacked by sea or salt water to a considerable extent. Many of the alloys are attacked by fresh water also although aluminum is much more resistant. The protection of these materials against corrosion, especially when used for construction purposes, is therefore of importance. Of particular significance is the question of the protection of aluminum alloys used for aircraft construction. Frames, beams, struts, and other stress-bearing members are built up out of sheet material the corrosion of which would affect the mechanical properties to a very much greater extent than would a similar attack of a more massive piece; that is, one of greater cross section. The means used for protecting against corrosive attack are varied and, of course, are governed by the severity of the service conditions to be met.

(a) ELECTROPLATING

Aluminum can be electroplated, but this is done primarily for improving the appearance rather than for protecting against corrosion. The coating metals available are all electropositive[3] toward aluminum; hence all such coatings afford no electrochemical protection against corrosion of the underlying metal, but only a mechanical protection. Electroplated coatings when exposed to severely corrosive conditions, as a rule, readily peel from the base when once the coating has been perforated. These points will be dealt with in the section on electrodeposition.

(b) OXIDE COATINGS

It has already been mentioned that aluminum owes its stability, in large measure, when exposed under ordinary atmospheric conditions to the oxide film which forms readily on any freshly cut or polished surface. Consideration of this fact has led to the development of a method for the protection of aluminum and its alloys against corrosion by a preliminary intensifying of the surface oxidation. This is accomplished by an anodic oxidation process; that is, the aluminum is made the anode of a suitable electrolytic cell. Skinner and Chubb (20b) were among the first to utilize anodic reactions in a practical way for producing a protective coating on aluminum, their aim being to obtain a coating thick enough to serve as electrical insulation on wire. Their best results were obtained by using a sodium silicate solution as the electrolyte, the applied voltage being relatively high (approximately 400 volts). Very adherent coatings, 0.0001 to 0.0004 inch thick, were obtained.

Recently, since duralumin has come to be used extensively as a material for aircraft construction, the anodic oxidation treatment has been utilized for increasing the corrosion resistance of the material. A warm solution of chromic acid as the electrolyte has been found to give excellent results (18k) and is generally used, although a borax solution as the electrolyte has also given promising results (19c).

The oxide coating on aluminum and aluminum-rich alloys formed by anodic oxidation in a chromic-acid solution has a very smooth glassy surface, and no visible cracks are formed on severely bending a coated sheet specimen. The coating forms in all crevices or holes into which the solution can penetrate.

The protection afforded by such an oxide coating can be greatly increased by the addition of a grease film. The grease which need be only very slight in amount—for example, 0.03–0.05 ounce per square foot of surface—is applied by immersing the coated article in a solution of a grease, such as lanoline, lard oil, etc., in a suitable

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[3] The designation of the other common metals as electropositive with respect to aluminum is in accordance with the recommendation of the American Electrochemical Society.

volatile solvent like gasoline. Information showing the behavior of aluminum treated in this way when exposed for long periods in the atmosphere is not available. In laboratory corrosion tests, however, excellent resistance to mildly corrosive agents has been demonstrated.

A somewhat similar coating can be obtained without electrolysis, the article being simply immersed for 15 to 30 minutes in a hot solution. Rather complex solutions, generally containing a chromium salt and potassium bichromate, are used (18k). The results vary quite decidedly according to the solution used and the condition of the surface of the specimen treated. For best results the surface should be freshly rubbed with a fine abrasive before treatment.

The degree of protection afforded by such coatings as a rule is comparable to that given by the "anodic oxide" coatings; that is, they are intended for mildly corrosive conditions, such as atmospheric, and not for severe corrosion as in sea water. The use of an oxidizing treatment on aluminum or its alloys before the application of a coating of the varnish or enamel type has been recommended as advantageous.

An oxidation method suggested by Tevis (18i) which may be applicable to castings or forgings of relatively large cross section, though not to sheet material, consists in covering the surface with a layer of a chromate or other easily reducible chromium salt by brushing or by immersion and then heating to a red heat, whereby a coating consisting probably of mixed oxides of aluminum and chromium is formed.

If aluminum or its alloys is to be immersed in a definite volume of water for long periods, the metal can often be protected by a suitable treatment of the water (18g) by the addition of oxidizing salts, such as a bichromate or a nitrate, the former being the most effective. The formation of an adherent scale renders the metal "passive."

(c) SODIUM SILICATE

The addition of a small amount of sodium silicate (water glass) has been found to exert an appreciable protective action on aluminum or aluminum alloys immersed in water or certain solutions. Seligman and Williams (18h) studied this effect in 5 per cent soda solutions and Rohrig (18h) in connection with the dye industry. In solutions of sodium hydroxide, sodium carbonate, and potassium sulphide the protection was appreciable. The protection afforded by the sodium silicate may be enhanced somewhat by the addition of a bichromate, as mentioned above (18g).

A preliminary treatment of the surface with a solution of sodium silicate followed by baking at a temperature of 300° F. (150° C.) for several hours (18,d,e) has been found to give a coating which protects the metal very appreciably against rather severe corrosion, such as that of the "salt-spray" box in which a 20 per cent sodium chloride was used. In the case of castings, this treatment also serves to decrease the porosity very decidedly. This has proved a very decided advantage in the case of aluminum alloy carburetor parts.

(d) VARNISH, PAINTS, AND ENAMELS

For severely corrosive conditions—for example, sea water—the use of a paint, varnish, or enamel coating appears to be the most satisfactory method for protecting aluminum. The experiments by Sabin in 1896 (18j) indicate the degree of protection obtainable by such means. In one series of tests, 30 plates of aluminum and various alloys coated in different ways were immersed in sea water 5 to 6 feet below the surface for 19 months at the New York Navy Yard. At the end of 6 months the following coatings were found to have given practically perfect protection: Baked pipe-coating enamel; "durable metal coating," both baked and unbaked; chromium oxide in Kauri resin-oil varnish, unbaked; spar varnish, baked and unbaked; and white zinc in Kauri resin-oil varnish. The plates were reimmersed for 13 months. Some were lost, but those which were examined were still uncorroded.

In a second series of tests, 25 coated plates were immersed at the Norfolk Navy Yard for 2 years. The results in general confirmed those of the first tests and indicated in addition that coatings in which oil alone was the vehicle were not suitable for such severe conditions.

At present, the most commonly used coatings of this class are of three general types, clear spar varnish, aluminum-pigmented spar varnish and bituminous varnish. The last one is used as a protection against severe corrosion, such as sea-water immersion. The varnish coatings are used primarily for atmospheric service, the pigmented varnish having a very much greater protective value than the plain varnish coating of equal weight. Both will "blister," however, under severely corrosive conditions. The tendency of bituminous paints to check on exposure can be eliminated by giving them a protective coating of aluminum paint made with spar varnish. With a suitable varnish, the black undercoat will not "bleed" through the aluminum paint and the finished surface will closely resemble the original aluminum sheet.

A rather comprehensive series of exposure tests is now in progress in cooperation with the Bureau of Aeronautics, United States Navy Department (18c). The results to date have served to emphasize the decidedly longer life of pigmented nitrocellulose and varnish coatings as compared with the corresponding clear coating. The linseed-oil paints because of their great flexibility appear to be exceptionally well suited for the protection of aluminum and its alloys. Such coatings are not suitable, however, for service involving appreciable abrasion.

A varnish type of coating which is scratched off in places or which blisters or peels in spots exposes those localities to corrosion, and repair of the coating at such spots may be too long postponed. Coatings which are not truly permanent, but which may be very readily renewed, have many points in their favor. A simple rubbing over with a thin film of slushing compound (93–a), an adherent oil, has been found to offer very good protection under rather severe conditions of service,[4] especially when dusted over with aluminum "bronze" powder. The powder may serve to combine with the moisture or other corroding agents which would otherwise attack the underlying metal, and its adherence shows that the film of oil is complete. Such a coating has desirable flexibility, but is much stiffer and less readily rubbed off than might be expected, and can be readily repaired as required. Such methods of protection preferably applied over an anodic coating deserve serious consideration in competition with the varnish type.

5. ALUMINUM FOR PROTECTION OF OTHER MATERIALS

(a) METAL SPRAYING AND "ALCLAD" PRODUCTS

A coating of aluminum applied by the metal spraying process has been found by laboratory corrosion tests at the Bureau of Standards, and by exposure tests on the seacoast, which have so far extended for a period of a year, to protect duralumin very efficiently. So far as is known such a coating had not previously been used for this purpose.

Very recently this scheme of protecting duralumin with a coating of pure aluminum has been applied to sheet by the Aluminum Co. of America. While the details of the method of applying the coating have not yet been made public, the resultant product appears as if it were made by placing thin sheets of pure aluminum each side of a heavier sheet of duralumin and hot-rolling the pack so as to secure welding of the sheets together. Duplex or triplex aluminum clad steel and copper sheets, also apparently produced by welding during hot-rolling, have been produced abroad, and such specimens have been examined at the Bureau of Standards.

The weld between copper or steel and aluminum in the specimens examined did not appear as good as that between aluminum and duralumin in the domestic product.

While the addition of the aluminum coatings over the duralumin decreases the strength of the resultant sheet, as compared with an all-duralumin sheet of equal thickness, the "Alclad" material, as the product is called, has, nevertheless, after heat treatment, a strength within, say, 5,000 lbs./in.^{2} of an unprotected duralumin sheet when the thickness of the pure aluminum coating is not too great.

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[4] Private communication from C. W. Hall.

Preliminary tests by the Aluminum Co. of America on the resistance to corrosion of duralumin so coated with aluminum corroborate the previous experience of the Bureau of Standards as to the ability of an outside layer of aluminum to protect an underlying layer of duralumin against corrosion, especially of the intercrystalline type. Dix (18–a) states that the aluminum exerts an electrolytic protection over cut edges or bare spots at which the duralumin is exposed in a fashion similar to the protection of small exposed areas of iron or steel in a zinc-coated sheet.

The use of an aluminum coating, either alone or in combination with one of the varnish or the slushing compound type, appears to offer advantages, obtainable in almost no other way, for the avoidance of the intercrystalline type of corrosion of the duralumin type of alloys.

Aluminum has been sprayed commercially by the Schoop process upon other metals (21–j), though its application to duralumin by metal spraying appears to have been confined to the experiments of the Bureau of Standards. Sprayed at the rate of 1 lb./hour, it will cover superficially an area of 30–40 square feet to a thickness of 0.0012 inch (21–f). In Germany aluminum is sprayed on grate bars to reduce wear, prevent the scaling of the iron, and adherence of slag. The iron and aluminum combine and an outer skin of aluminum oxide is formed (21–c) which has a melting point of 3,200 to 4,000° F. It is necessary to replace the coating from time to time.

(b) ALUMINUM PAINT

Aluminum powder, often called aluminum "bronze" powder, is made of fine flakes of aluminum suspended in a suitable vehicle. Powdered or atomized aluminum is granular in form and not suitable for use in making aluminum paint. The vehicles used include bodied linseed oil, short and long oil varnishes, gloss oils, and pyroxylyn lacquers. Linseed-oil paints give a softer surface when dry than varnish-base paints (17h). Walker and Hickson (22e) state that aluminum paint consisting of 25 to 30 per cent aluminum powder in boiled linseed oil, or linseed oil and spar varnish, will be durable for outside paint when applied in three coats. Two coats will give good service on metal; one coat is not recommended. Aluminum paint containing 15 per cent powder in spar varnish is not nearly equal to one containing 25 to 30 per cent as above. For extreme durability for outside use 2½ pounds of powder to a gallon of vehicle is recommended, while for interior use 1½ to 2 pounds powder to a gallon is sometimes sufficient. The Aluminum Co. of America recommends 20 to 25 per cent by weight of powder. A new paint (22c) contains flake silica and graphite pigment, in addition to aluminum, in boiled linseed oil.

Aluminum paint reflects 70 per cent of the light energy (22f) which falls upon it, and for this reason it is used for painting oil tanks and structures which must be kept as cool as possible. Aluminum paint also has a low emissivity and is used on ovens, furnaces, stacks, etc., where it is desired to radiate as little heat as possible. It is used in protecting metal against corrosion and wood against weathering. Aluminum paint is unaffected by hydrogen sulphide. The polished powder has the property of "leafing" in oils and varnishes, the aluminum flakes collecting at the surface to form an apparently continuous bright metallic film. The unpolished powder does not have this property. Edwards and Wray (22d) recommend the use of two coats of aluminum-bronze powder mixed with shellac as a protection against warping and cracking of wood patterns. The use of the paint also increases the ease with which the patterns may be withdrawn from the mold. For detailed discussion of aluminum paint reference should be made to Edwards (22a).

(c) CALORIZING AND OTHER PROTECTIVE METHODS

Aluminum finds some use as a protection on other metallic surfaces, being generally applied by calorizing (21e, g, i), sometimes by spraying, or even applied as foil. Ruder (21i) describes the calorizing process of coating metals with aluminum by heating in a mixture of aluminum and aluminum oxide at high temperatures. This is accomplished at from 700 to 800° C. for copper and from 900 to 950° C. for iron and steel. The layer formed varies from 0.0009 to 0.0004 inch in thickness. Guillet (21g) describes methods making use of granular aluminum, alumina, and aluminum chloride at about 800° C. He finds that materials that have been mechanically worked calorize better than cast material. The coating produced is very hard and may be polished. Guillet states that calorized material lasts five to twenty times as long at temperatures of 700 to 800° C. as uncalorized material and two to four times as long at higher temperatures. It may be applied to condenser tubes, furnace parts, or other parts used at high temperatures. Guillet states that calorization changes the electrical resistance of aluminum. Kayser (21b) states that oxygen or air, carbon dioxide, ammonia, and coal gas have no effect on aluminized nickel-chromium-iron alloys or steel, or on nickel-chromium-iron up to at least 1,000° C. Above 1,000° C. aluminized steel is attacked to a limited degree. Sulphur-bearing gases lead to rapid destruction of aluminized steel, the effect being most marked in reducing atmospheres, and a minimum in dry oxidizing atmospheres. The use of aluminized steel is restricted to uses in which it is not called upon to withstand even small stresses.

Cournot (22b) experimented with the use of powdered ferroaluminum on steel low in carbon, and found that a porous outer layer resulted under which was formed a continuous, resistant inner layer.

This inner layer developed by diffusion toward the interior. The time of cementation had a clear influence, but the chemical composition of the iron-aluminum powder had no appreciable influence on the coating. The resistance of the coating to heat is influenced by the initial thickness of the coating and the freshness of the powder. The protective effect was not so satisfactory on an eutectoid steel, and on cast iron the results were very poor. Howe and Brophy (21e) state that in the case of the calorization of cast iron the penetration appears to be retarded relative to the amount of free carbon present. The work of Martin on covering iron alloys by dip coatings, painting with Al and Fe_2O_3, treatment with Al vapor and volatilization of an aluminum salt is described and discussed by Cournot (21d). Guillet (21a) describes methods of cementation of copper and its alloys with aluminum, using an aluminum-copper alloy containing 20:100 Cu-Al. Ammonium chloride is also used in applying these coatings, and Guillet regards the chloride as the real agent of cementation. Brass, bronze, and cupronickel were found to be sharply hardened by the treatment, except the 84 per cent Cu bronze, which was softened. Tests on nickel gave a very feeble penetration, without any very interesting improvement of properties. Tests at higher temperatures gave deeper penetration, often double for the same length of time.

Calorizing is now being done on a rather large scale by a hot-dipping process. The articles are tinned first to cause them to take a better coating when immersed in the molten aluminum. The aluminum-coated articles are then heated to cause the diffusion of the aluminum into the iron base. Such calorized coatings are much thinner, however, than those made by the older process, but are much cheaper.

6. ALUMINOTHERMY

Very extensive use is made of aluminum in the production of pure metals, such as chromium, vanadium, manganese, silicon, and ferro-alloys by the Goldschmidt thermit process. This process depends on the reduction at high temperatures of the oxides of these metals by finely divided aluminum. The Metal & Thermit Co. has published quite a bit of literature describing the alloys and metals which are thus produced.

The reaction between finely divided aluminum and the oxides of iron is also utilized as a welding process for steel and iron. In this process the crack or cavity is cleaned out and a sand mold built up around it. Into this mold the reaction mixture, finely divided aluminum with iron oxide, is placed and, when ignited, forms molten iron which flows into the cavity and unites with the edges of the article to be welded. The aluminum oxide floats to the top of the weld mold. Welding by this method is very suitable for heavy repair work. The details are described in books on welding (41o).

7. CHEMICAL ANALYSIS OF ALUMINUM AND ITS ALLOYS (GRAPHITIC SILICON, OXIDE)

The analytical methods in widest commercial use are those given in a pamphlet issued by the Aluminum Co. of America (15g) and those of the American Society for Testing Materials (15h).

The analysis of aluminum and aluminum alloys is usually carried out on at least two portions of sample. One portion is usually decomposed by acid mixture for the determination of silicon, copper, and iron. Decomposition by acid is also used for determination of titanium. The second portion is decomposed by sodium hydroxide and analyzed for nickel, calcium, and magnesium. Manganese, tin, antimony, zinc, etc., are customarily determined on separate samples. Tin is titrated with iodine solution after suitable reduction, antimony is titrated with permanganate, manganese is determined by the persulphate method, with the bismuthate method optional, and zinc is separated as the sulphide and finally weighed as the oxide.

The methods cited do not include that for the determination of "graphitic" silicon. It is a question whether the determination of "graphitic" silicon by chemical analysis gives any real knowledge of the state in which the silicon existed in the alloy before chemical attack, or whether the size of the silicon particles governs the degree to which they are oxidized on chemical attack, so that the distinction between so-called "combined" and "graphitic" silicon is, in part at least, an artificial one.

Analytical figures for graphitic silicon, of course, have a partial relation to the condition of the silicon in the alloy itself. Schweizer (15c) points out that by heating specimens from which samples for analyses were to be taken to 550 to 600° C. for an hour, followed by quenching in water, the silicon determination can be made with avoidance of complication by "graphitic" silicon. Köster and Müller (15a, 76b) show how the amount of "graphitic" silicon found by analysis varies in alloys of different silicon content with various temperatures at which the alloys are heated, and have even given a curve for the solubility of silicon in aluminum determined on the basis that silicon held in solid solution is recovered on analyses as SiO_2 and that in the eutectic as "graphitic" Si.

American practice now disregards "graphitic" silicon on the basis that the analytical figure is without great metallurgical significance and considers that the figure obtained in a "graphitic" silicon determination is governed not only by the condition of the silicon in the alloy but also by the conditions of the analytical procedure. After decomposition of the sample some of the iron is in the ferrous and some in the ferric state, depending on the conditions of analyses. Similarly, the condition of the silicon after decomposition of the sample depends on the conditions of analysis too largely for the figures to have metallurgical value. Hence, only total silicon is reported just as only total iron is.

Methods for the determination of aluminum oxide in aluminum are found in the literature, but it is now generally recognized that these methods give false values, and metallurgists generally agree with the conclusion of Withey and Millar (15b, 16a) that metallic aluminum is not capable of dissolving Al_2O_3 and that any oxide that would be found on a correct analysis would merely represent the infinitesimal coating of oxide on the surface of the sample. See also Rosenhain (15d).

Mechanically entangled oxide or dross, not being uniformly distributed throughout the metal, would present a difficult sampling problem even if reliable methods of analysis were available. The detection of entangled dross is better carried out by microscopic examination or by mechanical tests, than by chemical analysis.

Selected papers on methods of analysis are listed in the bibliography, page 340.

The Bureau of Standards is now working on the preparation of samples of No. 12 alloy and duralumin for inclusion in its list of Standard Samples for Analysis. It is hoped that these will be ready for distribution in 1928.

8. ELECTROCHEMISTRY

(a) ELECTROPLATING

The deposition of aluminum from a bath of its fused salts has already been described (p. 11). The electrolytic separation of aluminum from its aqueous solutions, on the other hand, has so far proven to be extremely difficult, if not impossible, under ordinary conditions. This difficulty may be due in part to the very high heat of formation of aluminum compounds and in part to the low solubility of aluminum hydroxide, and its consequent precipitation if through hydrogen evolution the pH of the cathode film exceeds 6.

Tucker and Thomssen (19m) have announced the electrodeposition of traces of aluminum, usually in finely divided condition, from a pasty, aqueous solution of aluminum chloride, at an extremely high-current density and on a cathode rotated at great speed. Others have reported somewhat similar results, but so far as is known detailed confirmation is lacking, and the prospect of commercial application seems extremely remote.

It appears somewhat easier to obtain aluminum from nonaqueous solutions, as Plotnikoff (19p) announced the deposition from a solution of aluminum bromide in ethyl bromide, which was later confirmed by Patten (19o). While in this case it appears possible to deposit some aluminum under ordinary conditions of deposition, the method holds little commercial promise.

The electroplating of other metals on aluminum and high aluminum alloys can be readily effected in many cases if special precautions are taken to secure a clean and preferably slightly etched or roughened surface in order to get good adherence. In practice the metal deposited is commonly zinc or nickel; other metals are usually plated over a preliminary coat of one of those metals. Although marked deposition by immersion might be expected on account of the position of aluminum in the electromotive series, actually there is very little such action. This is probably due to the passivity of aluminum in nearly neutral solutions, which passivity may likewise explain some of the difficulty in securing good adherence.

Due to the marked tendency of aluminum toward slow corrosion through pores in the plated metal, which latter tends to accelerate this corrosion, it is doubtful whether plated aluminum products will prove satisfactory where much handling or outdoor exposure are involved. Promising results based on accelerated corrosion tests, however, have been reported from France. The process involves a preliminary coat of nickel, then a coat of copper from the acid sulphate bath, which is buffed, followed by a final coat of nickel. The three coats have a total thickness of about 0.03 mm (0.0012 inch). In this way it is claimed that the deposit is made nearly impervious.

Regelsberger (19k) gives numerous references to processes and patents for plating various metals on aluminum, most of which have probably had little application. The methods most used for plating nickel on aluminum have been developed by French investigators (19d, h, i, j, l, n).

These depend upon cleaning the aluminum in a mildly alkaline solution and then immersing it in hydrochloric acid (1 to 1 or about $6N$) containing a small amount (about 2 g/L) of some metal, such as iron. This is usually added as ferrous chloride, but sometimes as ferric chloride, which latter might have more initial etching effect but would gradually be reduced to ferrous chloride. Manganous, zinc, and cadmium chlorides have also been suggested. The aluminum is then rinsed and plated in the usual way in any suitable nickel bath. There seems to have been some difference of opinion as to the function of the foreign metal in the acid dip, whether it forms a protective film through deposition by immersion on the aluminum surface or merely causes an accelerated etching effect.

Another method (19g) of preparation of the aluminum surface for plating involves sand blasting (or pumice scrubbing), which both cleans and roughens the surface so that the nickel adheres better.

In plating aluminum it may be generally advantageous to make connection with the electrical circuit before immersing the article.

Desch and Vellan (19a, b) report good results by plating aluminum with cadmium for protection against corrosion, although other methods proved on the whole more useful. Two different ways of preparing the aluminum for plating were tried, based on the French processes. The first, which seems to be given the preference, involved sand blasting, then a light coating of copper deposited from the copper cyanide bath, followed by another sand blasting. The other method was similar, except that electrolytic etching (anodic and then cathodic treatment) in a slightly acid bath containing ferrous and calcium chlorides was substituted for the coppering. Various cadmium baths were tried, but for this specific purpose the most permanently satisfactory results were obtained by using an ammoniacal cadmium sulphate bath containing peptone.

In the electrometallurgy of zinc (19f) it has long been the practice to deposit zinc from acid solutions upon aluminum cathode plates, the zinc being subsequently removed by stripping and the aluminum plates returned to the cells. Aluminum proves to be quite durable under such conditions.

From present information and experience it appears probable that better protection of aluminum is obtainable by means of a varnish or paint (p. 36) than by electroplating with any metal.

(b) ELECTROLYTIC SOLUTION POTENTIAL

Neumann (19q) measured the electrode potential of amalgamated aluminum (purity not stated) in normal solutions of aluminum sulphate, chloride and nitrate, finding respectively, $e_h = -1.31$, -1.29, and -1.05 V.

Kahlenberg and Montgomery (19r) have also measured the electrode potential of aluminum and of its binary alloys with copper, zinc, and nickel, in a normal aluminum chloride solution. Much more negative potentials were obtained in each case after amalgamation and these were considered to be nearest to the correct values. The potentials were not constant, but became less negative quite rapidly due to oxidation. The alloys had less negative potentials than aluminum. The results with amalgamated aluminum (over 99 per cent aluminum) varied from $e_h = -1.28$ to $e_h = -1.36$ V, depending on purity, condition, and technique. The results which are more negative than Neumann's may be explained by differences in material and experimental conditions.

The computation of the "standard" or normal potential e_0 for such measurements involves the degree of dissociation or "activity" of the aluminum salts used, on which there are apparently little exact data. Allemand and Ellingham (2c) assign to this standard potential a value of -1.34 V, which is at least roughly consistent with the most negative value of -1.36 V obtained by Kahlenberg.

Drosbach (19s) has recently computed a value of $e_h = -1.33 \pm 0.01$ V for the "standard" potential of aluminum, based on heats of reaction and specific heats.

Burgess and Hambuechen (12a) give results obtained by Mott on the potential of unamalgamated aluminum in solutions of various acids, alkalies, and salts, which indicate that such potentials are variable and probably have little quantitative significance.

Kahlenberg and French (19t) have measured the potential of aluminum in *N* KCl solution and found it to vary depending upon whether oxygen, air, nitrogen, or hydrogen was passed through the solution.

Neumann and Richter (19u, v) have measured the decomposition voltage of fused salts of aluminum and computed the electrode potential for solutions at room temperature.

Smits (19w) has concluded from measurements of the potentials of aluminum amalgams that the potential of aluminum in *N* $AlCl_3$ solution would be $e_h = -1.43$ V.

(c) ELECTROLYTIC BEHAVIOR, FORMATION OF FILM

If aluminum is made the anode or positive terminal in an electrolytic cell containing any one of a number of electrolytes, an oxide film is formed on its surface. The properties of this film depend upon the potential difference applied, the temperature, and the kind of electrolyte used. If the film is formed in an electrolyte containing an ammonium or alkaline salt of some of the weak acids, such as borates, phosphates, oxalates, citrates, etc., it has the property of passing electric current readily from the electrolyte to the aluminum, and of preventing the passage of current from the aluminum to the electrolyte. It also has the property of being an insulator when dry. Such films serve as an essential element in electrolytic condensers and lightning arresters using aluminum plates, in electrolytic rectifiers in which one of the electrodes is aluminum, and in one class of insulation for aluminum wire.

The film may be formed by passing either a direct or an alternating current through an electrolytic cell of which one or both of the electrodes are aluminum and the electrolyte is of the type mentioned above. If direct current is used, the film is formed only on the electrode, which is at the higher potential and serves as the anode. If alternating current is used, a film is formed on both of the electrodes; that is, if both are of aluminum. When such an electrolytic cell is first connected into an electric circuit, the current may be fairly large, but gradually decreases as the film forms. The current continues to decrease as the thickness of the film increases to a point at which it no longer passes current from the aluminum to the electrolyte by conduction. If now the applied potential difference is increased, current will again pass while the thickness of the film further increases. With one of the more suitable electrolytes, especially if it is kept cool, a film formed in this way conducts but very slightly, even when the potential drop from the aluminum to the electrolyte is made as large as several hundred volts. At the same time it conducts readily when the potential drop is from the electrolyte to the aluminum. Such films, if kept in the electrolyte, are not very strong mechanically and are not very stable electrolytically. When not in use they gradually lose their electrical strength and are weakened by an increase in the temperature. Even in use, especially if the applied potential is fairly high, they are more or less continually breaking down. However, a weakened film is quickly restored by subjecting it to the conditions under which it was formed, and in most cases conditions of use are such that a film when broken down automatically re-forms itself. A breakdown of the film is accompanied by a series of sparks between the aluminum and the electrolyte, and in certain applications there is a small amount of sparking almost continuously.

A film which has been in use for some time may appear to be rather thick and spongy, but the part of it which is effective from the electrolytic standpoint, and which is adjacent to the aluminum, is always very thin.

(d) ELECTROLYTIC CONDENSERS, LIGHTNING ARRESTERS

If a number of aluminum plates are placed parallel in a suitable electrolyte and alternating plates connected to common terminals, the arrangement constitutes an electrolytic condenser, or, at any rate, becomes an electrolytic condenser as soon as oxide films of the requisite thickness are formed over the plates. Such condensers are not of a quality comparable with the so-called mica condensers in which sheets of metal are separated by sheets of mica, or even paper condensers in which sheets of metal are separated by sheets of paper impregnated with paraffin or similar material. However, because of the high dielectric strength and extreme thinness of the oxide film, the electrical energy which may be stored in such a condenser for a given volume is much larger than that which may be stored in a mica or paper condenser. It has the further advantage that in case of a breakdown the oxide film is readily and usually automatically re-formed.

An important commercial application of these condensers is in radio broadcasting and receiving equipment.

Lightning arresters depending for their action upon the properties of an aluminum oxide film in an electrolyte are made by nesting together a large number of aluminum trays. These trays are separated slightly by insulators and filled with a suitable electrolyte. This type of lightning arrester is connected between the line conductors and ground by a suitable gap to prevent power loss. The films are formed by applying a suitable alternating potential difference to the arrester. As they are gradually destroyed by the action of the electrolytes, the process of formation must be repeated from time to time and this is generally done in accordance with a definite schedule. The gap between the line conductors and the arrester is such that a certain excess of potential difference above normal results in a discharge through it and the arrester. If the excess potential difference is of very short duration it may break down only half of the films, in which case the discharge should cease as soon as the sign of the potential difference changes; that is, within a sixtieth of a second in the case of a 60-cycle power circuit. In case the current continues to pass for several cycles, new films form at the points broken down. This reduces the discharge current, allowing the electrodes of the gap to cool to a point at which the gap no longer conducts.

(e) ELECTROLYTIC RECTIFIERS

If one of the electrodes of an electrolytic cell is aluminum and other ferrosilicon, carbon, or a metal similar to lead, such a cell after the film is formed will pass current from an alternating-current circuit such as that ordinarily used to supply light in the home, in one direction readily and scarcely at all in the other. A cell of this type may therefore be used as a "trickle" charger for radio A batteries and as an element in B battery eliminators. It may also be used as a rectifier for charging small batteries, such as radio B batteries. Such rectifiers are described at length in Bureau of Standards Technologic Paper No. 265, Theory and Performance of Rectifiers, so need not be considered further here.

(f) OXIDE INSULATION

The oxide film which forms naturally on aluminum is an insulator. However, it is so extremely thin that it breaks down with an applied potential difference of less than 1 volt. If the film is formed by making the aluminum an anode, as outlined above, and then dried, it will withstand an applied potential difference of 100 volts or more. The film formed in sodium silicate with an applied potential difference of 425 volts is from 0.0001 to 0.0004 inch in thickness, smooth to the touch, not brittle, but abrasive. Two wires so insulated and twisted together without rubbing will withstand an applied potential difference up to from 200 to 500 volts. However, the slightest relative motion of the wires results in a grinding between the surface, which causes a short circuit.

IV. PHYSICAL PROPERTIES

1. ELECTRICAL, MAGNETIC

(a) ELECTRICAL RESISTIVITY

The resistivity of electrolytically refined (99.968 per cent) aluminum as recently determined at the Bureau of Standards for hard-drawn and annealed wire at 20° C. is, respectively, 2.688 and 2.674 μ per cm.

The density at 20° C. was 2.698. The temperature coefficient of resistance per ° C., at 20° C., is 0.00421 for hard drawn, and is estimated as 0.00423 for annealed.

Edwards (33b) gave 2.669 μ-cm at 20° C. and a temperature coefficient of 0.00425 for annealed wire of 99.971 per cent purity, and converted this figure to other bases of reference as follows:

Volume conductivity, compared with International Standard copper of same, length and cross section, 64.6 per cent.

Mass conductivity, compared with International Standard copper of same, length and mass, 212.9 per cent.

Specific mass resistivity-ohms per meter gram 0.0720.

Commercial samples, not refined, but selected for purity have been previously examined. Richards and Thomson (23p) have given lower values of resistivity than those given above on samples of aluminum which they described as having a purity of 99.58 and 99.66 per cent. Their figures, reduced to 20° C. by their value for the temperature coefficient become for hard-drawn wire 2.789 and 2.646 μ-cm, respectively. In view of more recent data on purer samples, the low value for the 99.66 per cent sample can no longer be accepted.

For commercial conductor grade aluminum the American Institute of Electrical Engineers standard is, for hard-drawn material, 2.828 μ-cm resistivity, 0.7644 ohm grams per meter^2 or 17.01 ohm circular mils per foot at 20° C.; temperature coefficient of resistance 0.00403; density at 20° C., 2.703; length-temperature coefficient 0.000023 (temperature in ° C.); volume and mass conductivity (compared with International Standard copper) 60.97 and 200.53 per cent, respectively, while the change of resistivity with change of temperature is 0.0115 μ-cm per ° C.

The temperature coefficient, ranging from about 0.0042 for pure material down to 0.0040 or 0.0039 for less pure material, holds over the temperature range 0 to 100° C. (23n, p). Pressure coefficients of electrical resistance are given by Bridgman (33c), and quoted by Edwards (33b).

Tests by the bureau (23k) on seven hard-drawn American samples averaging about 99.6 per cent pure (impurities about one-third iron, two-thirds silicon) gave, at 20° C., values varying from 2.7845 to 2.8175, with a mean of 2.806.

Tests at the Bureau of Standards on 28 samples of commercial aluminum of British manufacture gave, at 20° C., resistivities of 2.844 to 2.857 for hard drawn, and 2.817 to 2.825 μ-cm. Densities ran from 2.698 to 2.705.

Bureau of Standards tests on samples of French manufacture gave, for "extra pure" annealed, 2.76_8 and 2.77_4; for the same hard drawn, 2.77_6, for ordinary purity, annealed 3.05_1 and 3.05_7, for the same, hard drawn, 3.04_8 and 3.05_1 μ-cm. Analyses or density of these specimens are not available.

Further values for resistivity have been given by Jaeger and Dieselhorst (23n) and Northrup (23o).

The trend of the effect of the usual impurities, chiefly Fe, Si, and Cu, in commercial hard-drawn aluminum upon the resistivity is shown in Figure 10. This curve is only a rough approximation, but represents within reasonable limits the available data for the individual impurities as well as for combinations of them. The effect of calcium, as given by Edwards and Taylor, is also roughly represented by this curve. With larger amounts of impurities the curve does not continue straight, but for most impurities will bend down toward the horizontal axis.

According to Grogan (46a, 57a) and Rosenhain and Grogan (96e) the effect of Si can be to a certain extent neutralized by suitable additions of calcium in amount just sufficient to combine with the Si to form the insoluble compound $CaSi_2$. If an excess of either Ca or Si is present, the conductivity must fall, according to Edwards and Taylor, though Grogan claims that a slight excess of Ca is not harmful.

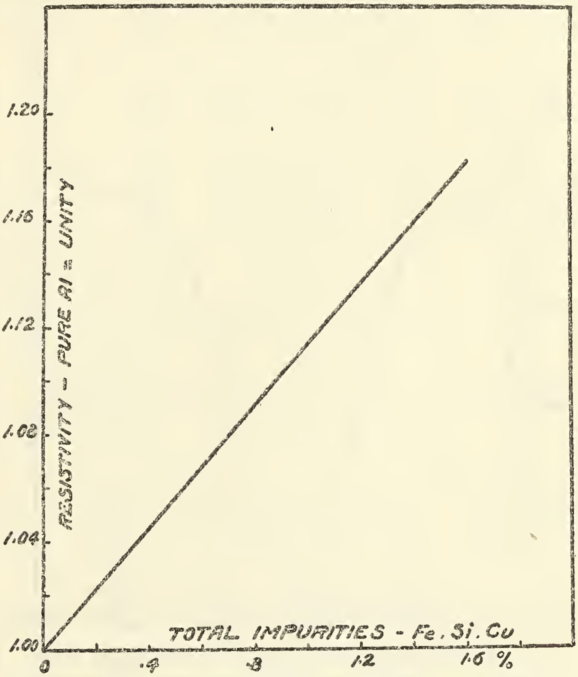

Fig. 10.—*Approximate effect of total amount of common impurities on resistivity of commercial hard-drawn aluminum*

Since the impurity present in largest amount in most commercial aluminum is iron, calcium additions would not be expected to be of much practical value, since the iron would not be affected.

The resistivity of hard-drawn commercial aluminum can be decreased by annealing at the proper temperature for the proper time, as indicated by Figure 11, but overannealing makes the resistivity increase again. The curve of Figure 11 is taken from Wunder (27a) and represents tests on hard-drawn wire of 4 mm diameter and of a purity of 99.3 per cent. The shape of the curve is characteristic of results on hard-drawn aluminum conductor, but the depth of the loop is greater than is obtained on American conductor wire of greater purity.

Northrup (34e) gives a curve showing the change in resistivity of solid and molten aluminum from room temperature to 1,100° C. The purity of the aluminum is not stated.

(b) USE OF ALUMINUM FOR ELECTRICAL CONDUCTORS

While copper is the material most used for electrical conductors, aluminum has had extensive application for this purpose. Owing to its lower conductivity it is necessary to use a larger cross section of aluminum to get the same conductance. Since the conductivity of aluminum is about 61 per cent that of copper, a cross section about 64 per cent larger is necessary for equal conductance. The density of aluminum being only about 30 per cent that of copper, the weight of an aluminum conductor of the same conductance is less than for copper.

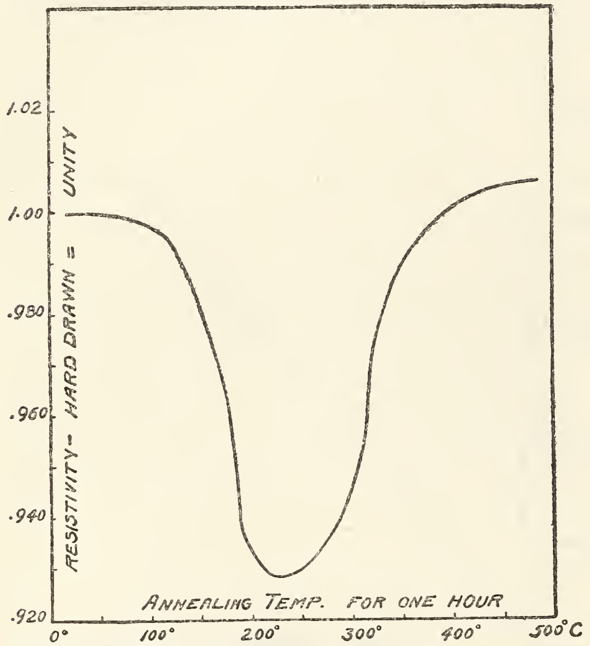

Fig. 11.—*Effect of annealing for one hour upon resistivity of hard-drawn 99.3 per cent aluminum. (Wunder)*

The larger cross section of aluminum for the same conductance as copper results in a slightly smaller self-inductance and a slightly larger electrostatic capacity and charging current. The voltage at which corona appears is higher for a larger diameter and this effect becomes of some importance at very high transmission voltages.

An aluminum conductor is weaker than one of copper having the same conductance. To provide greater strength aluminum conductors may be made up with a core of steel and the material is generally used in this way where strength becomes a controlling consideration. The accompanying tables (9 and 10) show the strength of stranded conductors of aluminum and of aluminum with steel core. In both cases the breaking load of the cable is assumed to be about 90 per cent of the sum of the breaking loads of the individual strands.

TABLE 9.—*Data for stranded aluminum conductors* [1]

Size in circular mils	Diameter	Area	Usual stranding	Copper equivalent in circular mils	Elastic limit	Breaking load
	Inches	*Square inch*			*Pounds*	*Pounds*
874,500	1.077	0.687	37×0.154	550,000	9,600	14,800
795,000	1.026	.624	37× .146	500,000	8,750	13,500
750,000	.994	.589	37× .142	472,000	8,250	12,700
715,500	.974	.562	37× .139	450,000	7,870	12,100
636,000	.918	.500	37× .131	400,000	7,000	10,800
556,500	.856	.437	19× .171	350,000	6,120	9,450
500,000	.810	.393	19× .162	314,500	5,500	8,500
477,000	.793	.375	19× .158	300,000	5,240	8,100
397,500	.724	.312	19× .145	250,000	4,370	6,750
300,000	.621	.236	19× .126	188,800	3,300	5,100
				A. W. G. No.		
336,400	.657	.264	19× .133	4/0	3,700	5,700
266,800	.586	.209	7× .195	3/0	2,940	4,550
A. W. G. No.:						
4/0	.522	.166	7× .174	2/0	2,330	3,570
3/0	.464	.132	7× .155	0	1,845	2,860
2/0	.414	.104	7× .138	1	1,465	2,270
0	.368	.083	7× .123	2	1,160	1,790
1	.328	.066	7× .109	3	920	1,420

[1] Data supplied by the Aluminum Co. of America.

TABLE 10.—*Data for aluminum cables, steel-reinforced* [1]

Size in circular mils	Equivalent copper in circular mils	Diameter	Stranding		Total area	Breaking load
			Aluminum	Steel		
		Inches			*Square inch*	*Pounds*
795,000	500,000	1.093	54×0.1214	7×0.1214	0.7060	25,150
715,500	450,000	1.036	54× .1151	7× .1151	.6350	22,680
636,000	400,000	.977	54× .1085	7× .1085	.5640	20,060
477,000	300,000	.883	30× .1261	7× .1261	.4620	20,700
397,500	250,000	.806	30× .1151	7× .1151	.3850	17,250
	A. W. G. No.					
336,400	0000	.741	30× .1059	7× .1059	.3260	14,580
266,800	000	.633	6× .2108	7× .0705	.2370	8,450
A. W. G. No.						
0000	00	.564	6× .1880	1× .1880	.1939	7,590
000	0	.501	6× .1670	1× .1670	.1537	5,995
00	1	.447	6× .1490	1× .1490	.1219	4,770
0	2	.398	6× .1327	1× .1327	.0967	3,780
1	3	.355	6× .1182	1× .1182	.0766	3,000
2	4	.316	6× .1052	1× .1052	.0608	2,394
3	5	.281	6× .0938	1× .0938	.0482	1,890
4	6	.250	6× .0834	1× .0834	.0383	1,500
5	7	.223	6× .0743	1× .0743	.0303	1,183
6	8	.198	6× .0661	1× .0661	.0240	940

[1] Data supplied by the Aluminum Co. of America.

While aluminum can be soldered and both soft and hard solders are available for this purpose, the operation is not so readily accomplished as with copper. Soldering is usually resorted to in connecting conductors to switch terminals, etc., but joints in transmission lines are usually made with mechanical devices. Satisfactory forms of clamps for this purpose have been worked out. Tie wires for aluminum conductors should always be made of aluminum.

The subject of proper sags and tensions in stringing aluminum conductors is fully covered in Handbook No. 10 of this bureau, entitled "Safety rules for the installation and maintenance of electrical supply and communication lines," in which tables are given for conductors of different sizes and for different temperatures and different geographical locations. The same tables will also be found in the latest edition of the National Electrical Safety Code, Handbook No. 3. The values given there and in the tables above are based upon data furnished by the Aluminum Co. of America and accepted by the committee which revised the National Electrical Safety Code. In that work the weight of stranded aluminum conductors is taken as 1.194 pounds per square inch of cross section per foot of length. The modulus of elasticity is taken as 9,000,000 lbs./in.^{2}. The coefficient of thermal expansion is taken as 12.8×10^{-6} per ° F. For cables having steel reinforcement these values vary with the size of cable. For cables of sizes Nos. 6 to 0000, the modulus of elasticity is taken as 12,000,000 lbs./in.^{2}; the weight per square inch of cross section per foot of length as 1.52 pounds, and the coefficient of thermal expansion as 10.5×10^{-6} per °F.

Williams (23f) states that compared with hard-drawn copper of the same conductivity aluminum-steel cable has an ultimate strength 18 to 63 per cent greater than that of copper, depending on the relative amounts of steel and aluminum. The span length of steel-aluminum cables is much greater than for either aluminum or copper (23g); there is greater security against corona losses with increasing transmission voltages than with copper (23l), which enables the use of longer spans. The inductance of steel-aluminum cable is the same as for a homogeneous conductor of the same diameter (23g). The aluminum used should be at least 99 per cent pure (23h, i, j). Aluminum cables have 3, 7, 19, 37, or 61 strands (23a), while steel-cored cables have 7, 37, or 61 strands in which the stranding is 1 and 6, 7 and 30, 7 and 54 steel and aluminum (23a). There appears to be some difference of opinion as to the necessity of zinc coating the steel to prevent electrolytic corrosion. Dusaugey (23c) and Williams (23f) state that a thick coating of zinc is necessary, while Hiller (23h) states that there is no appreciable corrosion from electrolytic action between steel and aluminum. Legros (23d) states that abnormal atmospheric attacks may occur with unusually hardened metal or in an atmosphere of excessive humidity. The Fifteenth Commission de l'Union des Syndicats de l'Electricite (23j) specified that aluminum must not contain impurities other than Fe or Si, and must not contain Na to which is attributed atmospheric attack. The relative costs of the two materials (Cu and Al) must necessarily vary with the market conditions. In 1924 Dusaugey (23c) calculated that there was a saving of expense of 55 per cent in the use of aluminum over copper conductors of the same section, 37 per cent if calculated for the same heating and 25 per cent if calculated for the same conductivity.

(c) THERMOELECTROMOTIVE FORCE

The thermal e. m. f. of 99.968 per cent electrolytically refined aluminum wire against pure platinum (Pt_{29}, the platinum standard) has recently been determined by the Bureau of Standards, and the data are given in Table 11.

The e. m. f. corresponds to the temperatures of the hot junction, the cold junctions being at 0° C. The plus sign indicates that the aluminum was connected to the plus terminal; that is, the aluminum was at a higher potential than the platinum.

TABLE 11.—*Temperature versus electromotive force for very pure aluminum*

Degrees centigrade	International millivolts	Degrees centigrade	International millivolts	Degrees centigrade	International millivolts
0	+0.000	240	1.374	460	3.480
20	.062	260	1.538	480	3.703
40	.135	280	1.708	500	3.931
60	.218	300	1.884	520	4.164
80	.312	320	2.065	540	4.403
100	.416	340	2.252	560	4.647
120	.529	360	2.444	580	4.896
140	.651	380	2.641	600	5.150
160	.781	400	2.843	620	5.409
180	.919	420	3.050	640	5.673
200	1.064	440	3.262	660	5.942
220	1.216				

Several samples of electrolytically refined aluminum were tested at 100° C. with the following results:

TABLE 12.—*E. m. f. of aluminum at 100° C.*

Purity (per cent)	E. m. f. millivolts
99.972	0.41_5
99.97	$.41_6$
99.968	$.41_6$
99.86	$.41_7$

Since the third decimal place is in doubt by at least one or two units, thermal e.m.f. determinations would have to be made at temperatures higher than 100° C. to differentiate between different samples of the refined metal of varying purity.

Data on less pure metal (99.67 per cent) against copper at 100, 232, and 419° C. are given by Northrup (25a). His results may be expressed by the following equation:

$$\text{(Al to Cu) } 10^6\,E\text{ (volts)}=4.51t-0^\circ\ .0122t^2+0^\circ.\ 0000433t^3$$

$$\text{(Al to Cu } 10^6\,\frac{dE}{dt}\text{ (volts)}=4.51-0^\circ\ .0244t+0^\circ\ .0001299t^2$$

Other measurements are by Wagner (25b) and Jaeger and Dieselhorst (25c), whose values for $\frac{dE}{dt}$ at temperatures between 0 and 100° C. are lower than Northrup's. The samples of aluminum used by them were not as pure as that used by Northrup.

Edwards (33b) has given figures on the effect of various impurities on the thermal e.m.f. of refined grade aluminum which are shown in Table 13.

TABLE 13.—*Effect of impurities on the thermoelectric properties of aluminum*

Thermoelectric e. m. f. against 99.971 per cent Al. Hot junction 660° C. Cold junction 0° C.	Added constituent	Thermoelectric e. m. f. against 99.971 per cent Al. Hot junction 660° C. Cold junction 0° C.	Added constituent
Microvolts	*Per cent*	*Microvolts*	*Per cent*
+5	0.037 silicon.	Maximum +4 Final +1.1	0.060 copper.
+6	0.157 silicon.	Maximum −11 Final − 4	0.160.
+8.5	0.336 silicon.	Maximum −25 Final − 4	0.820 copper.
+10.1	0.692 silicon.	+70	0.048 manganese.
+15.5	0.080 iron.		
+20.5	0.166 iron.		
+23.2	0.370 iron.		
+31	0.746 iron.		

(d) MAGNETIC SUSCEPTIBILITY

Aluminum is paramagnetic. Honda (24a) finds the following values for the susceptibility (k) at 18° C. for impure material.

Material	Susceptibility (k)
Kahlbaum aluminum in rods (Fe=0.80 per cent)	$+0.695\times10^{-6}$
Siemens-Halske aluminum in wire (Fe=0.42 per cent)	$+.685\times10^{-6}$
Neuhausen A. G. aluminum cast (Fe=0.08 to 0.24 per cent)	$+.65\times10^{-6}$

The susceptibility diminished from $+0.695\times10^{-6}$ at 18° C. to $+0.60\times10^{-6}$ at 657° C., and remained sensibly constant up to 1,050° C.

Honda's values of k are lower than values obtained by Wills (24b).

2. THERMAL

(a) CHANGE OF STATE (MELTING AND BOILING POINTS)

The value of the melting or freezing temperature of aluminum of 99.97 per cent purity is 659.8_0° C., and that of 99.75, 658.9_6° C., according to Edwards (33b) who determined these values by comparison with the standard sample of 99.66 per cent (Fe=0.18, Si=0.15 per cent), whose melting point this bureau has determined as 658.68° C. and which it furnishes as one of its standard samples for thermometric fixed points. (See Circular No. 66.) According to the most probable extrapolation, the melting point of aluminum 100 per cent pure would be very close to 660° C.

There is a considerable discrepancy between the two values for the boiling point of aluminum given by V. Wartenberg (26e) as over 2,130° C. and by Greenwood (26d) as 1,800° C. The latter value may be accepted probably as more nearly accurate, but it is very possibly only within ± 50° C. of the correct value. Experimental data from which to deduce the form of the vapor pressure curve are not available, but, by analogy, Johnston (26b) calculates it to be expressed by the equation

$$\log p = -\frac{11{,}500}{T} + 8.41.$$

The heat of fusion of aluminum may be taken from measurements by Laschtschenko (29c) as approximately 64 cal/g. Genders (11d) quotes the figure 208 cal/cc or 72 cal/g from Kaye and Laby. The heat of vaporization has never been determined. Richards (2h) calculates it to be 61,480 cal/g (that is, "about 23 times the temperature, absolute, at the boiling point"), and Johnston calculates it as 52,600 cal/mole.

(b) THERMAL CONDUCTIVITY

No thermal conductivity determinations on really pure, electrolytically refined aluminum appear to have been made as yet.

The thermal conductivity at 50° C. (approximate) as determined by this bureau $\frac{\text{Cal}}{\text{sec.} - \text{cm}^3 - 1^\circ \text{ C.}}$ for "Standard Sample Aluminum, 1922," of 99.66 per cent is 0.52 $\frac{\text{Cal}}{\text{sec.} - \text{cm}^3 - 1^\circ \text{ C.}}$.

Genders (11d) quotes figures by Schofield showing 0.53_2 at 129° C., and 0.54_2 at 372° C. for metal whose purity is not stated. Lees (27b) gives 0.504 and 0.502 at 18 and 0° C., respectively, for metal stated to be "99 per cent." He also gives values for lower temperature which are cited in Sec. VI. Other values, by Jaeger and Diesselhorst (23n, 27c), are lower, due most probably to a high percentage of impurity (including copper, 0.36 per cent) in the sample tested.

(c) THERMAL EXPANSIVITY

Three important series of measurements of the linear thermal expansivity of aluminum have been made. Two of these at least, by Dittenberger (28b), and by this bureau, were carried out with sufficient precision of measurement. That by Brislee (28a) was carried out with the purest material available at that time, but material of a higher degree of purity has since been studied at this bureau. The values of Dittenberger and Brislee are given below:

Dittenberger (A. E. G. "pure" aluminum): Between 0 and 610° C.

$$\frac{\Delta 1}{1_0} = (23.536t + 0.007071t^2)\ 10^{-6} \qquad (1)$$

Brislee (Si = 0.25 per cent, Fe = 0.25 per cent): Between 0 and 100° C.

$$\frac{\Delta l}{l_0} = \left\{\begin{matrix} 24.5t \times 10^{-6} \text{ annealed} \\ 24.3t \times 10^{-6} \text{ hard} \end{matrix}\right\} \qquad (2)$$

Bureau of Standards investigations (28c) on aluminum containing 0.014 per cent silicon, 0.015 per cent iron, 0.019 per cent copper, and 99.952 per cent aluminum (by difference) gave values of expansion coefficients given in Table 14. The most probable second degree equation for the expansion coefficient of cast 99.95 per cent pure aluminum from room temperature to about 610° C. is

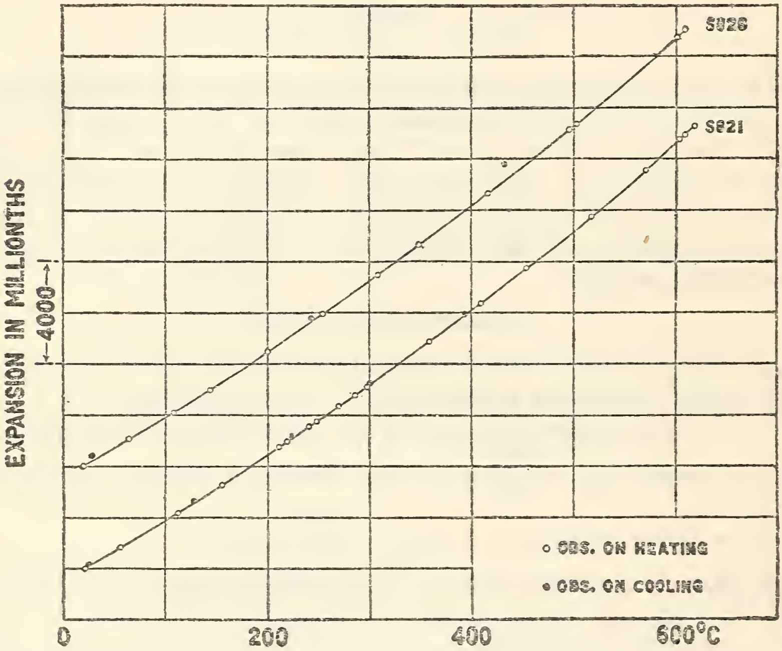

Fig. 12.—*Linear expansion of two samples of pure aluminum (99.95 per cent)*

$$L_t = L_0[(1 + (22.58t + 0.00989t^2)\ 10^{-6}] \qquad (3)$$

A length at any temperature calculated from this equation is accurate to ±0.00002 per unit length.

The average coefficients of the two samples of aluminum agree fairly well. The largest variation in the coefficients is 0.3×10^{-6}. The observations on cooling are generally slightly above the heating curves, as may be seen from Figure 12. At the end of the expansion tests, S821 was about 0.01 per cent longer than before the test and S828 was about 0.02 per cent longer.

TABLE 14.—*Average coefficients of expansion of aluminum*

Temperature range (in ° C.)	Average coefficients of expansion per degree centigrade		
	Sample S821	Sample S828	Average [1]
	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
20 to 100	23.8	23.7	23.8
100 to 200	25.6	25.5	25.5
200 to 300	27.5	27.5	27.5
300 to 400	29.4	29.6	29.5
400 to 500	31.4	31.6	31.5
500 to 600	33.3	33.6	33.5
300 to 600	31.4	31.6	31.5
20 to 200	24.8	24.7	24.7
20 to 250	25.3	25.2	25.2
20 to 300	25.8	25.7	25.7
20 to 400	26.7	26.7	26.7
20 to 500	27.7	27.7	27.7
20 to 600	28.7	28.8	28.7

[1] Coefficients given in the last column were computed from the equation.

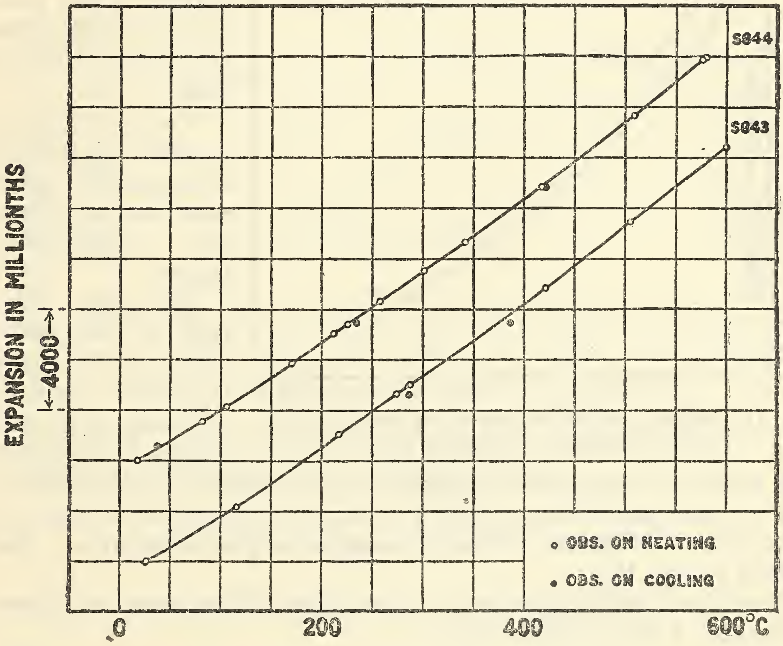

FIG. 13.—*Linear expansion of two samples of commercial aluminum (99.15 per cent)*

Expansion determinations from room temperature to about 600° C. were also made on two duplicate samples (S843 and S844) cut from commercially pure aluminum sheets, rolled to one-fourth inch. The composition of these specimens was as follows:

	Per cent
Silicon	0.32
Iron	.36
Copper	.10
Manganese	.07
Aluminum (by difference)	99.15

The Brinell hardness number was 45. The Aluminum Co. of America states that practically all of the rolled commercially pure aluminum sheet used in the United States consists of aluminum similar to S843 and S844.

The observations obtained on the two samples of commercial aluminum are shown graphically in Figure 13. Both expansion curves are regular. At the end of the test sample S844 was found to be about 0.01 per cent longer than before the test. The length of the other specimen was practically the same before and after the test.

Table 15 gives average coefficients of expansion which were computed from the expansion curves.

The mean variation in the coefficients of expansion of the two samples of commercial aluminum is 0.2×10^{-6}. For nearly all temperature ranges, the coefficients of expansion of the two samples of commercial aluminum are larger than the corresponding coefficients of the two samples of pure aluminum. (See Tables 14 and 15.)

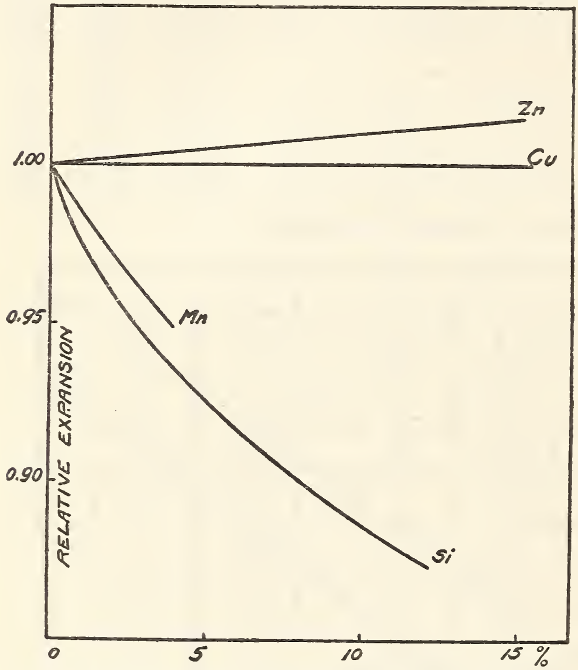

Fig. 14.—*Effect of added elements on the relative expansion of aluminum.* (*Guertler 2ii*)

The effect of alloying elements upon the thermal expansion is shown in Figure 14 after Guertler (2ii).

Table 15.—*Average coefficients of expansion of commercial aluminum*

Temperature range (in ° C.)	Average coefficients of expansion per degree centigrade	
	Sample S843	Sample S834
	$\times 10^{-6}$	$\times 10^{-6}$
20 to 100	23.9	24.0
20 to 200	26.1	25.7
20 to 250	26.6	26.4
20 to 300	26.8	26.6
20 to 400	27.3	27.0
20 to 500	28.0	27.8
20 to 600	28.7	28.6

(d) SPECIFIC HEAT

Determinations of specific heat are lacking on the refined grade of aluminum.

Accurate data on the specific heat of impure aluminum are given by Jaeger and Dieselhorst (23n). They give two values for an aluminum containing 0.48 per cent Fe, 0.3 per cent Cu (Si not determined), of a mean specific heat over a very small temperature interval, practically the true specific heat, $\frac{dq}{dt}$, as follows:

$$\frac{dq}{dt}\ (18^\circ\ \text{C.}) = 0.2143\ \frac{\text{Cal}}{\text{gram, }^\circ\text{C.}}$$

$$\frac{dq}{dt}\ (100^\circ\ \text{C.}) = 0.2228\ \frac{\text{Cal}}{\text{gram, }^\circ\text{C.}}$$

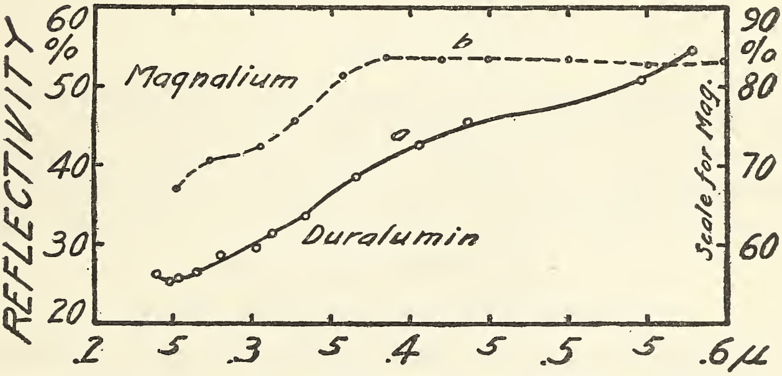

FIG. 15.—*Spectral reflection of duralumin and magnalium*

Brislee (29b) by calorimetric measurements determined the mean specific heat of 99.6 per cent aluminum to be:

$$\text{From 300 to } 20^\circ\ \text{C.: } \sigma_m = 0.2354\ \frac{\text{Cal}}{\text{gram, }^\circ\text{C.}}$$

$$\text{From 200 to } 20^\circ\ \text{C.: } \sigma_m = 0.2240\ \frac{\text{Cal}}{\text{gram, }^\circ\text{C.}}$$

From these results the equations are deduced:

$$\frac{dq}{dt}\ (\text{from 18 to } 100^\circ\ \text{C.}) = 0.2124 + 0.000104t\ \text{(Jaeger and Dieselhorst)}$$

$$\frac{dq}{dt}\ (\text{from 0 to } 300^\circ\ \text{C.}) = 0.2012 + 0.000228t\ \text{(Brislee)}$$

Jaeger and Dieselhorst's values are probably more accurately determined at least at temperatures of from 0 to 100° C. than Brislee's, although Brislee used a purer aluminum.

Laschtschenko's results on the mean specific heat of aluminum between higher and ordinary temperatures indicate that the total heat per gram of aluminum from 0 to 658° C., the melting point, is 187 calories. Recently, Umino (26a) has given the mean specific heat of aluminum of 99.116 per cent purity between 100 and 1,000° C. The results agree fairly well with those of Laschtshenko (29c).

Figures cited by Genders (11d) from Griffiths and Kaye and Laby for material whose purity is not stated are recalculated to calories per gram-degree 0.21 at 0° C., 0.22 at 15° C., and 0.28 at 600° C.

3. OPTICAL

The absorption index and the refractive index for aluminum (no further description given) have been given by Drude (30d).

$$N \text{ (for } \lambda = 0.589) = 1.44$$

$$K \text{ (for } \lambda = 0.589) = 5.32$$

The reflecting power of this metal is given by Drude (30d) as 83 per cent for λ = 0.583, and by Coblentz (30b) as 68.5 per cent for λ = 0.60.

Coblentz (30c) has studied the ultra-violet reflecting power of duralumin (94.19 Al, 4.2 Cu, 0.37 Fe, 0.51 Mn, 0.54 Mg. 0.19 Si) and magnalium (Al 69, Mg 31). The results are shown in Figure 15.

4. MECHANICAL PROPERTIES

(a) PROPERTIES OF SINGLE CRYSTALS OF ALUMINUM

Carpenter and Elam in 1921 (31g) first described a systematic method of producing large single crystals of aluminum (99.6 per cent Al). The method of production was based on the well-known fact that under certain conditions of strain followed by heating exceptional grain growth occurred. They found that by properly adjusting the critical relations that exist between a preliminary annealing, straining, and subsequent time and temperature of heating, the entire reduced portion of test specimens of flat sheet or round bar could be transformed into a single crystal. Single crystal test pieces 9 inches long by 0.564-inch diameter were obtained. It was not found possible to produce single crystals in square bars because owing to their shape they do not strain uniformly.

Details of the method of production are given briefly by Carpenter (31a) in the May lecture, 1926, before the Institute of Metals from which much of the following discussion is taken:

> The test pieces must, in the first place, be accurately machined along the parallel portion. In order to convert this into a single crystal three treatments are necessary—the first thermal, the second mechanical, the third thermal. The first treatment is necessary to soften the metal completely and produce new equiaxed crystals of as far as possible uniform size, the average diameter being

1/150 inch. The second consists in straining these crystals to the required amounts, and the third in heating the strained crystals to the requisite temperature, so that the potentiality of growth conferred by strain could be brought fully into operation. The most suitable temperature of the first heating was found to be 500° C. and the time six hours. The precise degree of strain for the aluminum used was an elongation of 1.6 per cent on 3 inches produced by a stress of 2.4 tons/in.^{2} (5,380 lbs./in.^{2}). The final heat treatment was begun at 450° C. and the temperature raised at about 25° C. per day up to 550° C. It was then brought finally up to 600° C. for one hour, in order to complete the absorption of small crystals on the surface, which persistently remained at lower temperatures. On an average, one test piece in four is converted into a single crystal in this way.

The growth of a large crystal in this way appears the more remarkable when one considers that in some cases the volume of the single crystal produced exceeded 2 cubic inches which previous to treatment contained approximately 7,000,000 crystals.

Single crystals may also be formed under similar conditions when the specimen is subjected to compressive instead of tensile strain.

The tensile properties of these single crystals are very different from the properties as determined on the crystalline aggregate. The tensile strength and elongation value instead of being comparatively uniform and consistent vary from specimen to specimen over a considerable range which has been shown to be due to differences in the orientation of the crystal in the test piece. These variations in tensile properties are accompanied by a marked difference in the method of stretching and the types of fractures produced. Instead of giving the ordinary cup and cone fracture a cylindrical single crystal specimen becomes narrower over the length of the reduced section on one diameter only while the other diameter remains practically constant. As the maximum extension is approached a characteristic lens-shaped figure is formed and as the bar is pulled apart this becomes a smaller fracture eventually taking place first at each side and finally in the middle. The final result is that the fractured surface of each half of the test piece is a very acute ellipse or wedge, the metal being grooved in each case. Characteristic flow lines also appear on the test specimens corresponding to the stretching of the metal.

The tensile strength of cylindrical specimens of single crystals varies between 6,700 and 9,000 lbs./in.^{2}, and the elongation from 57 to 85 per cent, depending upon the orientation of the crystal relative to the direction of stress.

The great ductility and malleability of a single crystal is very remarkable. It can be cold-rolled into a strip or drawn cold into wire, and although hardened apparently retains its malleability.

Detailed studies have been made by Taylor and Elam (31d, f) of the distortion under tensile stress of a single crystal bar machined from cylindrical specimens. Under tensile stress the bar is pulled out and assumes a final shape of a parallelopiped with two broad and two narrow sides. The surfaces of the bar remain smooth and the corners sharp in spite of an elongation of over 75 per cent. The investigators showed that of the 12 crystallographically similar modes of shearing, the one for which the component of shear stress in the direction of shear was greatest was the one which actually occurred. During the first part of the deformation slip generally occurred on one crystal plane, but during the latter part slip always occurs on two planes. Fracture can not occur by slipping on a single crystal plane. Single crystals of aluminum have no primitive elastic limit (31b).

Brinell hardness tests of single crystals indicate very clearly the directional properties. The impression is never circular, although a spherical ball is used, but is always square with slightly rounded corners. According to O'Neill (31e), the rhombic dodecahedral (011) face has the greatest hardness, the Brinell hardness being 23.3. The octahedral face (111) is softer, being 21.3, and is apparently slightly harder than the cube face (001), which is 20.6.

Tests of single crystals in compression (31c) indicate that the distortion is similar to distortion under tensile stress.

Gough, Hanson, and Wright (31b, h, i, j) have investigated the endurance properties of single crystals of aluminum under reversed direct stresses and reversed torsional stresses as well as single-blow tensile impact tests and slow cycles of repeated tensile loading.

The following general conclusions have been drawn by them:

Single crystals of aluminum possess no primitive state of elasticity; plastic strain occurring under the lowest stresses applied. In all cases the plastic strain consists of shear in the direction of a principal line of atoms on one or more of the octahedral planes of the crystal. Slip bands appear on the polished surfaces of the crystal which are traces of these planes. The effect of slip on any plane is, at first, to increase its resistance to further slip. At the same time a similar hardening effect is produced on other planes parallel to the original slip planes and intersecting the original slip planes; apparently the resistance to slip is increased to a greater degree on the former than on the latter planes.

Studies of the properties of single crystals of aluminum (and other metals) have opened up a vast and new field of research. Formerly, all theories of the properties of metals were necessarily based on the results of tests on crystalline aggregates, an essentially complex structure in which the individual properties of the two chief "components," the crystal grain and the boundary material were not known. The obtaining of single crystals has made possible the study of these component parts. The results obtained so far have shown that many theories must be entirely rejected or considerably revised.

There is not space here to discuss even briefly the numerous new theories that have been advanced as a result of these investigations. The reader is necessarily referred to the references given in the bibliography (p. 353).

(b) METHODS FOR TESTING SHEET METAL

Aluminum, duralumin, and various other alloys of aluminum are largely used as sheet. The testing of thin sheet metal to determine the mechanical properties presents some difficulties. These are chiefly due to tearing action and to the effect of the concentration of stresses at the ends of the reduced portion of a tensile specimen. Considerable attention has been paid during the last few years to the testing of thin sheet metal and much progress has been made in developing satisfactory methods.

The following precautions should be taken in testing any thin sheet metal:

(*a*) To obtain elongation values which are free from the effect of the ends the reduced portion should be at least 4 inches for the gauge length of 2 inches.

(*b*) The width of the reduced portion should be ½ inch for thin sheet.

(*c*) The radius of the fillets should be sufficiently large (at least ¾ inch) to avoid high concentration of stresses and the possibility of failure of the specimen at the fillets.

(*d*) The high concentration of stresses may be further reduced by using a width of ends that is 13 per cent greater than the width of the reduced portion.

(*e*) A taper of 0.003 to 0.005 inch in width from the fillets to the middle of the reduced section is desirable to assist in obtaining fractures in the middle third of the gauge length.

(*f*) The gripped length of the specimen should be at least 2½ inches at each end.

(*g*) When the specimen is sheared from the sheet its width should be sufficient to permit the removal of sufficient material from each edge to eliminate the effects of the shearing from the reduced section.

(*h*) By using self-aligning grips, the effect of eccentric loading is reduced.

As aluminum and its alloys are more ductile than some other metals, tensile specimens which differ considerably from the specimens recommended here may be used and satisfactory results obtained. However, the results obtained from different specimens may not be identical.

In many cases, there is a commercial advantage in using the tensile specimen recommended by the American Society for Testing Materials (32b) which has a reduced portion 2¼ inches long, fillets

½ inch radius, and ends which are 2⅜ inches long having a width which does not exceed the width of the reduced portion by more than 50 per cent.

This subject is very fully discussed in references (32b, c, d, e).

In Table 32 are collected the properties of sheet aluminum as given in specifications from several sources.

(c) ELASTICITY

The best value for E, the (Young's) modulus of elasticity is given, by private correspondence with the Aluminum Co. of America, for commercial aluminum bars and wire as: $E = 10{,}000{,}000$ lbs./in.^{2} at 17° C. The value for bars is given by Brislee (33f), $E = 9{,}840{,}000$ lbs./in.^{2}; for wire, $E = 9{,}790{,}000$ lbs./in.^{2} Koch and Dannecker (34d) give the modulus of torsion at 20° C. as 3,870,000 lbs./in.^{2} For values at higher temperatures, see page 71.

Poisson's ratio (μ) is given by the Aluminum Co. of America as 0.31 to 0.32 and by Schaefer as 0.359. Katzenelsohn finds that μ increases 15.7 per cent between 0 and 100° C.

(d) TENSILE PROPERTIES

The tensile properties of electrolytically refined aluminum are compared below with the average properties of the commercial grade, both as given by Edwards for wrought, annealed material tested in standard 0.505-inch diameter, 2-inch gauge length specimens, as well as with the average for commercial material.

Purity	Tensile strength		Elongation in 2 inches	Reduction of area	Brinell 50 kg ⅛-inch ball
	Lbs./in.^{2}	*kg/cm*^{2}	*Per cent*	*Per cent*	
99.97	8,465	595	60	95	15–16
99.4	13,000	912	45	80	22
Commercial	14,000	983	40	75	24

The "yield point" of commercial aluminum is usually taken as 3,000 to 6,000 lbs./in.^{2} or 550 to 630 kg/cm^2 but the material has no true yield point. The yield-point figures correspond to the stress for extension under load of one-half of 1 per cent. The proportional limit is very low.

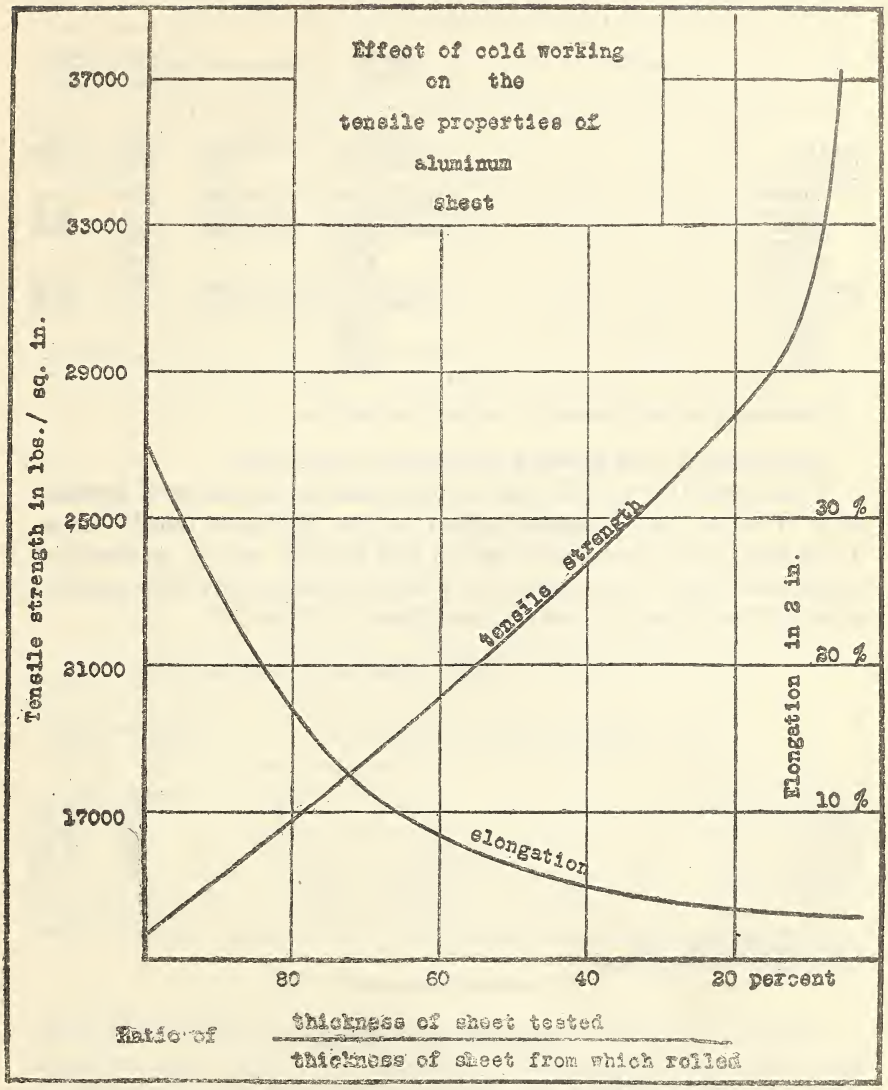

FIG. 16.—*The effect of cold-working on the tensile properties of aluminum sheet; taken from the data of the Aluminum Co. of America*

The abscissas represent the ratio of the thickness of the sheet tested to that of the original annealed sheet from which it was rolled. The curves represent the average of 15 tests of sheet rolled from 12, 14, and 16 gauge annealed sheet. The portion of the curve beyond a ratio of 30 per cent—that is, between 30 per cent and 0—is drawn from results of tests of 22, 24, and 26 gauge sheet drawn without annealing from ¼ to ⅜ inch hot-rolled sheet.

Table 16 will give an idea of the tensile properties of this metal in other forms.

TABLE 16.—*Tensile properties of commercial aluminum* [1]

Form	Tensile strength	"Yield point"	Elongation in 2 inches	Reduction of area
	Lbs./in.^{2}	*Lbs./in.*^{2}	*Per cent*	*Per cent*
Sand cast	11,000-13,000	4,000-6,000	15-30	30-50
Chill cast	12,000-14,000	9,000	15-25	
Sheet:				
Annealed	12,000-15,000	3,000-6,000	12-35	20-40
Half-hard	18,000-22,000	9,000-12,000	5-12	20-40
Hard	22,000-35,000	12,000-25,000	1-7	20-40
12-gauge	25,000		15-20	
16-gauge	28,000		15-20	
20-gauge	30,000		15-20	
Bars (hard)	18,000-26,000	14,000-23,000	5-15	30-40
Wire (hard)	25,000-55,000	16,000-33,000		40-50
40-mil	31,000			
80-mil	28,000			
120-mil	25,000			
200-mil	22,000			

[1] These figures are by the Aluminium Co. of America (2g) and others.

The effect of cold working is shown in Figure 16.

Wilson and Gavey (23m) have found that the duration of application of stress has a marked effect on the ultimate tensile stress. Hard-drawn aluminum wires which had been in service as electrical conductors for a few months and had become somewhat corroded showed the ultimate tensile stress given in Table 17.

TABLE 17.—*Effect of duration of stress upon aluminum wire*

Time of application of ultimate breaking load	Breaking load	Tensile strength [1]
	Pounds	*Lbs./in.*^{2}
Ordinary tensile test	325	25,300
One-half hour	300	23,300
5 hours	280	21,800
118 hours	240	18,700
525 hours	220	17,100
1,900 hours [2]		

[1] Wire weighed 75 pounds per mile and was apparently No. 10 British wire gauge. The values in column 3 are calculated on this basis.

[2] Not broken but still stretching.

(e) COMPRESSION

Aluminum will show a strength in compression equal to or greater than that which it possesses in tension. The high values obtained in test are misleading and are due to the fact that aluminum flows under pressure, and at the time fracture occurs in the standard compression test specimen, the actual area is very much greater than the original area which is used in calculating results. The elastic limit in compression is normally the same as that in tension.

(f) HARDNESS, COMPRESSIBILITY

For hardness of the pure metal see page 64. The scleroscope hardness (magnifying hammer) of annealed or of cast commercial aluminum varies from 4 to 6. The hardness of cold-rolled sheets is increased to from 13 to 15; the Brinell values varying from 22 to 55 according to the temper of the sheet; the Brinell hardness (500 kg, 10 mm ball, 30 seconds) of cast aluminum varied from 23 to 28. Bohner (33j) has discussed the relation between hardness and tensile strength.

Bridgman (33c) gives values of compressibility of drawn annealed rod of electrolytically refined aluminum at 30° C., as $\frac{\Delta V}{Vo} = -10^{-7}(13.34 - 3.5 \times 10^{-5}p)p$ and at 75° C., as $\frac{\Delta V}{Vo} = -10^{-7}(13.91 - 3.5 \times 10^{-5}p)p$, and for cast aluminum at 30° C., $\frac{\Delta V}{Vo} = -10^{-7}(13.43 - 5.0 \times 10^{-5}p)p$ and at 75° C., $\frac{\Delta V}{Vo} = -10^{-7}(13.76 - 5.1 \times 10^{-5}p)p$ when V = vol. at 30° C., and atmospheric pressure. Previous measurements on material of commercial purity gave lower values.

(g) DUCTILITY (ERICHSEN TEST)

The ductility of soft annealed aluminum sheets, such as are used for stamping and drawing, is well indicated by the Erichsen test. Average Erichsen values (32a, 42g) are given below for different gauges of commercial aluminum sheets:

TABLE 18.—*Erichsen value for commercial aluminum sheet*

B. & S. gauge	Thickness in inches	Erichsen value	B. & S. gauge	Thickness in inches	Erichsen value
28	0.0126	5.5–7.5	18	0.0403	8.0– 9.5
26	.0159	7.0–8.0	16	.0508	9.0–10.5
24	.0201	7.0–8.0	14	.0640	10.0–11.5
22	.0253	7.0–8.5	12	.0808	10.5–12.0
20	.0319	7.5–9.0	10	.1018	11.0–12.5

Curves showing the behavior of aluminum in slow-bending tests are given by Dix (45f).

(h) ENDURANCE LIMIT

Moore (46h) has determined the endurance limit of 99.24 per cent aluminum in ¾-inch diameter rolled bar, cold worked to a tensile strength of 22,600 lbs./in.^{2}, 16 per cent elongation in 8 inches, 45 Brinell hardness number (500 kg), 23 Rockwell hardness number (⅛-inch ball), as ±10,500 lbs./in.^{2} (stress range 21,000 lbs./in.^{2}) by rotating beam tests.

Most endurance test data in respect to aluminum are upon the alloys rather than on the metal itself. (See page 273.)

(i) DENSITY

The density of electrolytically refined aluminum (99.97 per cent) at 20° C. referred to water at 4° C. is 2.698 g/cm³ for annealed material. Hard-drawn wire of this purity showed identical results. With less pure material there is an appreciable decrease in density on cold working. Annealed metal having a density of 2.702 will have a density of about 2.700 when in the hard-drawn or fully cold-worked condition.

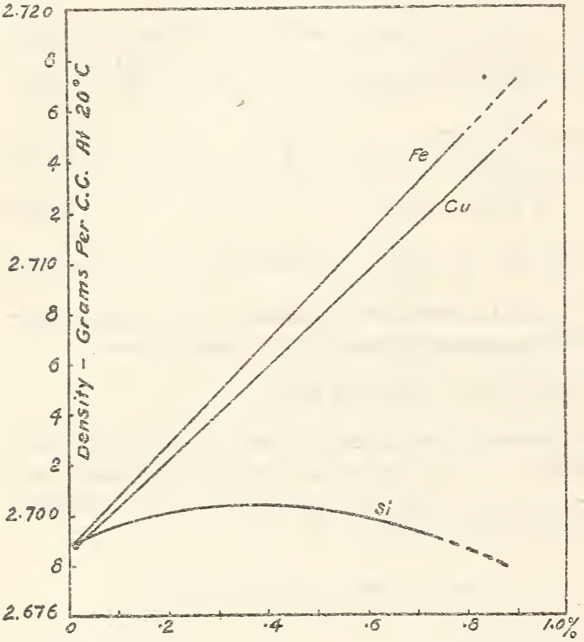

FIG. 17.—*Effect of iron, copper, and silicon upon the density of aluminum, cold-rolled ⅜ inch diameter rod.* (*Edwards, 33b*)

Seven samples of hard-drawn wire of from 99.52 to 99.60 per cent aluminum tested at this bureau averaged 2.6991 in density, ranging from 2.6983 to 2.6996 (23k). Brislee (33e, g) has shown that the density of aluminum depends upon the heat treatment and amount of mechanical working it has received. He found that the mean increase of seven samples of density of cold-worked metal upon annealing was 0.0017, or 0.063 per cent.

Edwards and Moorman (33d) give the following for 99.75 per cent and 99.5 per cent aluminum:

TABLE 19.—*Effect of physical treatment upon density of Al*

Purity of sample	Condition and treatment of sample	Density (20° C.)
		g/cm³
99. 75	Sample sawed from pig	2. 6827
	Do	2. 6861
	Same, cold rolled from ⅞ to ⅛ inch	2. 7031
	Preceding sample, annealed 15 minutes at 450° C	2. 7030
	Same, annealed 2 hours longer	2. 7030
99. 5	Hard-drawn aluminum wire, 10-gauge	2. 7029
	Same, after annealing	2. 7063
	Hard-drawn aluminum wire, 6-gauge	2. 7019
	Same, after annealing	2. 7048

The low density for cast metal (sawed from pig) is probably due to voids or blowholes. Archbutt (94b) gives values for cast metal of 99.5 per cent purity varying from 2.64 to 2.70, depending on whether solidification has taken place in such a way as to retain or release dissolved gas, so that the casting contains, or is free from, pinholes.

The effect of impurities upon density is shown in Figure 17 after Edwards.

The density in the liquid state is given by Edwards and Moorman as follows:

TABLE 20.—*Density of aluminum from 20 to 1,000° C.*

Temperature	Condition	99.75 per cent Al	99.4 per cent Al	98.25 per cent Al
20	Solid	2.703	2.706	2.727
100	do	(2.69)		
200	do	(2.67)		
400	do	(2.62)		
658.7	do	(2.55)		
658.7	Liquid	2.382	2.384	2.405
700	do	2.371	2.373	2.394
800	do	2.343	2.345	2.366
900	do	2.316	2.318	2.339
1,000	do	2.289	2.291	2.311
1,100	do	2.262	2.264	2.285

Values in parentheses are calculated from expansion formulas. Density of liquid Al (99.75 per cent) expressed by $D_t = 2.382 - 0.000272 (t—658°)$ where D_t is the density at the specified temperature, t.

Other studies of the density of liquid Al have been made by Pascal and Jouniaux (33h) and by Richards (33i).

The shrinkage of aluminum is given by Edwards and Moorman as:

Shrinkage of aluminum ° C.	Total of solidification and liquid shrinkage from t° C. to solid at 658° C. Percentage of original volume
658	6.6
700	7.2
800	8.2

Edwards and Moorman give the total change of volume, due to thermal expansion in the liquid state and to change of volume on solidification—that is, from liquid metal at the temperature given to solid metal at the melting point, as 8.2 per cent from 800° C. and 7.2 per cent from 700° C., while the change of volume from liquid metal to solid metal, both at the melting point, is 6.6 per cent.

(j) WEAR OF ALUMINUM AND MAGNESIUM

Aluminum, magnesium, and their light alloys are seldom used industrially where resistance to wear is an important requirement and are not usually considered to have good "bearing properties." Some instances of commercial use for purposes involving resistance to wear, as in certain gears, have been successful, but it would be difficult to predict, from present knowledge, under just what conditions such use will or will not be successful.

Experiments can be cited on the wear of these metals, but care must be used in the interpretation of data, as it is not yet possible to translate with certainty the results obtained under one set of conditions into others.

The results of abrasive wear tests carried out by Brinell (95c) and by Robin (95d) are summarized in Table 21. Brinell's tests showed that aluminum with a somewhat lower Brinell hardness had a much higher wear resistance than magnesium. In Robin's wear tests aluminum and certain aluminum-nickel alloys, as shown in Table 21, were compared to a bronze coinage alloy. In general, the weight losses in unit time were greater for the aluminum and its alloys than for the bronze.

TABLE 21.—*Experiments relating to the wear of aluminum. magnesium, and their alloys*

[For details of tests refer to references given in text]

Investigators	Metal	Brinell hardness No. (500 kg load)	Wear resistance [1]	Wear (weight loss)
Brinell	Al	33	694	
	Mg	36	220	
	90 Mg, 10 Zn	55	199	
	96 Al, 2 Mg, 2 Cu	80	632	
				mg in 1 minute [2]:
Robin	Al	22		115.
	98 Al, 2 Ni	33		110.
	97 Al, 3 Ni	47		100.
	Bronze coinage	74		85.
				mg in 2½ minutes [2]:
	95 Al, 3 Ni, 2 Cr	53		36.
	96 Al, 4 Ni	47		41.
	Bronze coinage	78		35.
				mg in 3 minutes [2]:
	Al			160.
	Bronze coinage			140.
				gm per h. p. when friction coefficient=0.3:
Honda and Yamada	Cu			0.67.
	Cd			1.10.
	Mg			1.27.
	Pb			1.27.
	Sn			1.33.
	Sb			2.93.
	Zn			3.40.
	Bi			14.73.

[1] Reciprocal of the volume of metal removed by 1 mm disk×1,000.
[2] Different abrasives or contact pressures used. These three sets of tests not directly comparable.

Honda and Yamada (95b) determined the weight loss per unit of frictional work when magnesium and other metals were rubbed in contact with cast iron. The weight loss in grams per horsepower, when the coefficient of friction was kept constant at 0.3, is shown for a number of metals in Table 21. The value for magnesium is the same as that for lead and almost twice as high as copper.

French and Herschman made tests with hardened-steel plug gauges operating in hardened steel, cast iron, and a heat-treated and aged aluminum piston alloy containing about 10 per cent copper, 1¼ per cent iron, and one-fourth of 1 per cent magnesium. They used a testing machine designed for the study of the wear of plug gauges (95a), but found that under otherwise comparable conditions the weight losses for the heat-treated aluminum piston alloy were roughly five to ten times that of hardened high-carbon steel and ten to twenty times that of their grey cast iron.[5]

V. PHYSICAL PROPERTIES OF ALUMINUM AND ITS ALLOYS AT HIGHER AND LOWER TEMPERATURES

Koch and Dannecker (34d) give the following values for the modulus (F) of torsion ($E=$(approximately) 2.72 F) at higher temperatures (E is the modulus of elasticity in tension):

Table 22.—*Modulus of torsion of aluminum at elevated temperatures*

Temperature in degrees centigrade	Modulus of torsion in pounds per square inch
20	3,870,000
100	3,730,000
200	3,450,000
300	3,100,000
400	2,630,000
450	2,030,000
500	680,000

As temperature increases above room temperature the tensile strength and hardness of aluminum decrease rapidly, the elongation and reduction of area increasing. The effect of temperature on the properties of aluminum and a few of its alloys is considered below.

Niccolai (34g, 231) has determined the specific electrical resistivity of aluminum at temperatures from −189 to 400° C. His values are given in Table 23 and plotted in Figure 18. Lees (27b) also gives similar values for the electrical resistivity at lower temperatures. Northrup (34e) gives a curve for resistivity of solid and molten aluminum up to 1,100° C.

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[5] Taken from data in a forthcoming report by French and Herschman, Bureau of Standards.

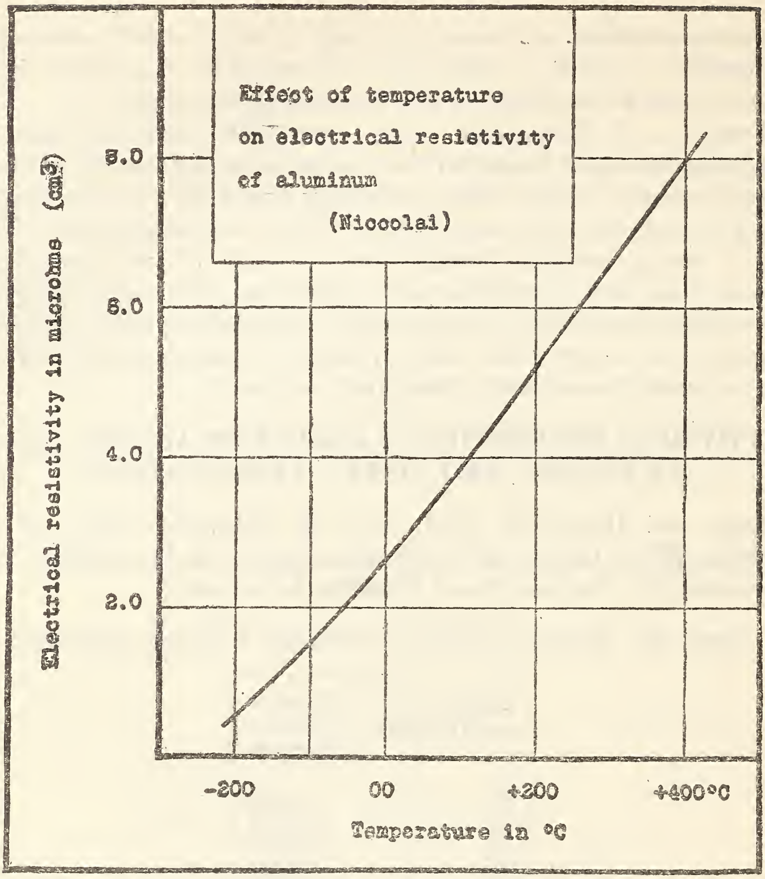

FIG. 18.—*Effect of temperature on electrical resistivity of aluminum. (Niccolai, 34g)*

TABLE 23.—*Effect of temperature on the electrical resistivity of "Kahlbaum" aluminum* [1] *(Niccolai, 34g)*

Temperature in degrees centigrade	Electrical resistivity in microhms per cubic centimeter	Temperature in degrees centigrade	Electrical resistivity in microhms per cubic centimeter
−189	0.641	+125	4.192
−175	.795	+150	4.496
−150	1.038	+175	4.827
−125	1.282	+200	5.172
−100	1.535	+225	5.518
−75	1.782	+250	5.850
−50	2.067	+275	6.204
−25	2.321	+300	6.559
±0	2.618	+325	6.917
+25	2.925	+350	7.274
+50	3.237	+375	7.633
+75	3.562	+400	7.991
+100	3.858		

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[1] Purity not given.

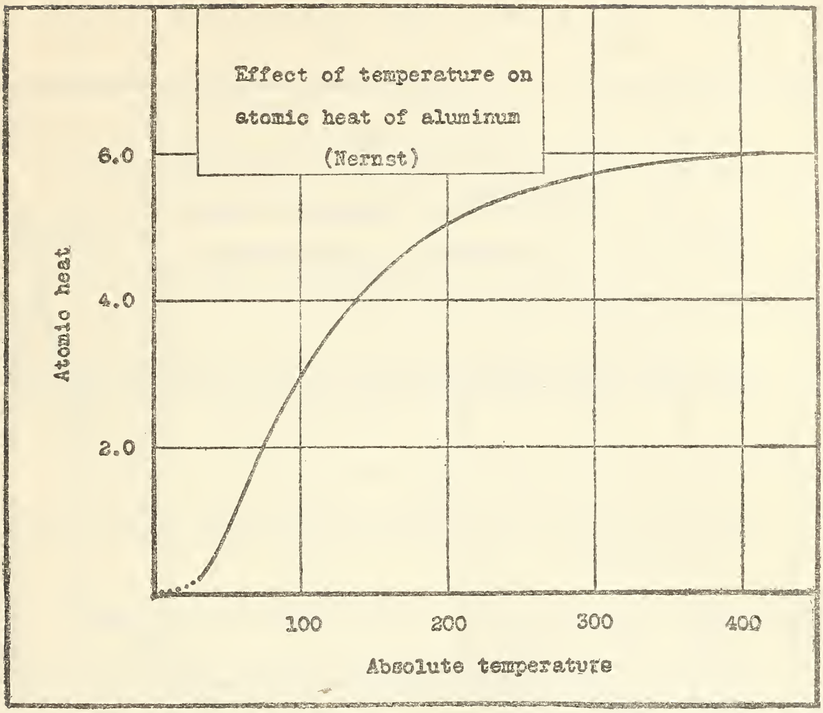

FIG. 19.—*Effect of temperature on the atomic heat of aluminum.* (*Nernst, 29d*)

Lees (27b) gives the following values for the thermal conductivity of 99.0 per cent aluminum:

TABLE 24.—*Thermal conductivity at low temperatures*

Temperature in degrees centigrade	Thermal conductivity in calories per second per cubic centimeter per 1 ° C.	Temperature in degrees centigrade	Thermal conductivity in calories per second per cubic centimeter per 1 ° C.
−170	(0.524)	−75	(0.493)
−160	.514	−50	.496
−150	.508	−25	.499
−125	.491	0	.502
−100	.492	+18	.504

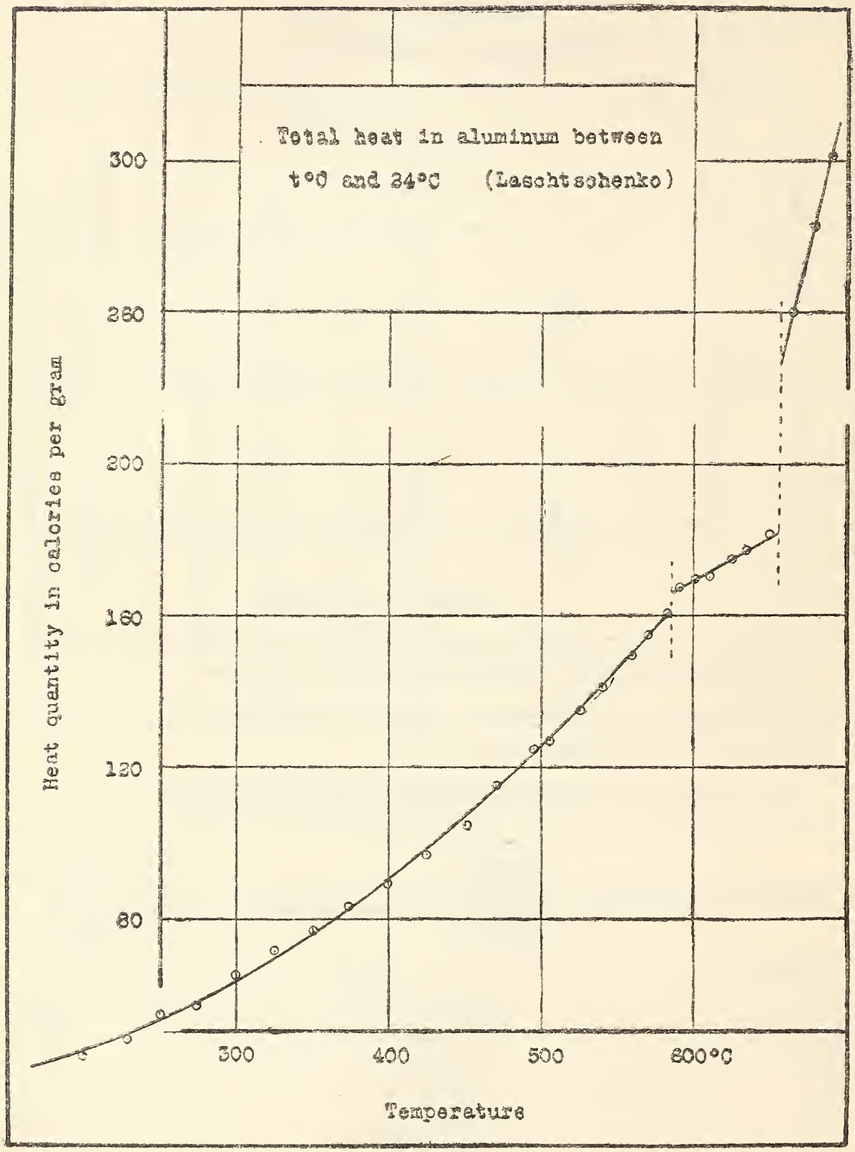

FIG. 20.—*Total heat of aluminum at higher temperatures. (Laschtschenko, 29c)*

The effect of low temperatures upon the atomic heat of aluminum is shown in Figure 19 from data by Nernst (29d). Guillet and Cournot (34c) give the values for Brinell hardness of commercial aluminum at −20° C., −80 °C., and liquid air temperature as 25, 24, and 53, respectively, the resistance to shock at the same temperatures showing no appreciable drop down to liquid air temperatures.

Total heat of aluminum at higher temperatures has been measured by Laschtschenko (29c) from *t*° to 24° C. His results are plotted in Figure 20.

The specific heats of aluminum at 100, 200, 300, 400, 500, and 600° C. have been determined by Eastman, Williams, and Young (29a) as 6.16, 6.42, 6.68, 6.95, 7.21, and 7.47 calories per ° C., the results being estimated as accurate to within 1 per cent.

Tables 25, 26, and 27 give high-temperature tests by several investigators. (See also fig. 21.)

TABLE 25.—*Tensile tests of hard-drawn aluminum tubes (Breuil, 42i)*

EFFECT OF ANNEALING [1] TESTS AT ROOM TEMPERATURE

Temperature of anneal in degrees centigrade	Tensile properties			
	Tensile strength	Yield point	Elongation in 2.7 centimeters	Reduction of area
	Lbs./in.^{2}	*Lbs./in.*^{2}	*Per cent*	*Per cent*
Hard	31, 600	30, 900	4. 0	18
100	35, 800	31, 600	6. 6	15
200	31, 600	18, 100	5. 6	31
300	21, 600	15, 000	22. 2	42

TESTS AT ELEVATED TEMPERATURES. EFFECT OF TEMPERATURE ON PROPERTIES [2]

Temperature of test, ° C.				
20	31, 600	30, 900	4. 0	18
100	29, 900	29, 900	9. 6	24
200	20, 800	15, 800	22. 2	41
300	10, 100	10, 100	31. 4	35

---

[1] Tubes were annealed in oil (time not given) and tested at room temperature.
[2] Tests made at temperature indicated.

Tensile properties of 99.57 aluminum (with 0.21 per cent Fe, 0.22 per cent Si) and of quite impure (98.87) aluminum have more recently been studied by Martin (34b) and the results obtained on the 99.57 aluminum are shown in Figures 22 to 24. In the figure, by "slow" is meant a rate of loading 0.36 inch/min. and by "fast" 1.07 inch/min. Ingalls (34a) does not obtain as smooth a curve as Martin.

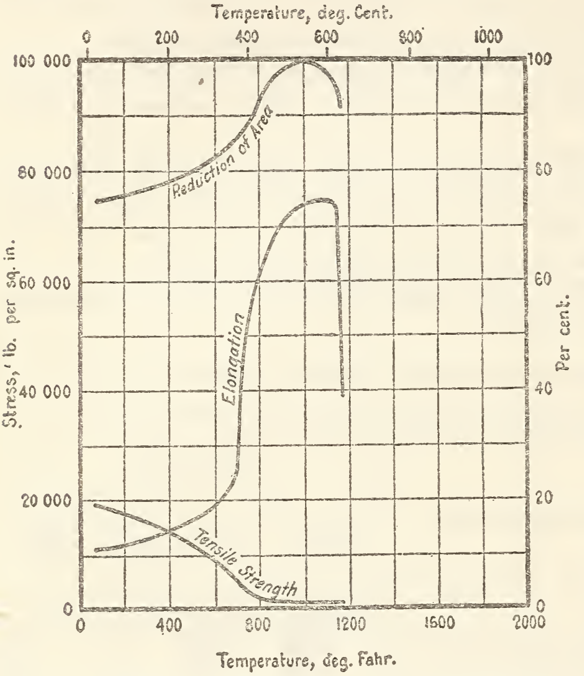

FIG. 21.—*Effect of temperature on tensile properties of aluminum, according to Bengough*

The hardness of aluminum, 12 per cent copper-aluminum, 12 per cent zinc and 3 per cent copper, 4 per cent copper, duralumin, and of aluminum with varying percentages of copper at elevated temperatures are given by Grard (2e) and are shown in Figures 25 to 30. Tensile properties, Brinell hardness and mass strength of various piston alloys at elevated temperatures as given by Aitchison (10d) are shown in Table 28.

TABLE 26.—*Tensile tests of aluminum bars at higher temperatures*[1] (*Baumann, 34i*)

ANNEALED

Temperature in degrees centigrade	Tensile properties		
	Tensile strength	Elongation in 5 centimeters (1.97 inches)	Reduction of area
	Lbs./in.^{2}	*Per cent*	*Per cent*
20	14, 000	43. 3	64. 5
60	12, 600	49. 9	71. 9
100	9, 960	66. 8	76. 6
200	5, 890	78. 1	87. 2
300	3, 360	79. 8	92. 8
NOT ANNEALED			
20	19, 900	16. 3	43. 7
100	13, 700	35. 8	66. 0
200	9, 230	44. 7	76. 9
300	4, 270	59. 9	83. 7

---

[1] These tests were made on 99 per cent aluminum bars 17, 12, 8, and 4 mm thick. The values given are averages of the results for the bars of the four thicknesses.

TABLE 27.—*Effect of temperature on the tensile properties of aluminum* [1] (*Bengough, 34h*)

Temperature of test in degrees centigrade	Tensile properties		
	Tensile strength	Elongation in 2 inches	Reduction of area
	Lbs./in.^{2}	*Per cent*	*Per cent*
20	19, 200	11	75
20	19, 200	12	75
200	14, 100	15	78
275	11, 100	17. 2	79
330	7, 600	20. 3	88
375	3, 800	25	88
396	2, 150	56	90
450		65	96
520	900	68. 5	(2)
565	540	70. 3	(2)
610	660	75	(2)
625	420	39	92

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[1] The metal tested contained 99.56 per cent aluminum.

[2] Reduction of area to finest possible point.

TABLE 28.—*Properties of piston alloys at high temperatures* (*10d*)

Tensile properties	Condition	Maximum stress at 250° C.	Maximum stress at 350° C.		
		Lbs./in.^{2}	*Lbs./in.*^{2}		
Al plus 12 per cent Cu	Chill-cast	15, 400	10, 500		
Y alloy	do	25, 300	11, 400		
Al plus 14 per cent Cu, 1 per cent Mn	do	22, 400	14, 100		
Al plus 8 per cent Cu	do	15, 700	7, 400		
Al plus 13 per cent Zn, 3 per cent Cu	do	9, 400	3, 300		
		Brinell hardness No. at —			
BRINELL HARDNESS		15° C.	200° C.	300° C.	400° C.
Al plus 12 per cent Cu	Sand-cast	67	58	33	14
	Chill-cast	82	63	35	13
Al plus 8 per cent Cu	Sand-cast	55	43	25	11
	Chill-cast	60	46	28	12
Al plus 13 per cent Zn, 3 per cent Cu	Sand-cast	79	36	15	
	Chill-cast	62	35	16	
Y alloy	Sand-cast	71	61	46	17
	Chill-cast	76	68	53	
		Maximum stress/specific gravity			
MASS STRENGTH		250° C.	350° C.		
Al plus 12 per cent Cu	Chill-cast	5, 100	3, 400		
Al plus 14 per cent Cu, 1 per cent Mn	do	7, 400	4, 700		
Al plus 8 per cent Cu	do	5, 400	2, 700		
Al plus 13 per cent Zn, 3 per cent Cu	do	3, 100	1, 100		
Y alloy	do	13, 900	4, 000		
Cast-iron A	Sand-cast	3, 800	3, 800		
Cast-iron B	do	3, 400	3, 100		

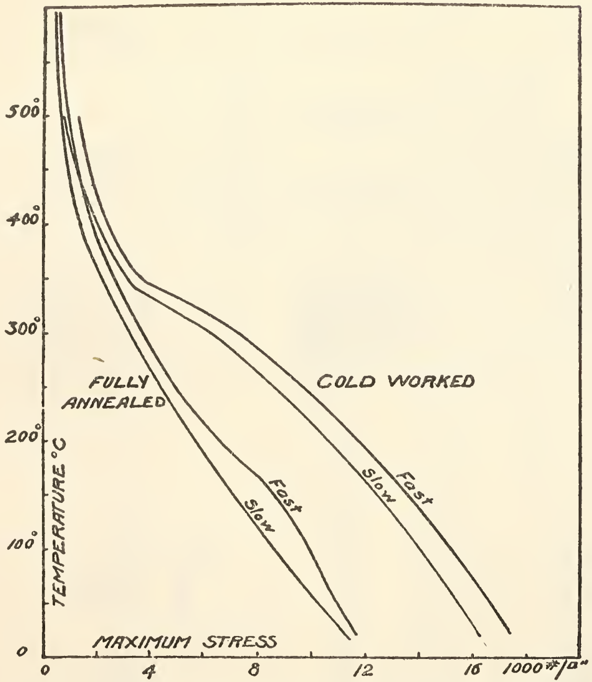

FIG. 22.—*Tensile strength of cold-worked and annealed aluminum (99.57 per cent) at elevated temperatures for two rates of loading.* (*Martin, 34b*)

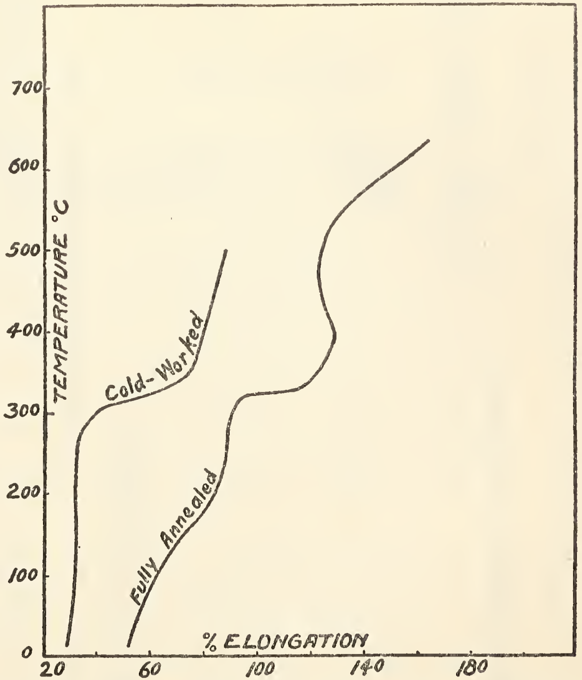

FIG. 23.—*Elongation at increasing temperatures of 99.57 per cent aluminum, cold-worked and fully annealed.* (*Martin, 34b*)

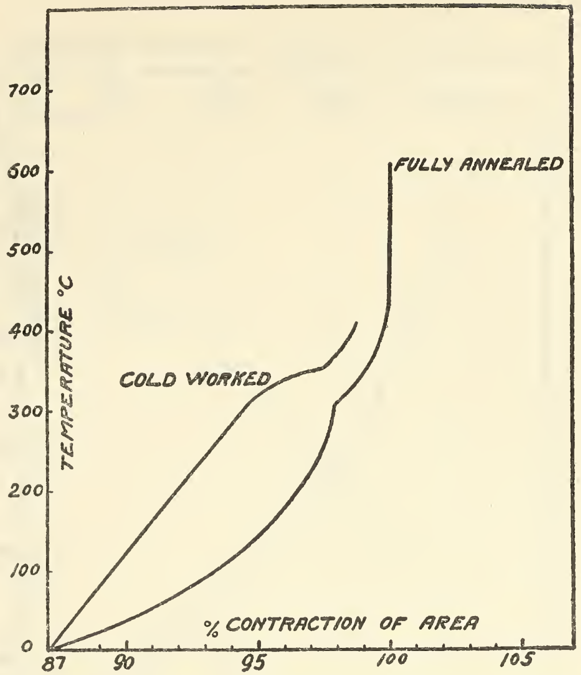

Fig. 24.—*Contraction of area at increasing temperatures of 99.57 per cent aluminum, cold-worked and fully annealed. (Martin, 34b)*

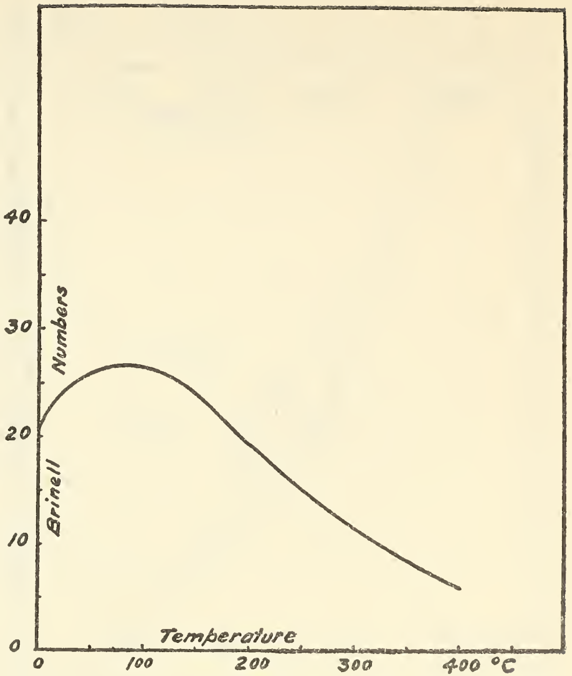

Fig. 25.—*Hardness of aluminum at high temperatures under 500 kg load. (Grard, 2e)*

Fig. 26.—*High temperature hardness tests (500 kg) on duralumin quenched from 475° C. (Grard, 2e)*

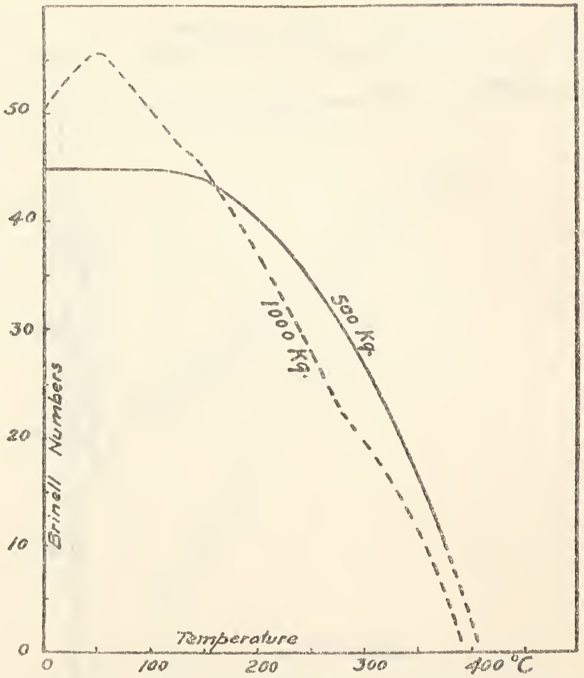

Fig. 27.—*Hardness of copper-aluminum alloy containing 4 per cent copper at high temperatures under 500 and 1,000 kg load. (Grard, 2e)*

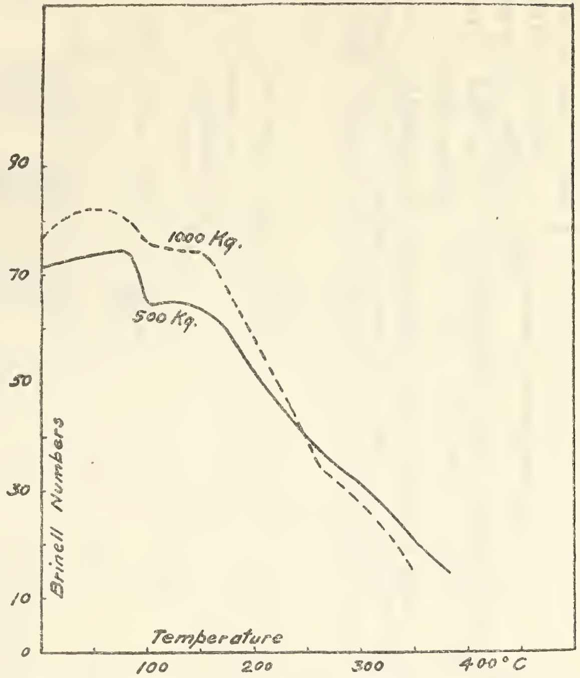

FIG. 28.—*Hardness of copper-aluminum alloys containing 12 per cent copper at high temperatures under 500 and 1,000 kg load.* (*Grard, 2e*)

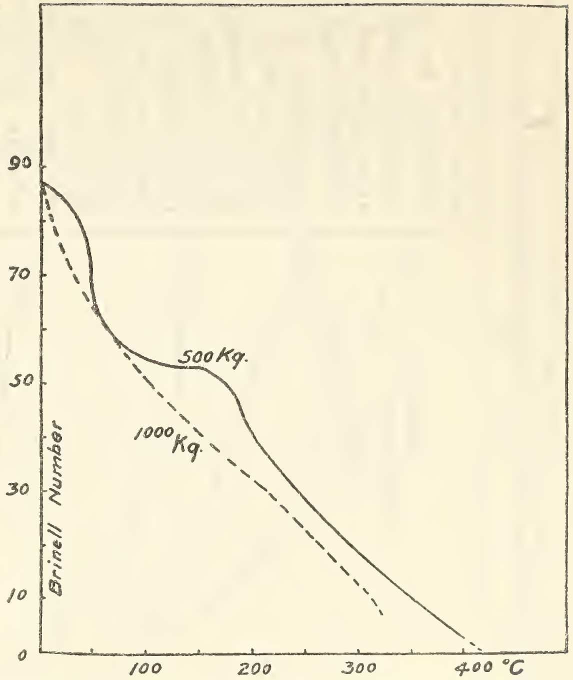

FIG. 29.—*Hardness of zinc-copper-aluminum alloy containing 12 per cent zinc, 3 per cent copper at high temperatures under 500 and 1,000 kg load.* (*Grard, 2e*)

The relative weakening at high temperatures of the alloys containing zinc and the effect of manganese in tending toward the retention of strength at high temperatures is shown, as in Aitchison's data, by data obtained several years ago in the laboratories of the Aluminum Castings Co., cited below. The provisions for insuring that the temperature measured actually represented the temperature of the specimen were not complete enough to insure accuracy, and the indicated temperatures are probably higher than the true ones. The figures are comparable among themselves, but should be taken as of comparative value only. All the alloys were sand-cast.

Iron is said to have an effect rather similar to that of manganese (6a).

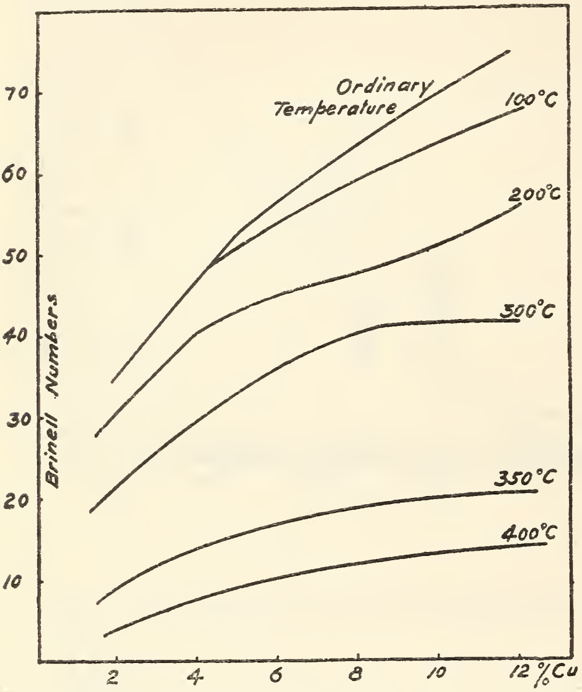

FIG. 30.—*Variation in hardness under 500 kg load, with copper content at different temperatures.* (Grard, 2e)

Figures 31 to 34 also show the sudden drop in strength at about 250° C. (480° F.) of most alloys, the worthlessness of the alloys high in zinc for high temperature service and the beneficial effect of manganese.

TABLE 29.—*Tensile strength of cast alloys at higher temperatures*

Alloy	Tensile strength at—			
	Room temperature	150° C.	260° C.	370° C.
	Lbs./in.²	*Lbs./in.²*	*Lbs./in.²*	*Lbs./in.²*
8 per cent Cu	22, 800	20, 800	19, 300	17, 800
8 per cent Cu, ¼ per cent Mn	21, 600	21, 500	20, 900	20, 300
2 per cent Mn	18, 000	18, 000	17, 000	16, 200
2½ per cent Cu, 19 per cent Zn	33, 700	26, 500	19, 500	13, 000
1¾ per cent Cu, 30 per cent Zn	45, 400	35, 000	26, 000	17, 000

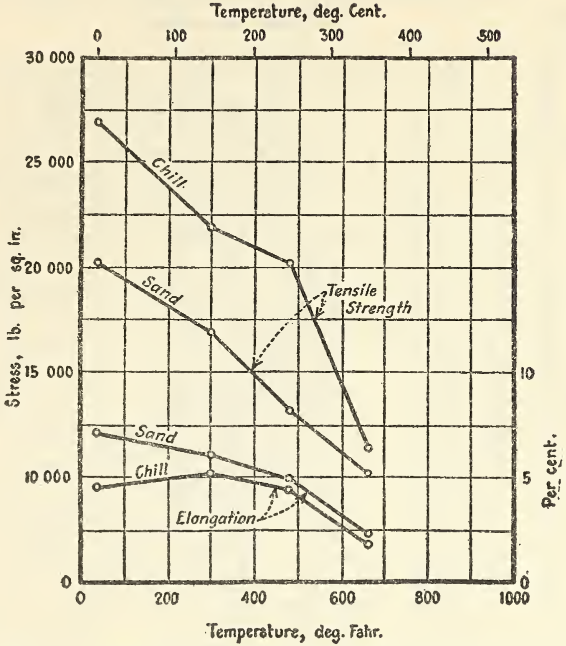

FIG. 31.—*Effect of temperature on tensile properties of copper-aluminum alloy, 10 per cent copper, chill and sand castings, according to Lea (34j)*

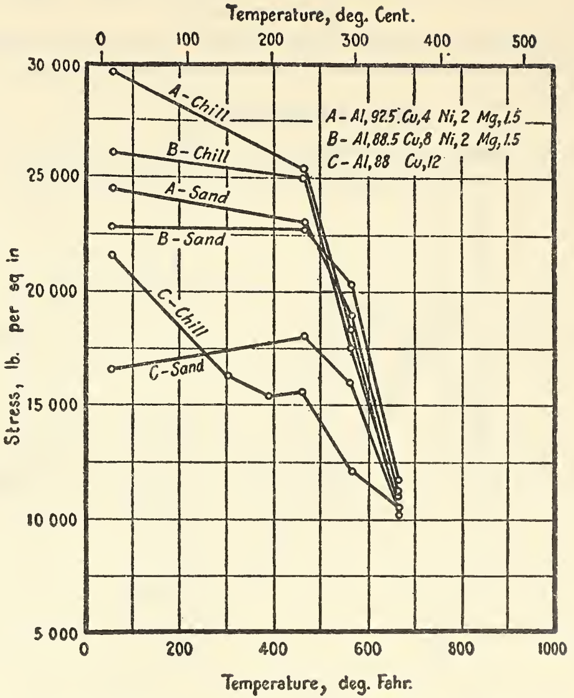

FIG. 32.—*Effect of temperature on tensile properties of aluminum alloys, chill and sand castings. (Eleventh Report to British Alloys Research Committee)*

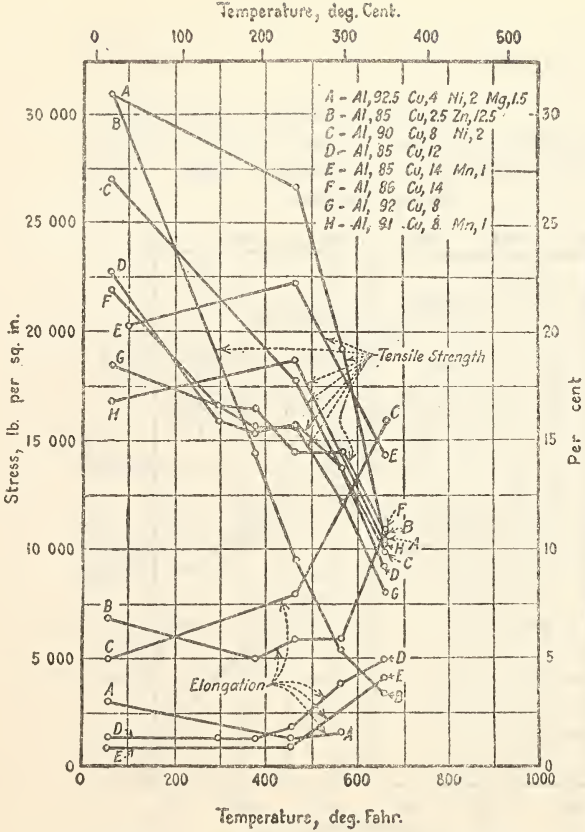

FIG. 33.—*Effect of temperature on tensile properties of aluminum alloys, chill castings. (Eleventh Report of British Alloys Research Committee)*

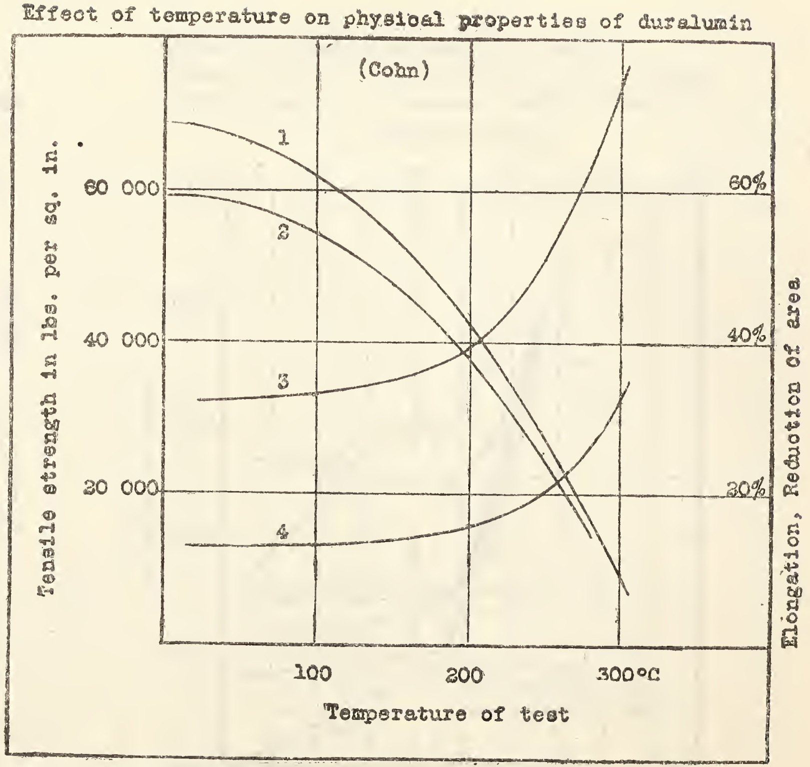

FIG. 34.—*Effect of temperature on the tensile properties (tension test) of duralumin. (Cohn, 43gg, ss)*

Curve 1, tensile strength. Curve 2, yield point. Curve 3, reduction of area. Curve 4, elongation

Figure 35, after Basch and Sayre, shows that the silicon alloys lose strength at high temperatures in much the same way that the copper alloys do.

The strength of the 12 per cent copper alloy at increasing temperatures is given by Swan (92b, 61g) as 22,500 lbs./in.^{2} at 15° C., 16,500 at 150° C., and 15,500 at 250° C., and by Anderson and Boyd (10f) as 21,000 lbs./in.^{2} at 20° C., 15,000 lbs./in.^{2} at 200° C., and 10,000 lbs./in.^{2} at 350° C. The coefficient of expansion is given by both as 26.4×10^{-6}. Anderson and Boyd recommend pouring the 10 per cent copper alloy at 725 to 775° C.

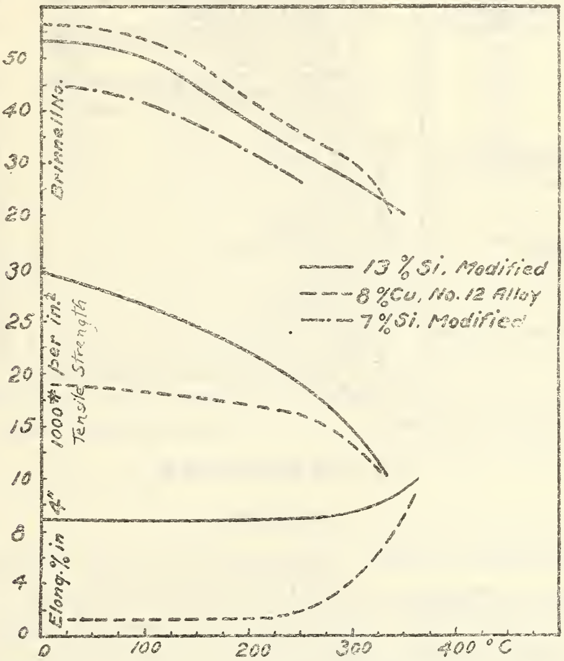

FIG. 35.—*Variation of tensile properties of some aluminum alloys of copper and of silicon with temperature. (Basch and Sayre, 76w)*

Data on the properties of duralumin and of an alloy of Al-Zn-Cu-Mg at low temperatures, given by Cohn (43gg), Table 30, show that both strength and ductility increase at temperatures below room temperature.

TABLE 30.—*Tensile properties of aluminum-zinc-magnesium alloy and of duralumin at low and slightly elevated temperatures (Cohn, 43gg)*

Alloy	Test conditions		Tensile properties	
	Temperature	Medium	Ultimate tensile strength	Elongation [1]
	°C.		*Lbs./in.^{2}*	*Per cent*
Cu 0.32 per cent, Zn 9.40 per cent, Mg 0.39 per cent extruded (and drawn).	−80	CO_2 snow	50,500	20.3
	−20	Ice and salt	46,500	13.3
	0	Ice and water	45,300	16.0
	20	Air	45,900	16.1
		Water 70°, 1 hour in contact with iron then tested in air.	45,000	15.3
		Stressed in tension, load released, held 2 hours in water in contact with iron, tested in water.	38,500	[2] 6.4
	70	Stressed in tension load released and held ¼ hour in water 70° C.	35,000	[2] 5-7
		As above, held 1 hour 70° in water	31,600	4.2
		1 hour in oil	40,000	11.5
Above alloy annealed 400° C., quenched in water, aged 1 week, room temperature.	−80	CO_2 snow	46,500	19.8
	−20	Ice and salt	45,000	21.1
	0	Ice and water	44,000	21.1
	20	Air	42,600	20.8
	70	Water	35,800	17.4
Duralumin (composition not stated) heat-treated.	−80	CO_2 snow	67,300	22.5
	−20	Ice and salt	64,800	21.7
	0	Ice and water	64,400	20.0
	20	Air	62,400	20.0
	70	Water	60,000	20.0
Duralumin heat-treated and cold-worked.	−80	CO_2 snow	78,000	6.8
	−20	Ice and salt	76,000	7.0
	0	Ice and water	75,300	6.9
	20	Air	76,000	6.1
		Stressed in tension, load released, held 3 hours in water in contact with iron.	75,100	6.9
	70	Water	72,800	5.5

[1] Gauge length not given.

[2] Broke outside gauge length.

VI. TECHNOLOGY

1. CASTING

Pure aluminum is too soft, machines with too much difficulty, and has too great a propensity toward shrinking and piping to be widely useful in the cast state. Except for experimental purposes or for cases where cast shapes of high electrical conductivity or resistance to some types of chemical corrosion must be produced, castings are made only in the alloys of aluminum and will be discussed under that heading (p. 160).

2. WORKING

Sheet aluminum is usually rolled from one of the standard rolling ingots. The ingots are reheated after casting to about 425 to 450° C. and rolled down hot in from 10 to 12 passes to a sheet, ¼ to ⅜ inch thick. This is then rolled cold to gauge without intermediate annealing. Sheet as thin as 0.0003 inch may be rolled; this is, of course, foil. If soft sheet is desired, the cold-rolled sheet is annealed, generally at from 350 to 500° C. for 2 to 5 hours, and cooled in air. The effect of cold rolling on inhomogeneous aluminum cast blocks has been reported by Seidl and Schiebold (39h) and this work should be consulted for information on the effect of rolling on crystal structure.

The weights of aluminum sheets and slabs in various gauges and thicknesses are given in Table 31.

TABLE 31.—*Weights per square foot of aluminum sheet and slab*

Sheet gauge, A. W. G.	Thickness	Weight per square foot	Sheet gauge, A. W. G.	Thickness	Weight per square foot
	Inch	*Pound*		*Inch*	*Pound*
0000	0.4600	6.406	19	0.0358	0.499
000	.4096	5.704	20	.0319	.445
00	.3648	5.080	21	.0284	.396
0	.3248	4.524	22	.0253	.353
1	.2893	4.029	23	.0225	.314
2	.2576	3.588	24	.0201	.279
3	.2294	3.195	25	.0179	.249
4	.2043	2.845	26	.0159	.221
5	.1819	2.534	27	.0141	.197
6	.1620	2.256	28	.0126	.176
7	.1442	2.009	29	.0112	.156
8	.1284	1.789	30	.0100	.139
9	.1144	1.594	31	.0089	.124
10	.1018	1.418	32	.0079	.110
11	.0907	1.264	33	.0070	.098
12	.0808	1.126	34	.0063	.087
13	.0719	1.002	35	.0056	.078
14	.0640	.892	36	.0050	.069
15	.0570	.796	37	.0044	.062
16	.0580	.707	38	.0039	.055
17	.0452	.630	39	.0035	.049
18	.0403	.561	40	.0031	.043

For suggested tolerances in thickness, width, and length of sheet see specifications (Table 32).

Rods and wire are first hot-rolled and then drawn cold to size, the methods differing but little from those in vogue for copper. Wire, for example, may be rolled hot from a square section billet weighing about 85 pounds (usually about 4 inches square in section and 5 or 6 feet long), to from ½ to ⅜ inch. These rods are drawn cold to the wire sizes desired. Sometimes, particularly in European practice, all of the rolling is done cold instead. Tallow is used as a lubricant, and the wire may be drawn at from 150 feet (initial) to 600 feet per minute final speed.

Tubes are made by the cupping of plates, followed by drawing on the press, and then on the standard draw bench. This is done cold with intermediate annealing if necessary.

Sections, rods, and tubes are also made by extrusion at higher temperatures (about 400° C.) by hydraulic pressure. Sections up to 6 inches in diameter are made in this manner with wall thicknesses as small as ⅛ inch. Continuous tubing may be made also by this method.

Aluminum is very readily stamped, drawn, and spun. Cooking utensils and vessels of various kinds are produced by spinning annealed aluminum sheet. In thicknesses above No. 20 B. & S. gauge, aluminum will take a draw of from one-fourth to one-third more depth than will copper, brass, or steel (39f).

Aluminum foil, 0.0005 inch in thickness may be still further beaten into aluminum leaf almost as fine as gold leaf.

The effect of cold working upon 98.98 per cent pure aluminum sheet, as well as upon the alloy with 1 per cent manganese, has been discussed by McAdam (39c), who gives several curves for strength, hardness, and ductility of sheet at different degrees of reduction.

TABLE 32.—*Specifications for aluminum sheets*

Specification	Designation	Grade	Aluminum (minimum)	Tensile properties							Permissible variations in thickness		
				Thickness	Soft		Half hard		Hard				
					Tensile strength (minimum)	Elongation per cent in 2 inches (minimum)	Tensile strength (minimum)	Elongation per cent in 2 inches (minimum)	Tensile strength (minimum)	Elongation per cent in 2 inches (minimum)	Width 20 inches and under	Width 20 to 36 inches	Width 36 to 60 inches
		Per cent	*Per cent*	*Inch*	*Lbs./in.*^{2}		*Lbs./in.*^{2}		*Lbs./in.*^{2}		*Inch*	*Inch*	*Inch*
Federal Specifications Board [1]	Proposed	99	99	0.258–0.051	12,000	30	16,000	7	[2] 22,000	4	------	------	------
				.050– .032	12,000	25	16,000	5	24,000	3	------	------	------
				.031– .021	12,000	20	16,000	4	26,000	2	------	------	------
				.019– .013	12,000	15	16,000	3	30,000	1	------	------	------
				.258– .220	------	------	------	------	------	------	±0.014	±0.016	±0.018
				.219– .115	------	------	------	------	------	------	±.010	±.012	±.014
				.114– .073	------	------	------	------	------	------	±.006	±.007	±.008
				.072– .030	------	------	------	------	------	------	±.005	±.005	±.006
				.029– .019	------	------	------	------	------	------	±.004	±.004	±.006
				.018– .014	------	------	------	------	------	------	±.004	±.004	±.004
				.013– .005	------	------	------	------	------	------	±.003	±.003	±.003
American Society for Testing Materials.	B25-26T	99	99	.258– .251	12,000	30	16,000	7	------	------	------	------	------
				.102– .151	------	------	------	------	22,000	4	------	------	------
				.050– .032	12,000	25	16,000	5	24,000	3	------	------	------
				.031– .020	12,000	20	16,000	4	26,000	2	------	------	------
				.019– .013	12,000	15	16,000	3	30,000	1	------	------	------
				.258– .220	------	------	------	------	------	------	±.007	±.008	±.009
				.219– .115	------	------	------	------	------	------	±.005	±.006	±.007
				.114– .072	------	------	------	------	------	------	±.003	±.0035	±.004
				.072– .013	------	------	------	------	------	------	±.0025	±.0025	±.003
				.029– .019	------	------	------	------	------	------	±.002	±.002	±.003
				.018– .014	------	------	------	------	------	------	±.002	±.002	±.002
				.013 and less	------	------	------	------	------	------	±.0015	±.0015	±.0015

											All widths		
Society of Automotive Engineers	No. 78	99	99	.258- .204 .203- .114 .113- .072 .071- .029 .028- .020 .019- .013	Same as Federal Specifications Board						±0.0100 ±.0060 ±.0030 ±.0025 ±.0020 ±.0015		
									Permissible variations in thickness				Weight
									Width 350 to 500 mm	Width 350 to 600 mm	Width 600 to 750 mm	Width 700 to 1,000 mm	
DIN[3, 4]	1753		98-99	*Thickness mm*					*mm*	*mm*	*mm*	*mm*	*kg/m*
				0.2					±0.015				0.55
				.25					±.02				.68
				.3					±.02				.82
				.35					±.03				.96
				.4					±.03				1.09
				.45						±0.035			1.23
				.5						±.035	±0.05		1.37
				.6						±.035	±.05		1.64
				.7						±.035	±.05		1.91
				.8						±.04	±.05		2.18
				.9						±.04	±.06		2.46
				1						±.04	±.06	±0.08	2.73
				1.1						±.04	±.07	±.09	3.00
				1.2						±.04	±.07	±.09	3.28
				1.3						±.05	±.07	±.09	3.55
				1.4						±.05	±.07	±.09	3.82
				1.5						±.05	±.07	±.09	3.09
				1.8						±.06	±.09	±.11	3.91
				2						±.06	±.09	±.11	5.46
				2.2						±.06	±.09	±.11	6.01
				2.5						±.08	±.11	±.13	6.83
				3						±.08	±.11	±.13	8.19
				3.5						±.10	±.13	±.15	9.55
				4						±.10	±.13	±.15	10.92
				4.5						±.12	±.15	±.17	12.28
				5						±.12	±.15	±.17	13.65

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[1] Permissible variations in width and length same as that given for aluminum alloy sheets.

[2] Hard temper for thicknesses 0.102 to 0.051 inch only.

[3] DIN = Deutsche Industrie Normen, Berlin, NW 7, Sommerstr. 4a.

[4] Variations in width: Fabrication tolerance +10 to 50 mm; specified width admissible deviation +5 mm. Variations in length: Fabrication tolerence average 2,000, lowest 1,000, highest 3,000; specified lengths, admissible deviation +10 mm.

TABLE 32.—*Specifications for aluminum sheets*—Continued

UNITED STATES ARMY ORDNANCE DEPARTMENT METALS SPECIFICATIONS NO. 57-151. MAY 9, 1923; ALUMINUM PLATES, SHEETS, AND STRIPS[5]

Size (inches)	Tensile strength (minimum)			Elongation 2 inches or proportional gauge length (minimum)			Bend test degrees		Thickness		Width		Tolerances—				
									Permissible variations—		Permissible variations—		Permissible variations in length up to 12 inches wide—				
													Maximum permissible percentage by weight of short lengths				
	Soft	Half hard	Hard	Soft	Half hard	Hard	Soft flat	Half hard[6]	30 inches wide and less	Over 30 inches wide	For thickness of 0.1020 inches and less	For thickness over 0.1020 inches	8 to 10 feet	6 to 8 feet	4 to 6 feet	2 to 4 feet	Under 2 feet
Thickness	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent	Per cent											
0.0126-0.0179	12,500	16,000	28,000	15	5	2	180	180									
0.0201- .0285	12,500	16,000	26,000	20	5	2	180	180									
0.0320- .0453	12,500	16,000	24,000	25	5	3	180	180									
0.0508 and over	12,500	16,000	22,000	30	7	4	180	180									
0.0100-.0142									±0.0015	±0.0020							
0.0159-.0254									±.0020	±.0025							
0.0285-.0403									±.0025	±.0030							
0.0453-.1020									±.0030	±.0035							
0.1140-.1820									±.0060	±.0065							
0.2040 and over									±.0100	±.0100							
Width																	
10 and less											±0.060	±0.060					
Over 10 to 18											±.060	±.090					
Over 18 to 36											±.090	±.125					
Over 36											±.125	±.190					
Nominal or stock length			Required by per cent weight														
10			60										40	30	20	10	0
8			70											30	20	10	0
6			80												20	10	0

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[5] The material shall contain not less than 99 per cent aluminum.

[6] On a radius equal to the thickness of the material.

3. MACHINING

Wrought aluminum and its industrial alloys, which are nearly all furnished in various tempers, show some differences in machining qualities. However, there are certain fundamentals to be observed for the successful machining of any of these alloys, as well as those which are ordinarily used in the cast condition.

The three important factors to be taken into account are tool design, tool finish, and the cutting compounds used. In general, tools used for the machining of aluminum alloys should have small included angles in comparison with those found in similar tools to be used on mild steels. The tools should be sharp and finished smooth; hence, the grinding which is used in shaping the tools should preferably be followed by stoning with a rather fine oilstone.

Tool angles, which are important, will vary for different alloys and the conditions under which they are to be machined. Recommendations can generally be secured from suppliers, but certain numerical values may be cited for guidance. The quoted figures are not necessarily the best, but are indicative of the form of tools found to machine aluminum satisfactorily.

Turning tools may have a clearance of around 10°, top rake of 50°, side rake of 15°, which makes the total angle of the cutting edge around 30 or 35°. Considerable side rake is desirable whenever possible. For planer and shaper work, the roughing tool should do nearly all of its cutting on the side of the tool and should be followed by a tool which has a clearance, cutting edge, and top rake indicated for above turning tools, but with a greater side rake in the neighborhood of 40 to 60°. For ordinary engine lathe work a round nosed tool may be used when set for the proper clearance and so as not to curl the chip any more than necessary. It is also advisable to set the tool higher on the work than when machining steel or brass. On the other hand, inside tools, such as boring bars and threading tools, should be set below center.

Milling cutters, end mills, straddle mills, etc., should be of the high-speed spiral coarse-tooth type. Ordinary twist drills work fairly well for drilling aluminum, but the straight fluted drills often used for brass are not suitable. Thinning the point of a twist drill has advantages when using large sizes. A "gun" tap is preferable to the ordinary hand tap for tapping aluminum. This tap has but two flutes which are cut to have more top rake to the cutting edges than ordinary taps.

The cutting compound used in machining aluminum and many of its alloys is generally of great importance. For heavy cuts and slow feeds such as are used in roughing work pure lard oil is satisfactory. Paraffin base cutting compounds, such as are used for cutting brass, are unsatisfactory for machining aluminum. A mixture of equal parts of lard oil and kerosene is generally useful but may be replaced, economically, for milling, sawing, and drilling by the soluble cutting oils.

The cutting speeds and feeds which may be used will vary greatly, depending upon the conditions of cutting. In general, the finer the feed the higher the speed, but the more curl there is to the chip the lower the speed. To increase the amount of metal removed from the stock in a given time it is often better to increase cutting speed than feed for there is a decided tendency for aluminum to heat when using coarse feeds. Since the coefficient of linear expansion of aluminum is high the stock will tend to warp.

Additional information on the machining of aluminum will be found in the references in the bibliography, page 371.

4. WELDING

Aluminum can be welded by several different processes, the principal difficulty being the removal of the layer of oxide from the surface before the metal can flow together.

Recently two new welding processes have been brought out by the General Electric Co.—the hydrogen atmosphere arc and the atomic hydrogen flame (41a), (41b, c).

In these two methods the difficulties with the oxide film are said to be much reduced. It is claimed by some that the use of a flux may be found unnecessary, while others feel that even the oxide film which forms at room temperature will in itself be sufficiently thick to cause difficulty and require the use of a flux for best results. Experience with these methods has not as yet been sufficient to enable a judgment to be formed as to their field of usefulness.

Aluminum sheet is generally welded by the oxyhydrogen torch (oxyacetylene or oxygas is also used), the edges being butted for all but light gauges, for which they are lapped or flanged. In these methods a flux should be used for sheet welding, and consists of a mixture in varying proportions of the chlorides and fluorides of sodium, potassium, lithium, aluminum, and calcium. The flux should contain no acid or alkali which is injurious to the metal (41n). For aluminum cooking utensils, a recommended analysis of flux consists of 3 per cent potassium carbonate, 6 per cent lithium fluoride, 40 per cent sodium chloride, and 51 per cent potassium chloride (41j). The flux is used mixed with water, the flux being partly in solution and partly in suspension, and is suitable for any type of weld. A few typical compositions of fluxes are given in Table 33.

TABLE 33.—*Composition of welding fluxes* (*Pannell* (*6c*) *and others*)

	Sodium chloride	Sodium fluoride	Sodium sulphate	Lithium chloride	Potassium chloride	Potassium fluoride	Potassium sulphate	Calcium chloride	Cryolite
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	30		3	15	45	7			
2		33		33	33				
3	12.5			20.8	62.5		4.0		
4	16				79		5.0		
5	17				83				
6	6.5		4.0	23.5	56				10
7					60			30	6

Castings may be welded in the same manner, but autogenous welding with the use of a puddling rod rather than flux to break down the oxide is the more common practice (41j). The casting should be well supported, so that no stress comes upon the welded joint while it is hot, as the metal is fragile and brittle at a temperature a little below the melting point. Welding is used to repair broken machinery parts and defective castings, but the advisability of welding is questionable if the welded parts must carry stresses (41j, k). Conservatively used, welding of castings permits salvage of many otherwise scrap castings, and since castings are normally designed overstrong to take care of internal defects not detectable on inspection, or because the thickness of section required from the foundry point of view is greater than that required from the point of view of use, may often be used without decreasing the utility of the casting. But the location of the defect to be welded should always be carefully studied in respect to the stresses the casting is to bear before welding is permitted. In welding castings, they should preferably be preheated in order that internal stresses caused by shrinkage are not left in the welded casting when cool. The preheating temperature should not exceed 450 to 500° C. (41d).

Rods and wires are best butt welded by a combined heating and pressure method. The older methods of Heroult and of Cowper-Coles consisted in squaring off the ends of bars, heating these ends to about 400° C., and bringing them together and hammering them (Heroult), or under pressure (Cowper-Coles). The electric-resistance, butt-welding machines have, however, furnished a much more suitable means of heating and applying pressure than the older processes, and are in general use. Skinner and Chubb (41p) have described a method of welding applicable to aluminum.

Spot welding of sheet aluminum is in the development stage. While it does not seem to give as reliable a joint as the oxyacetylene process, it promises to be applicable to some problems.

The structure of the weld is that of cast material, while the zone surrounding the weld shows a softening due to heating. The strength of both the weld and the surrounding zone may be increased by hammering in sufficiently malleable alloys (41g). Rohrig (41i) found that the recrystallized zone was attacked least in a corrosive media of brine solution, but when hammered the zone showed no difference in degree of attack from the rest of the material. A similar result was obtained by Knerr on duralumin (41m), the region 1 inch from the weld showing corrosion in brine, the weld itself being unattacked. Duralumin may be heat treated following welding to prevent corrosion and to increase the strength of the welds (41m). Welding of wrought heat-treated dualumin should be avoided unless the thickness of the welded joint and of the parts affected by the welding temperature is made sufficient to compensate for the loss of strength. Heat treatment of a weld is poorly effective because the metal of the weld is cast, not wrought, and will not respond so readily to heat treatment as does wrought metal, nor will it assume as good physical properties as will wrought metal. (See p. 254 on heat treatment of castings.) Mechanical joints are usually to be recommended in stressed parts.

Welded joints can be expected to show small corrosive attack in the atmosphere and even with gasoline or benzol in which sulphur is present there is no attack (41m), although impurities taken up by the metal from the oxyacetylene flame, and pores present in an unskillful weld may serve as the focus for corrosive attack (41l,f,j).

Welding, chiefly oxyhydrogen or oxyacetylene, is now quite widely practiced, both on aluminum castings and on sheet. Large numbers of welded aluminum vessels, pans, and containers of various sorts are manufactured each year. The welds are in most cases so perfect that they can not be detected in the finished article. However, the welding of aluminum by any of the above methods is not easy, and requires experience. Welders familiar only with iron and steel work will generally make a complete failure of their first aluminum work.

5. SOLDERING

Although welding is the only process to be recommended where the joint must have strength and is exposed to weather, it may, in some instances, be advisable to solder aluminum articles instead of welding them as in the repair of slight defects in aluminum castings which are not subject to stress (40d). The application of solder is easier, does not require as skilled an operator, and since the temperature of application is not so high, there may be less buckling or distortion in the soldered piece. On the other hand, few of the aluminum solders can be classed as entirely successful since the metals used in such solders are all electropositive to aluminum, and the joints tend to disintegrate in the presence of water or moisture. Only when the joint may be varnished or protected, or for very heavy joints where slight corrosion would not be serious may solders be relied upon with entire confidence.

There is a large variety of solders on the market, some of which have been described in Circular No. 78 of this bureau on Solders for Aluminum. Many others have been suggested, and a complete list would include about 500.

Most of the solders are proprietary articles, put out with an abundance of extravagant claims and a dearth of metallurgical and engineering information.

Many of these solders differ but little from the composition 60 per cent tin, 40 per cent zinc, although small amounts of nearly every metal in the periodic table have been added by various inventors. It is doubtful if any of the proprietary solders offer much that can not be had in simple solders in the range 55 to 70 per cent tin and 45 to 30 per cent zinc.

The addition of aluminum to Sn–Zn base solders is generally harmful from the corrosion point of view, though it tends to increase the strength of the joint as immediately tested and after aging (40g). The effect of the addition of 1 per cent of copper to Sn–Zn–Al alloys produced little change in properties (40h), but the addition of 3 per cent copper had more effect. The best solder of this group from the standpoint of strength and fusibility is said to be the alloy of 56.4 per cent Sn, 37.6 per cent Zn, 3 per cent Cu, 3 per cent Al. Aged soldered joints made with such alloys tend, in general, to be of lower strength than joints tested immediately after soldering.

Solder is best applied without a flux. Metallic salts, such as zinc chloride, are especially to be avoided. Any traces of such a flux retained in the joint will greatly hasten corrosion. The edges of the aluminum are filed clean and tinned with the solder, which should be thoroughly rubbed into the surfaces with a wire brush or a pad of steel wool. The joint is then readily made in the usual manner between tinned surfaces, using an iron if necessary. Hydrofluoric acid is used to brighten inaccessible parts that can not be filed or scratch brushed. The acid has to be kept in wax bottles and will produce painful burns if it comes in contact with the skin. It should be pointed out that soldering and welding should not be used for heat-treated alloys, for the heat of the operation will make them lose their acquired properties. Solder joints should not be quenched but should be allowed to cool slowly.

Eyles (40b) states that the "hard" aluminum solders, which consist largely of aluminum itself, and which have recently been advocated in Germany, have melting points so high that they can not be applied with a soldering iron but must be applied with a torch. He considers that such solders have little or no real value in industry. When such solders are needed, the problem is far better handled by autogenous welding. Rostosky and Lüder (40c) deny that the objections to solders high in aluminum are well founded. German interest in solders for aluminum seems to be much more active than in other countries, as the Deutsche Gesellschaft für Metallkunde held a competition in 1923 for aluminum solders (40e).

Solders rather high in aluminum are sometimes used in American practice for filling up blowholes in castings when the strength of the casting is not injured by the defect and where the casting will not come in contact with moisture. Holes that appear on the machined face of a crank case, and which are not objectionable except on the score of oil-tightness, are sometimes filled with moistened plaster of Paris or plaster of Paris aluminum powder mixtures. Mixtures of powdered sulphur and powdered aluminum are sometimes used, the sulphur being melted into the hole to be plugged. Compositions of this sort are sometimes offered to the housewife for plugging holes in cooking utensils. Such a composition is dangerous as slight overheating results in almost explosive combustion.

All these methods of soldering or plugging are applicable chiefly to problems where no real joint is required. Joints that must stand stress, unless absolutely protected from moisture, may be unreliable. In electrical meters, for example, it is sometimes necessary to solder an aluminum wire to a copper wire to secure electrical connection. If the aluminum wire is copper plated (see p. 34) a joint can be made with ordinary solder, provided the copper plating adheres to the aluminum wire, but the uncertainty as to such adhesion is great. "Tinning" the aluminum wire with the tin-zinc solder, and the copper wire with ordinary solder, after which the two are joined with ordinary solder, is the usual procedure.

All soldered joints in aluminum should be designed so that there can be no heavy stress upon the joint and the joint is preferably covered with some moisture-proof coating.

Edwards (40a) states that out of some 460 aluminum solders examined only about 10 were exceptionally good.

While the soldering of aluminum with most of the solders put forward for the purpose gives results of doubtful utility, joints made with some solders, after careful cleaning of the aluminum surface, with the avoidance of a corrosive flux and with the best workmanship, have stood up well. Nevertheless there is not available any recent published discussion of the subject by which the few good proprietary solders can be differentiated from the many poor ones, and claims for the utility of any particular solder should be carefully scrutinized before acceptance as facts.

6. MISCELLANEOUS

(a) FINISH

Aluminum is given several types of finish. The two most important are the polished and the satin finish. The former is obtained in the usual manner by buffing with rouge. The latter is obtained:

1. By Caustic Dipping.—The metal is cleaned in benzine, dipped in boiling concentrated caustic soda, washed, dipped in hot strong nitric acid, washed in boiling water, and dried very quickly.

2. By Scratch Brushing.—The metal is carefully freed from grease and then brushed on the wire-brush wheel.

3. The anodic and the chemical oxidation processes described under protection of aluminum against corrosion are also applicable for decorative purposes, some such finishes being of pleasing appearance. The oxide coating so formed can be dyed. It serves also as a base over which paints and varnishes can be applied that would not adhere well to the smooth unoxidized metal. Paint or varnish coatings adhere much better to sand-blasted, or otherwise roughened surfaces than to a polished surface.

Gardner (18c, 43i) describes a number of paints for protective purposes.

(b) GRANULATING

Granulated aluminum has been produced to put the metal into a form convenient for use in deoxidation of steel. It may be made by pouring molten aluminum in thin streams into cold water, which is stirred. The metal may for this purpose be poured through a sieve.

If commercial aluminum which is somewhat impure so that it does not have a sharp melting point, but rather a melting range, is cooled very slowly from just above the melting point and vigorously stirred while cooling the crystals may be to some extent kept from coalescing so that when the mass is finally solid, it may be rather readily crushed into granulated form.

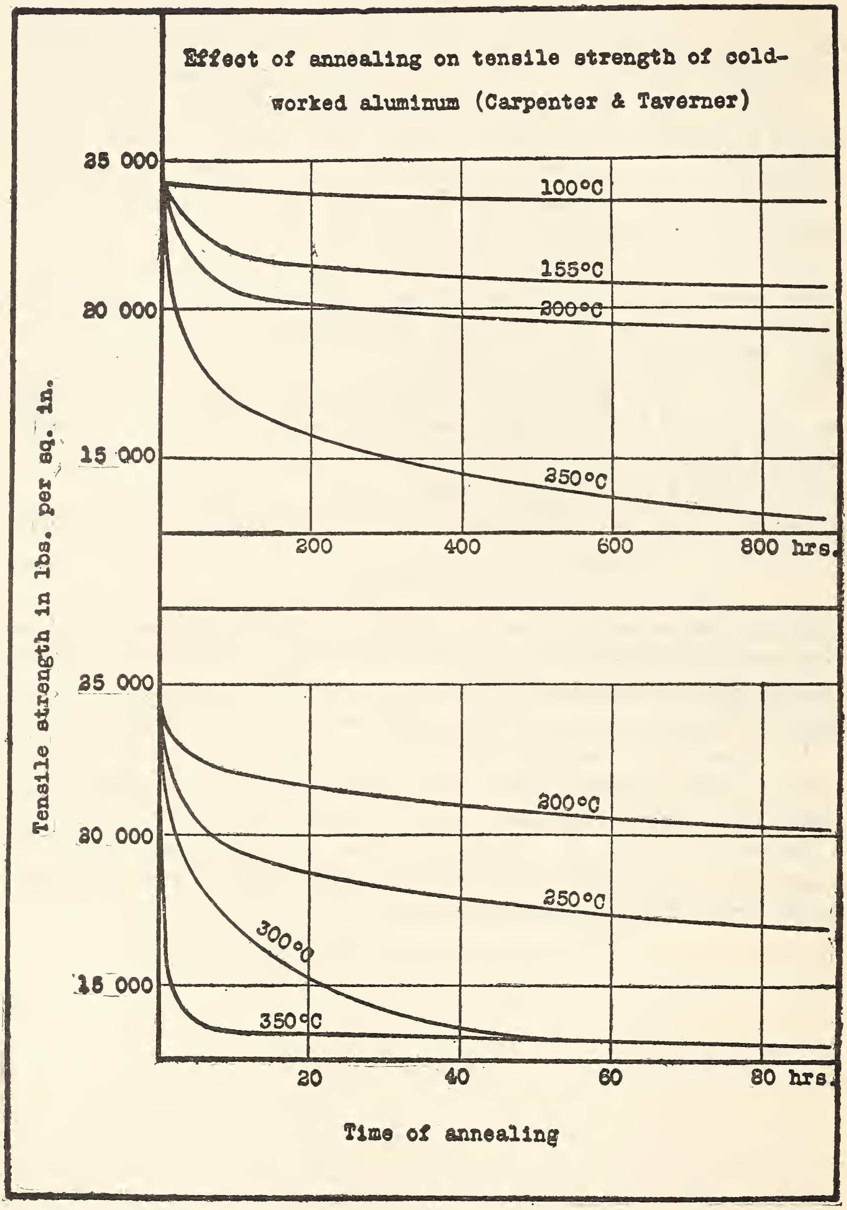

FIG. 36.—*Effect of annealing on tensile strength of cold-worked aluminum. (Carpenter-Taverner, 42h)*

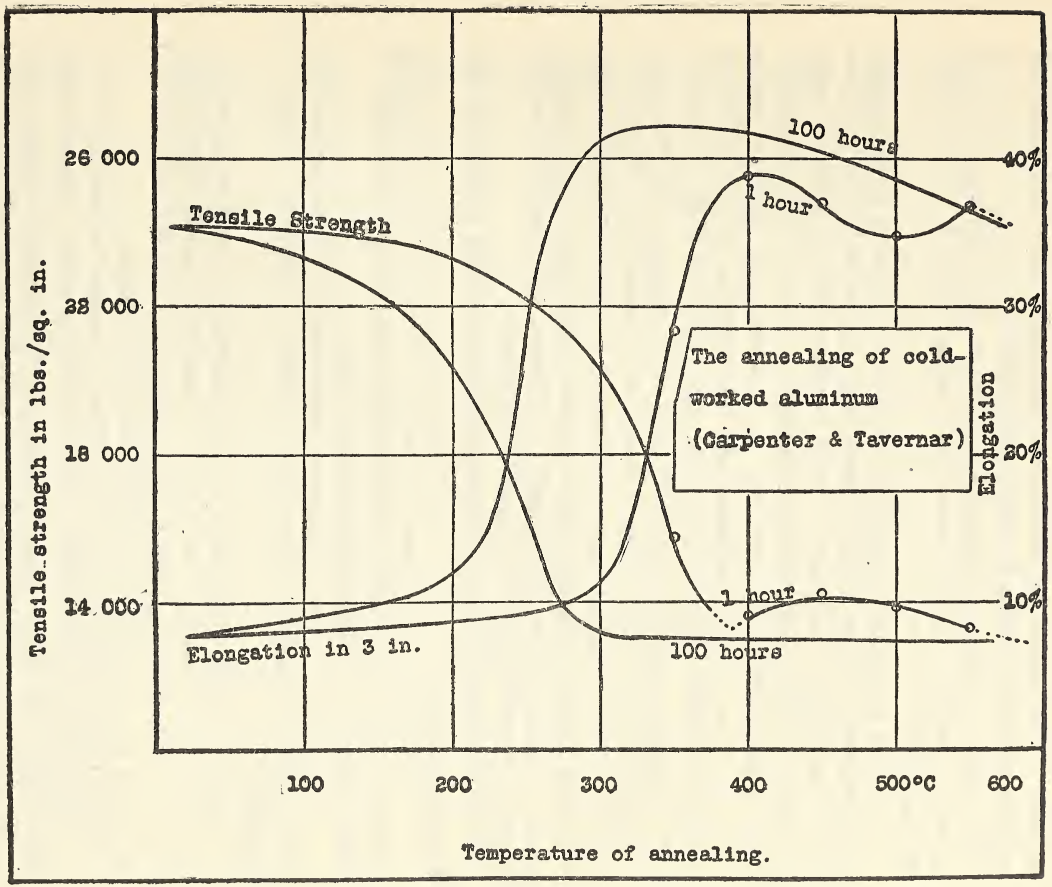

FIG. 37.—*The annealing of cold-worked aluminum.* (*Carpenter and Taverner, 42h*)

VII. PROPERTIES OF ALUMINUM AS AFFECTED BY MECHANICAL WORK AND BY ANNEALING

When aluminum is cold worked, the hardness or tensile strength is increased and the ductility or elongation in the tensile test decreased. The manner in which these properties vary with different amounts of cold working is shown in Figure 16.

The Shore scleroscope hardness number (magnifying hammer) increases also from 5 to 6 for annealed aluminum sheet to from 15 to 20 for hard sheet.

Annealing produces a recrystallization and softening of the metal. Carpenter and Taverner (42h) have made a systematic study of the rate of softening of aluminum sheet by annealing at different temperatures. They used sheet cold-rolled to 0.125 inch (probably from three-eighth inch, but the exact amount of cold reduction was not known to the authors) of four materials of the following average analysis: Silicon, 0.75 per cent (0.70 to 0.80 per cent); iron, 0.34 per cent (0.34 to 0.36 per cent); copper, 0.03 per cent.

A general idea of the results of their tests is gained from Figures 36 and 37. The principal facts developed by this investigation are:

1. The hardness caused by mechanical work is lost very rapidly upon annealing at from 300 to 500° C. The same final tensile strength of about 12,700 lbs./in.^{2} is obtained in all cases.

2. The softening is most marked within the first portion of the annealing period.

3. No increase in hardness was noticed, on annealing cold-worked aluminum, although such a phenomenon is observed in some stages of the annealing process upon copper and brass.

4. Below 300° C. the decrease in hardness is very slow, but occurs within the temperature range 100 to 200° C. with no increase of ductility.

The authors did not study the effect of previous cold reduction on the rate of softening by annealing, but there is no doubt but that the extent of this reduction has a great effect upon the annealing of the metal, as has been shown to be the case with copper.

While hard-worked material will give the results indicated, it is also true that aluminum gradually softens at temperatures which are very much below the instantaneous annealing temperatures noted. For purposes of design it is, therefore, not safe to use values higher than those obtained with annealed metal for any installation which must withstand high temperatures over long periods of time even though a harder temper is initially used.

Anderson has published several articles on annealing of aluminum which are summarized in his book (2d).

B. LIGHT ALUMINUM ALLOYS

I. CONSTITUTION

1. EQUILIBRIUM DIAGRAMS AND COMMENTS

Up to this point the properties of pure aluminum and the influence of impurities upon those properties have been dealt with, without reference to the alloys of aluminum, save as considerations of space made it desirable to include some reference to the properties of the alloys, as under the headings of "corrosion," and "physical properties at higher and lower temperatures," for example, and to some extent under "uses."

Equilibrium diagrams will be given with brief comments on the high aluminum or light alloy end of the series for the binary alloys, and for such of the ternary alloys as have been described. The most useful alloying elements will be further considered under wrought alloys, cast alloys, and heat-treatable alloys.

It is observed from the equilibrium diagrams that some of the metals form compounds with aluminum. There is often some question whether or not a compound really is formed, but the interpretation of the author whose diagram was chosen as most closely representing the probable facts in regard to any system, has been taken in such cases. The equilibrium diagrams are plotted on the basis of percentage by weight. The solubility of the second metal or of an aluminum-rich compound in the solid aluminum is generally low. The three prominent exceptions to this are zinc, copper, and magnesium.

The useful light alloys of aluminum even with these metals usually contain only small quantities of the added metal, as with increasing amounts the alloy quickly becomes brittle.

Metallographically, the light alloys are therefore usually heterogeneous, with a groundmass of almost pure aluminum and crystals of the compound of aluminum with the added metal. These are generally hard and brittle.

(a) BINARY ALLOYS OF ALUMINUM

(1) Arsenic.—Arsenic alloys have been studied by Mansuri (51a) who reports that no action takes place between aluminum and arsenic up to 600°, or even 750° if the pressure of the arsenic vapor is too high. Al_3As_2 forms at 800° under low pressures and does not melt at that temperature, or dissolve in molten aluminum. Al_3As_2 is stable at high temperatures, but begins to break up at lower temperatures; it evolves arsenic trihydride freely when exposed to moisture. Heated in air the compound oxidizes to alumina and arsenous oxide. The solid compound does not seem to dissolve in molten aluminum nor does it alloy with arsenic to form an eutectic.

(2) Antimony.—Antimony under 5 per cent is said to increase the resistance to corrosion (3d) of aluminum, but the mechanical properties are little changed. The diagram is given in Figure 38 and the specific volume of antimony-aluminum alloys as determined by Sauerwald is shown in Figure 39. Webster (3a) states that antimony-aluminum alloys may be hot-rolled, with partial lamination from 8 per cent antimony on; the addition of 1 per cent antimony increases the ductility after which it falls.

(3) Beryllium.—Beryllium alloys have been studied by Oesterheld (53c), who reports that the solubility of beryllium in solid aluminum is very small. (Fig. 40.) These alloys have not been thoroughly described. Available information on them is given on page 316.

(4) Bismuth.—Bismuth is reported to have an injurious effect on aluminum (3a, d). It is insoluble in solid or liquid aluminum. (Fig. 41.)

(5) Boron.—Alloys of boron with aluminum (see fig. 42) have been studied by Haenni (55a, b), who investigated alloys of aluminum containing up to 4 per cent boron, aluminum-copper alloys containing 4, 8, and 12 per cent copper, and 0 to 8 per cent boron, as well as silicon-aluminum, nickel-aluminum, aluminum-copper-nickel, duralumin with boron. Haenni concluded that, on the whole, boron improves the tensile strength and hardness and decreases the elongation, and that the addition of boron to aluminum-silicon alloys of the nature of "Alpax" seems to produce a refining similar to that of sodium, and the alkali fluorides. Corrosion data given do not show any consistent improvement in resistance of the alloys on addition of boron.

(6) Cadmium.—The influence of cadmium on the mechanical properties of aluminum has been studied by Budgen (56a), who found that cadmium and aluminum were almost completely immiscible in both the solid and liquid states. With high cadmium content (10 per cent or more) there was considerable segregation. Budgen found that cadmium caused no systematic change of physical properties and had no marked effect in removing the undesirable qualities of "burnt" aluminum which had been claimed for it. Figure 43 shows the diagram, after Groyer (56b).

(7) Calcium (fig. 44).—The effect of calcium on the resistivity of aluminum has been studied by Edwards and Taylor (57b), who state that the resistivity is proportional to the calcium content in the ranges studied, the resistivity of cast material being higher than for the rolled material. In cast material the resistivity rose from 2.988 μ/cm for 0.89 per cent calcium to 3.632 μ for 3.34 per cent calcium, while in rolled material, it rose from 2.742 μ for 0.25 per cent calcium to 3.168 μ for 2.32 per cent calcium. The density of the cast alloys at 20° C. fell from 2.677 for the 0.89 per cent calcium alloy to 2.636

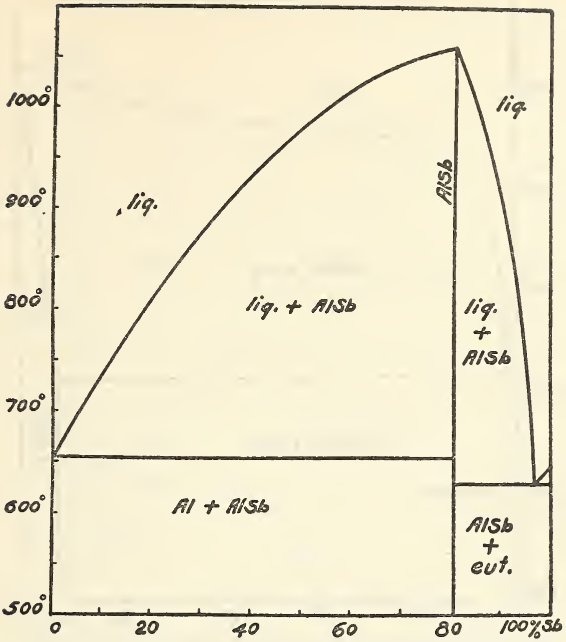

FIG. 38.—*Antimony-aluminum system.* (*Tamman, 52b, Bornemann, 62a*)

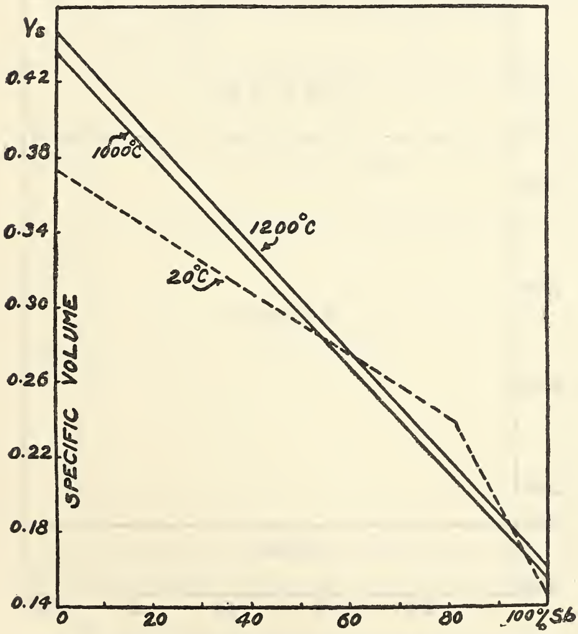

FIG. 39.—*Specific volume of the antimony-aluminum alloys.* (*Sauerwald, by Guertler, 28d*)

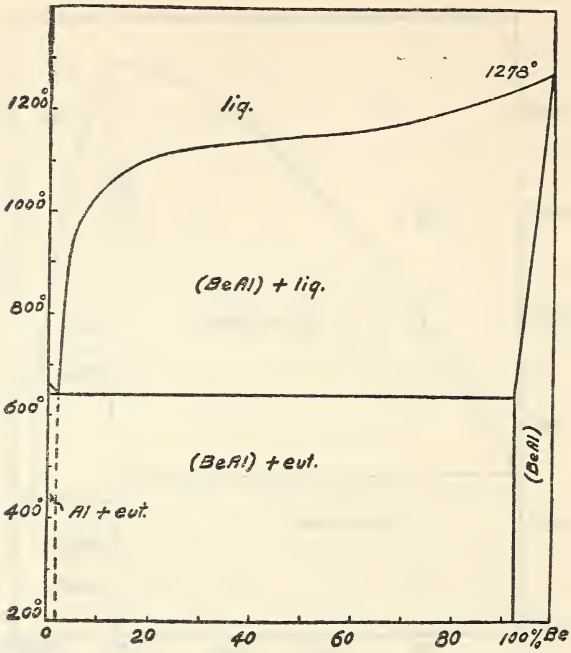

Fig. 40.—*Beryllium-aluminum system.* (*Oesterheld, 53c*)

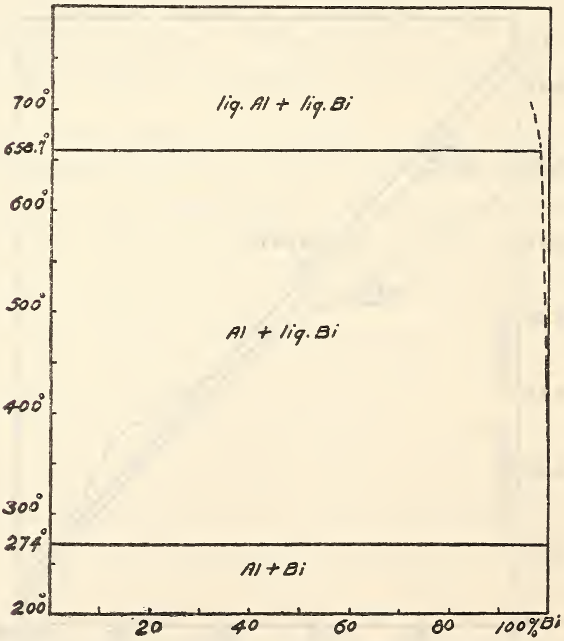

Fig. 41.—*Bismuth-aluminum system.* (*Gwyer, 54a*)

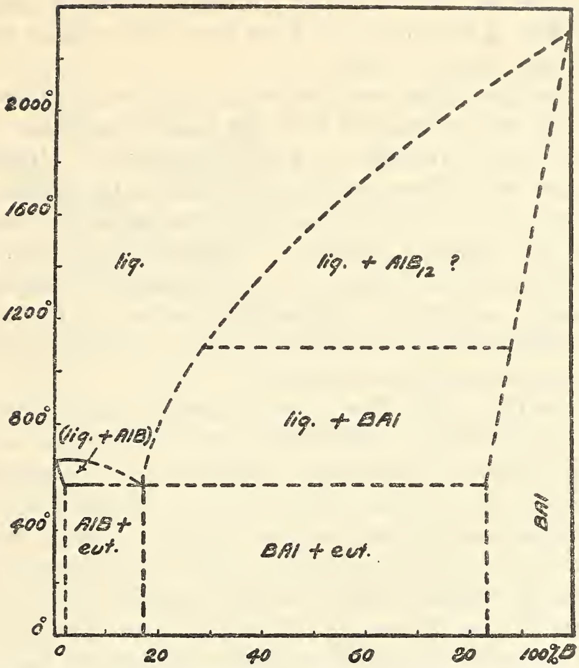

FIG. 42.—*Boron-aluminum system. Corson's imaginary diagram, designed to represent the few facts known about this system. This represents probabilities rather than actual data*

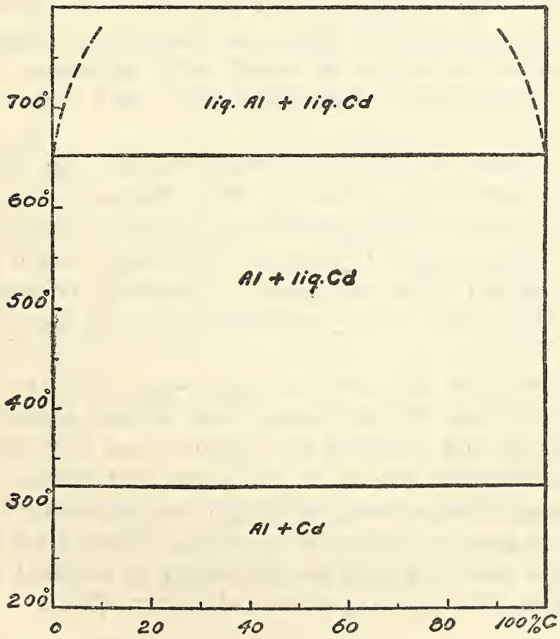

FIG. 43.—*Cadmium-aluminum system.* (*Gwyer, 56b*)

for the 3.34 per cent calcium alloy, while in the rolled condition the density fell from 2.693 for the 0.25 per cent calcium alloy to 2.658 for the 2.32 per cent calcium alloy.

Calcium used to replace magnesium in duralumin has been studied by Kroll (91f), who concluded that the calcium addition raised the temperature most favorable for aging duralumin. Meissner (44e) does not agree with these results and believes the higher strength obtained is the result of a favorable aging treatment and has nothing to do with the calcium addition. Grogan (57a) states that the solubility of the calcium compound in aluminum is less than 1 per cent by weight, and that it exerts slight effect on the mechanical properties of aluminum, to which it imparts no hardening properties. The $CaSi_2$ also produces no hardening.

(8) Cerium (fig. 45).—The alloys of cerium and aluminum have no commercial application and it has not yet been proved conclusively that cerium exerts a beneficial influence upon aluminum. An improvement in properties is claimed by some German investigators. This improvement is attributed in part by Barth (58e) to the decrease of silicon and gas content, by Schulte (58e) to the decrease of nitride content, and by Meissner (58b) to the breaking up of $FeAl_3$. An investigation of the Bureau of Mines (58c) on the effect of the addition of cerium to copper-aluminum alloys lead to the conclusion that cerium had no useful effect on the alloys, and probably no marked effect either way. The expense of the alloys, in connection with the doubtful improvement caused by the cerium, makes it seem probable that the alloys will not prove of any extensive use. Webster (58a) states that cerium-aluminum alloys are resistant to corrosion.

(9) Cobalt.—The alloys of cobalt with aluminum have been studied by Gwyer (59e), Schirmeister (59d), and more recently by Daniels (59a).

Although Gwyer's diagram has been reproduced (fig. 46), it should be noted that according to Daniels (59a) the Al-Co_3Al_{13} eutectic is at about 0.6 per cent cobalt instead of, as shown by Gwyer's diagram, the eutectic being so close to zero per cent cobalt that it can not be shown in a diagram of the scale used. It is also to be noted that the existence of the transformation at 550° C. shown in Gwyer's diagram is doubtful.

Daniels states that the strength of sand-cast alloys containing up to 20 per cent cobalt did not exceed that of pure aluminum. The alloys are dense and resistant to corrosion and free from pitting, being superior in that respect to the 8 per cent copper alloy. An alloy containing 0.94 per cent cobalt and one containing 9.9 per cent cobalt act the same in salt spray corrosion. The 9.9 per cent cobalt alloy is better than the 0.94 per cent alloy in distilled water, but neither of them is as resistant as pure aluminum (59a).

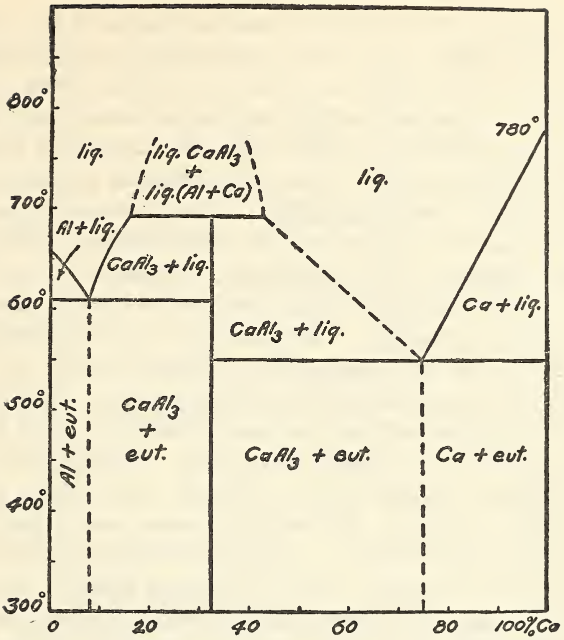

FIG. 44.—*Calcium-aluminum system.* (*Donski, 57c.*)

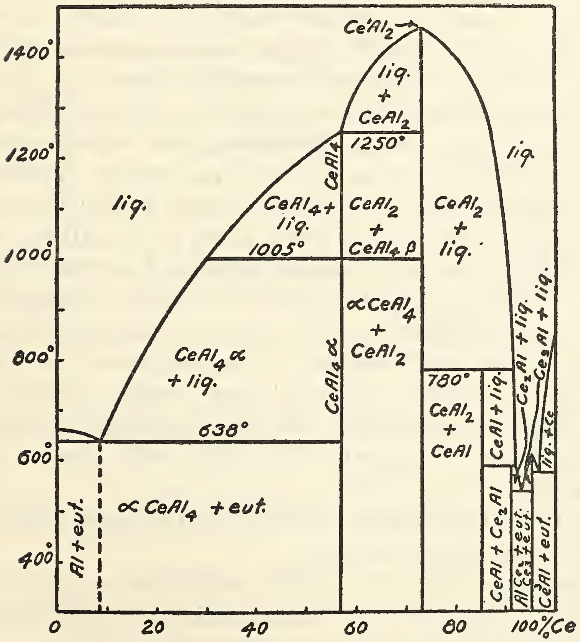

FIG. 45.—*Cerium-aluminum system (approximate).*
(*Vogel and Corson 58e, 2a*)

Rolling is possible with alloys containing up to 11 per cent cobalt, but 4 per cent cobalt is the most advantageous composition. The melting point of alloys poor in cobalt is not far above that of the eutectic (644° C.), but with alloys containing over 2 per cent cobalt the melting point increases rapidly with the increase of cobalt.

The addition of more than 1 per cent cobalt to aluminum is detrimental from every standpoint (59a). The presence of only 0.5 per cent cobalt materially increases the solidification shrinkage, and more cobalt enhances this condition, regardless of the pouring temperature. The best properties are obtained when the alloys are poured as cold as possible. The strength of aluminum-rich alloys of cobalt reaches the low maximum of 15,000 lbs./in.^{2} at 1 per cent cobalt, while the elongation suffers a sharp decline. The best tensile properties are obtained with 0.4 per cent cobalt, giving 14,500 lbs./in.^{2} tensile strength and 28 per cent elongation. Schirmeister, however, stated that alloys containing 9 to 12 per cent cobalt possess the greatest tensile strength. Brinell hardness and specific gravity increased with cobalt content. Daniels finds that cobalt carries its peculiarities over to ternary and quarternary alloys. One per cent cobalt added to the 4 per cent copper-aluminum alloy increased the piping tremendously, while the tensile strength, elongation, and Brinell improved from 17,780–4.0–44 to 23,390–6.0–47, respectively. The sand-cast 2 per cent ternary alloy had inferior properties of 20,760 lbs./in.^{2} tensile strength, 3.3 per cent elongation, and 50 Brinell with heavy shrinkage and coarsely crystalline fracture. The addition of 1 per cent silicon to 4.75 per cent copper counteracted the shrinkage due to 0.5 per cent cobalt. Quenching and aging binary alloys containing 0.5 and 2.0 per cent cobalt was without beneficial effect.

Alloys of higher cobalt content are reported from Germany (59c), the more common composition being alloys of 8 to 10 per cent cobalt to which either 1.2 per cent tungsten or 0.6 to 1 per cent molybdenum are added. In this report, the cobalt rich alloys are stated as preferable for casting, the lower cobalt contents for forging and rolling. It is said that as the cobalt content of the tungsten alloy reaches the upper limits, the rolling properties and tensile strength increase. The same results are obtained with the molybdenum alloys except that the hardness is somewhat less than with the corresponding tungsten alloys.

Webster (59b) states that cobalt gives the same effect as nickel and shows no advantages over it.

(10) Chromium (fig. 47).—These alloys have been studied by Sisco and Whitmore (60a), who report that they have heavy shrinkage, which prevents their use for casting thin sections. Chromium exercises a hardening effect on aluminum in the cast condition. In the 1 per cent alloy the ultimate strength is increased approximately

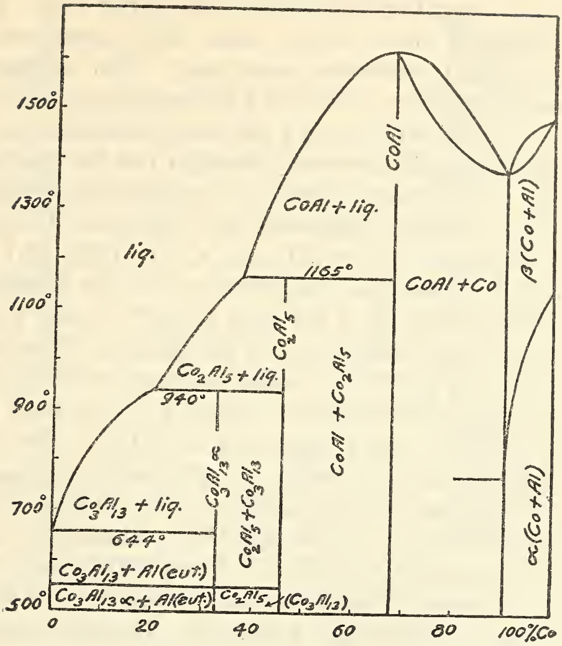

FIG. 46.—*Cobalt-aluminum system.* (*Gwyer, 59e*)
(See text for comment)

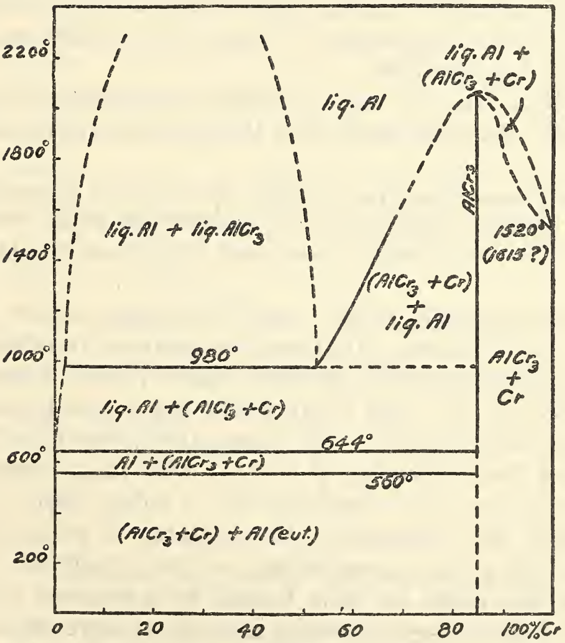

FIG. 47.—*Chromium-aluminum system.* (*Guillet, 61d*)

35 per cent, the elongation being decreased 50 per cent. The Brinell hardness is increased about 35 per cent. Heat treatment does not improve the physical properties in any way. The addition of chromium decreases brittleness. Beyond 3 per cent chromium the crystals are coarse (3a). The alloys up to 4 per cent chromium may be rolled at 500° C., giving greatly increased strength but low ductility.

(11) COPPER.—The constitution of the copper-aluminum alloys has been studied by Gwyer, Carpenter and Edwards, Curry, Guillet, Obtani and Hemmi, and others (61 j, s, t, v, w). (Fig. 48.) The solubility of copper in aluminum was given in 1919 by Merica, Waltenberg, and Freeman (61p) as 4 per cent at 525° C. and 1 per cent at 300° C. In 1921 Rosenhain (61m), of the National Physical Laboratory, gave 5 per cent at 540° C. and 3 per cent at 20° C., and in the same year Obtani and Hemmi gave values of 4.8 per cent at 525° C., 2.6 per cent at 460° C. and 1.5 per cent at 420° C. New data (61a) show that the solubility of copper in aluminum decreases rapidly with falling temperature from over 5½ per cent copper at 548° C. to about 2 per cent at 430° C. (See fig. 101.) The rate of decrease of solubility slows from 430 to 300° C. From 300 to 200° C. there is slight change. The solubility at normal temperatures is given in this new work as less than one-half of 1 per cent. Hardness measurements with a 5 mm ball, 125 kg load, gave the following results for a 4.05 per cent copper alloy: Chill cast, 44; slowly cooled, 39; chill cast and slowly cooled from 540° C., 30.4; chill cast and quenched from 540° C., aged at room temperature 1 year 65.8; subsequent aging at 200° C. for 9 days gave 68.

This is one of the few cases in which equilibrium relations have been studied in an alloy made with the pure, electrolytically refined aluminum.

Since the aluminum-copper alloys are the most important of the commercial casting alloys they will be described under that heading, page 161. They will also be considered under heat-treatable alloys, page 255.

X-ray investigations of the copper-aluminum alloys by Jette, Phragmen, and Westgren (61d) confirm previous knowledge that at ordinary temperature four different stable phases appear in this system. (See fig. 1.) The $CuAl_2$ phase has a tetragonal structure with an axial ratio of 0.805. The elementary prism is body centered and contains four molecules of $CuAl_2$. The phase present in the range 16 to 25 per cent aluminum has a cubic lattice. In the 16 per cent alloy the elementary cube contains 52 atoms and in the 25 per cent alloy the corresponding number is only 49. The solutions within the range are thus formed by a complex substitution. The curve of the change of density is in closest agreement with that obtained by supposing that three copper atoms in the lattice are replaced by two aluminum atoms. A photogram of a quenched

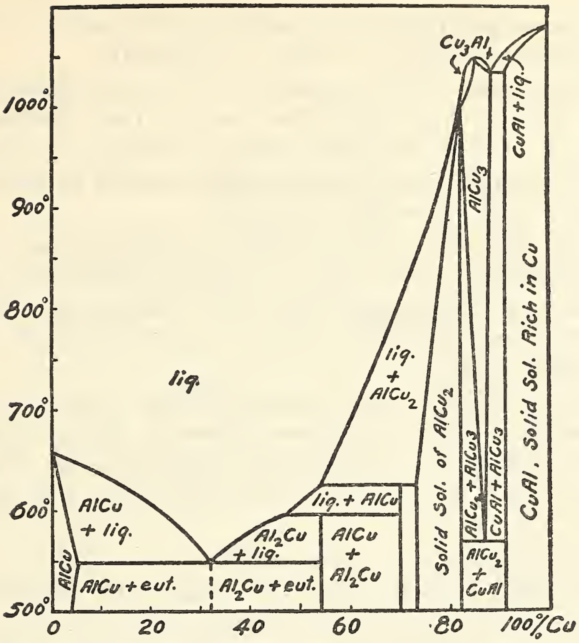

FIG. 48.—*Copper-aluminum system. (Guillet, 61a, Curry, 61v, Dix and Richardson, 61a)*

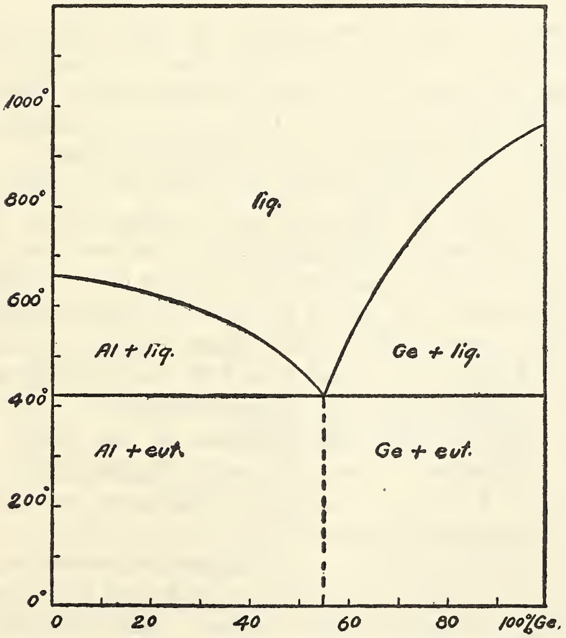

FIG. 49.—*Germanium-aluminum system. (Kroll, 62a)*

specimen containing 12.5 per cent aluminum showed lines corresponding to a phase stable only at higher temperature.

(12) GERMANIUM.—The properties of the aluminum-germanium series (fig. 49 after Kroll (62a)) have not yet been described. Since germanium is in some properties similar to silicon, in others similar to tin, it is possible that interesting alloys might be produced were the metal available in sufficient quantity.

(13) GOLD (fig. 50).—Light alloys of aluminum and gold have not been described. The alloys at the gold end of the series have been studied by Saeftel and Sachs (3c). Regelsberger (3d) states that the 6 per cent gold alloy is white, 10 per cent gold violet, 21.5 per cent gold purple.

(14) IRON.—The iron-aluminum alloys (fig. 51) have been studied by Schirmeister (64j), Guillet and Portevin (64h), Tamman and Sotter (64f), Kurnakow, Urassow and Grigoriero (64i), Krause (64g), Czochralski (64e), and Masing and Dahl (64a), and recently by Dix (64c).

The binary light alloys of iron and aluminum find no commercial employment and are not suitable for engineering structures (64d). The alloys may be made by the direct addition of iron to molten aluminum at about 1,000° C., by the addition of intermediate Fe–Al alloys to the melt, or by the thermit process whereby Fe_2O_3 is reduced by adding it to aluminum (64d).

The rolled alloys have been studied by Schirmeister (64j) and by Czochralski (64e). Czochralski states that iron affects the rolling of aluminum only in that more power is required and less bending to prevent tearing at the edges. He states that ordinarily a high content of iron is not found around rolling edge defects.

The addition of small percentages of iron up to 2 per cent raises the tensile strength in sand and chill castings (2d). The tensile strength is raised more rapidly with up to 1 per cent iron than by the same amount of copper, but from 0 to 2 per cent it results in little increase of strength and above 2.5 per cent iron the strength falls rapidly (64d), though Webster (64b) states that the strength increases slowly up to 4 per cent Fe and then falls slowly while the ductility falls rapidly. The ductility of cast alloys is low.

Electrical conductivity and hardness of the alloys have been studied by Kurnakow, Urassow, and Grigoriero (64i), while the electrochemical behavior of alloys of high-iron content has been studied by Tamman and Sotter (64f).

Masing and Dahl (64a) have investigated the apparent expansion of aluminum-iron alloys on freezing as evidenced in the exudation of metal through cracks as an ingot freezes. They found the expansion to be only apparent and to be caused by the passing of gases from the solution, hydrogen being the most soluble in iron-aluminum alloys.

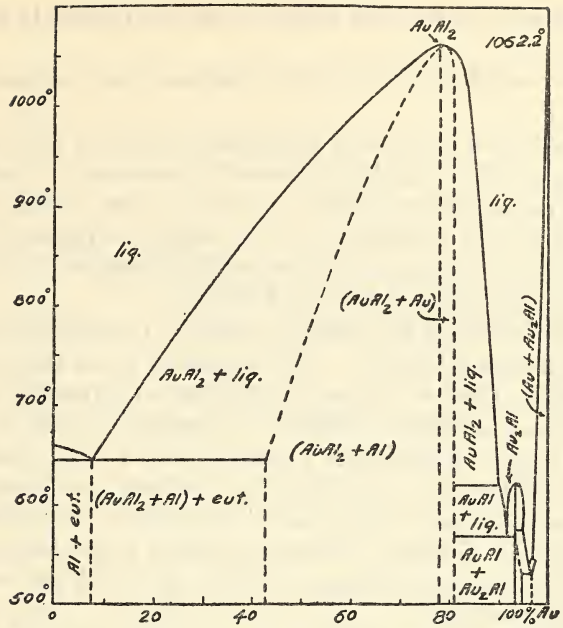

FIG. 50.—*Gold-aluminum system.* (*Bornemann 63a, Heycock and Neville, 63b, Corson, 2a*)

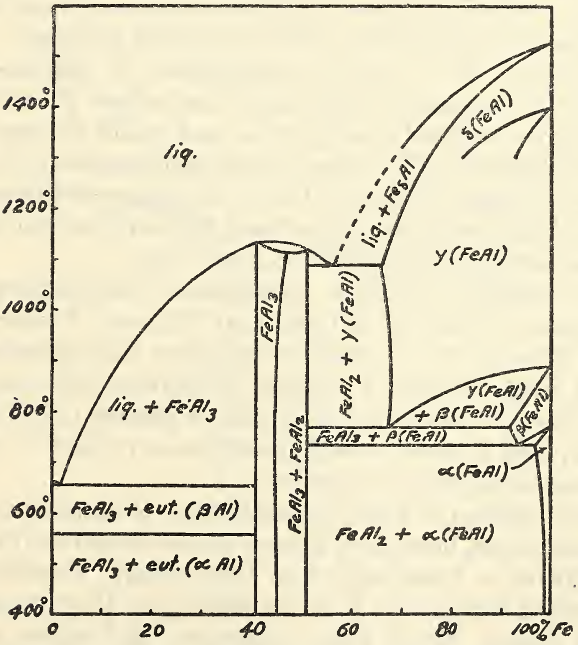

FIG. 51.—*Iron-aluminum system.* (*Guillet, modified after Dix, 64c*)

The experiments showed the alloys to be too porous to be of practical use.

The high-iron alloys of aluminum find some use as deoxidizers for steel.

Iron is used as an intentional hardening element in some aluminum-copper alloys, and is regularly present in amounts of, say, 1½ per cent in die-casting alloys which are made from metal continually held molten in iron melting pots. Its action as impurity or intentional addition in commercial alloys of aluminum with other metals will be dealt with under commercial alloys.

(15) Lead.—Lead is not soluble in molten or solid aluminum, and forms no compounds with it. When present as an impurity, it appears in small globules, themselves lacking in strength, so that the strength of the aluminum alloys is impaired. Lead is therefore considered a most undesirable impurity and is never intentionally introduced. When it is introduced by accident, as through the use of borings contaminated with lead alloy borings, its action is detrimental, although Webster (3a) states that in pure aluminum it has no bad effect but no advantages, and that up to 0.5 per cent, it may even increase ductility.

On account of the great difference in specific gravity of aluminum and lead, lead present as impurity tends to collect at the bottom of the melting pot and to make the inhomogeneous mixture of the two metals taken from the bottom useless for casting purposes.

(16) Lithium.—In a recent investigation of lithium-aluminum alloys (fig. 52), Assmann (66d) found that alloys of more than 10 per cent lithium oxidized quickly in air and would decompose water, giving off hydrogen. The chips ignited spontaneously in air. The alloy of 12.1 per cent lithium had an almost glassy brittleness.

At normal temperatures 2.2 per cent lithium goes into solid solution in aluminum, and at 598° C., 3.5 per cent.

With the addition of lithium to aluminum the hardness increases to a maximum of 130 for 12.1 per cent lithium. A sharp increase occurs for lithium alloys after overstepping the saturation limits. On adding equal amounts by weight of lithium and magnesium to aluminum the hardening due to lithium is greater than that due to magnesium, but if equal atomic percentages of each is added the hardness due to magnesium is greater.

The use of lithium in heat-treatable alloys of aluminum is a fairly recent development, being used in some of the Scleron alloys developed by Metallbank u Metallurgischen Gesellschaft, Frankfort, A. M. The analysis of these alloys is not available, but they are understood to contain copper, nickel, zinc, manganese, and silicon as well as lithium (66b). The effect of the lithium is said to be somewhat similar to that of magnesium in duralumin (66b). The improvement

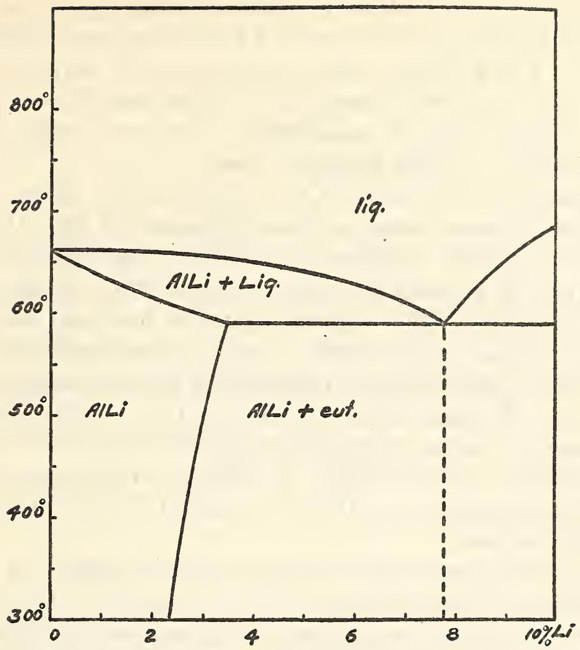

Fig. 52.—*Lithium-aluminum system.* (*Assman, 66d*)

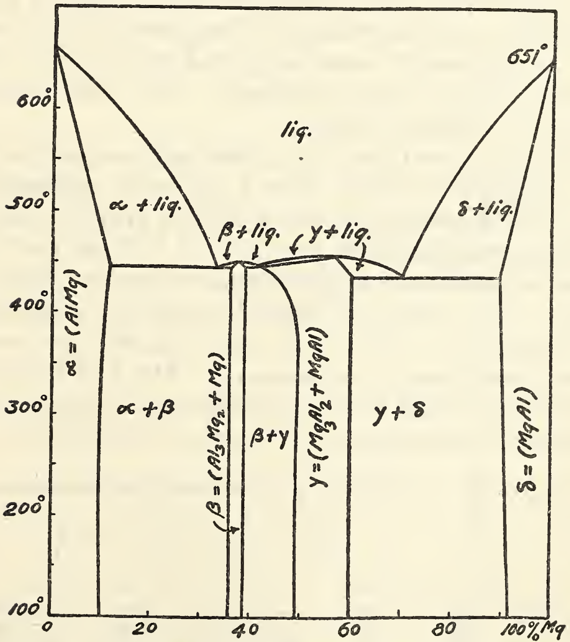

Fig. 53.—*Magnesium-aluminum system.* (*Hanson and Gaylor, 67a*)

is thought to be related to the silicon present, the hardening increasing with increasing mixture of a Li_3Si compound similar in effect to Mg_2Si. The Scleron alloys are said to be strong and highly elastic. Assmann (66e) claims that 0.3 per cent lithium is sufficient for the improvement of commercial aluminum, while 1 per cent lithium spoils the alloy in almost all cases.

Heat-treated Al–Li, Al–Li–Cu and Al–Li–Zn alloys showed results similar in many cases to those obtained for Mg–Al alloys. In many alloys a slight increase of hardness was obtained which increased with the annealing temperature and was the greatest for the quenched material. The highest value for hardness was always in the region of the saturation limit. Aging of the annealed and quenched alloy at 100° C. exerted little influence on the hardness, but aging at 200° C. was detrimental in all cases. The sensitiveness of heat-treated alloys at aging temperatures higher than 100° C. appears to be an essential characteristic of lithium-containing alloys. The effect of heat-treatment on Al–Li–Cu and Al–Li–Zn alloys is also discussed by Assmann.

In the present stage of knowledge of lithium alloys, it is doubtful if properties are being obtained by its use superior to those obtainable with other alloys that are cheaper and more easily handled.

(17) MAGNESIUM (fig. 53).—The use of alloys of aluminum with magnesium is limited to the two upper ranges, that is, to aluminum alloys containing small percentages of magnesium (up to about 6 per cent) and to magnesium containing small percentages of aluminum (up to about 12 per cent aluminum). For these, see page 298. These alloys are extremely light.

At the aluminum end the 2 to 10 per cent magnesium alloys are used for sand castings (2d). The 5 per cent magnesium alloy is used for electrical castings, having a specific gravity when sand cast of 2.5, tensile strength, 20,000 lbs./in.^{2}, 0.5 to 2 per cent elongation. Among the aluminum-rich aluminum-magnesium alloys are the Magnaliums, the analyses of typical American Magnaliums being shown in Table (34). The 12.7 per cent Mg, 85.9 per cent Al Magnalium has a coefficient of expansion $\beta = 23.8 \times 10^{-6}$ from 12 to 39° (2ii). The density of the 30 per cent Mg alloy is given by the American Magnesium Corporation as 2.00 g/cc or 124.8 lbs./ft.^{3}

TABLE 34.—*Composition of typical American Magnaliums*

Sample	Cu	Si	Fe	Mg	Mn	Ni	Al	Specific gravity
1	0.25	0.23	0.50	4.75	0.06	----------	Diff.	2.64
2	.25	.18	.50	5.58	.06	----------	Diff.	2.67
3	2.00	.35	.80	2.75	.03	0.97	Diff.	2.67
4	.67	.56	.92	1.99	.02	.57	Diff.	2.69
5	1.78	----------	.61	.97	----------	----------	----------	----------

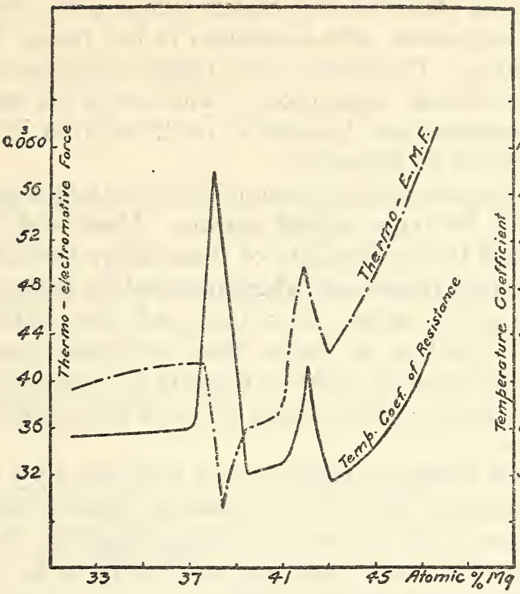

Fig. 54.—*Thermoelectric force and temperature coefficient of resistance of Al-Mg alloys.* (*Halstead and Smith, 105b*)

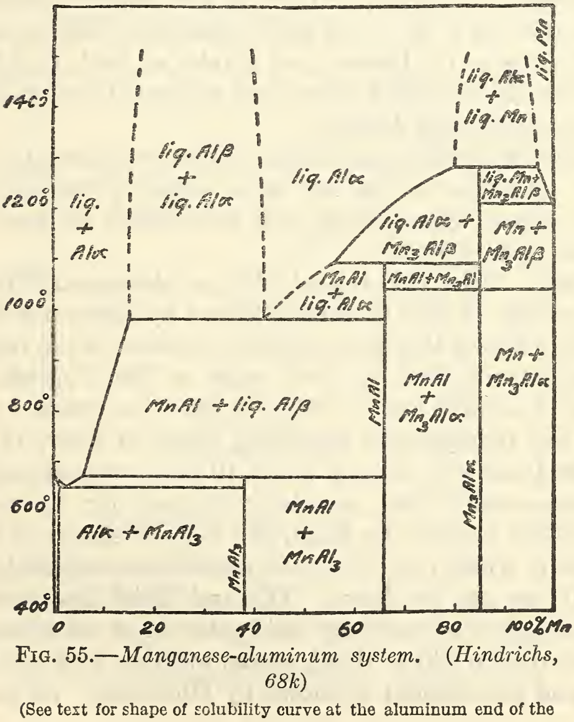

Fig. 55.—*Manganese-aluminum system.* (*Hindrichs, 68k*)

(See text for shape of solubility curve at the aluminum end of the diagram)

Mehl (105cc) and Halstead and Smith (105b) have worked with these alloys of magnesium with aluminum in the range of 32 to 48 per cent magnesium. The alloys in this range are porous and brittle and have no commercial applications. The curves for temperature coefficient of resistance and thermal e. m. f. as given by Halstead and Smith are shown in Figure 54.

The alloys of magnesium and aluminum have attained some recognition as suitable for large optical mirrors. Mach and Schumann (30a) have studied the adaptability of these alloys for this purpose. The alloy containing 46 per cent aluminum and 54 per cent magnesium is the best of the series. It is hard, and when polished has a reflecting power equal to or better than a silvered glass mirror. Special precautions must be taken to prevent the formation of blowholes. This is done by melting under a flux of salts, preventing the absorption of gas.

Waltenberg and Coblentz (105dd) found that the alloy best combining high reflectivity with fair resistance to tarnish corresponded to the composition of the compound Al_3Mg_4 alleged by Grube (67c) to be present in this system, and also considered to be present by Merica, Waltenberg, and Freeman (67b).

Besides these two alleged compounds various others have been thought to exist, but Hanson and Gayler find only two compounds, Al_3Mg_2 and Mg_3Al_2. Halstead and Smith consider, on the basis of the thermal e. m. f. and the temperature coefficient of resistance of alloys (fig. 54) in Hanson and Gayler's β field, that this region consists of two fields instead of one and suggest the possibility of the existence of a compound Al_5Mg_3.

The middle of the diagram seems still to be speculative, but the equilibrium relations at the two ends, covering the commercially used binary alloys, appear fairly well established, at least as to the general form of the curves.

It is probable (107a) that the solubility of aluminum in magnesium is slightly greater at 435° C. than is shown by Hanson and Gayler's diagram (fig. 53) and that the solubility decreases more rapidly with falling temperature; that is, both edges of the diagram are very similar, and a similar opportunity for heat treatment by solution quenching and precipitation hardening exists in alloys of about 10 per cent aluminum and those of about 10 per cent magnesium.

(18) MANGANESE.—The complete diagram for the manganese-aluminum alloys as given by Hindrichs (60c) is shown in Figure 55. On the scale to which it is drawn, the modification added by Dix and Keith (68a) can not be shown. Dix and Keith find that the line separating the field of complete solid solution of manganese in aluminum from that in which $MnAl_3$ exists, together with solid solution, is curved, and not straight as shown by Hindrichs. At the eutectic

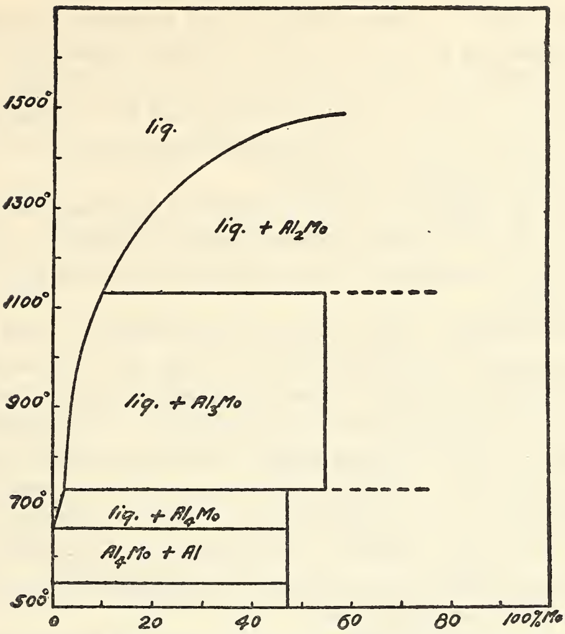

FIG. 56.—*Molybdenum-aluminum system.* (*Reiman, 69d*)

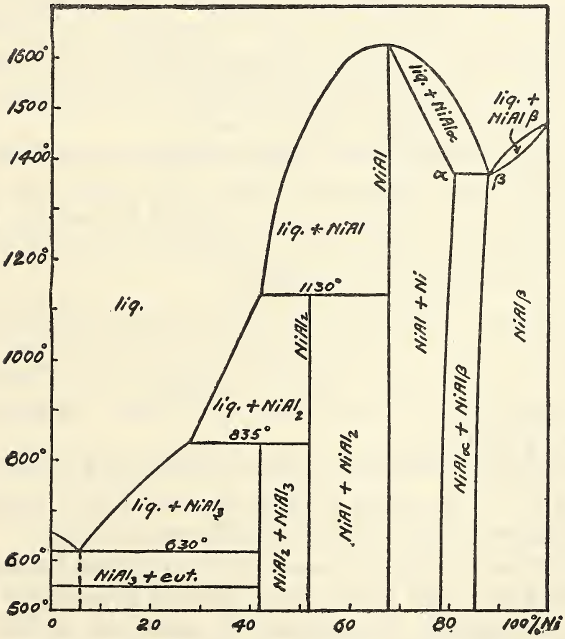

FIG. 57.—*Nickel-aluminum system.* (*Gwyer, 70h*)

temperature, 651° C., about 0.65 per cent manganese is in solution, but with decreasing temperature the solubility falls to less than 0.23 per cent at 550° and to less than 0.14 per cent at 200° C.

For comment on some unusual features of the mechanism of the change of solubility and the resultant microstructure, the paper by Dix and Keith should be consulted.

The alloys of aluminum with manganese find limited use in cast and rolled form and are described on pages 143 and 185. As a minor alloying element, manganese finds use in duralumin and in a number of casting alloys.

(19) MOLYBDENUM.—The alloys of molybdenum with aluminum have been studied by Reiman (69c, d) (fig. 56), who attempted to produce a sulphur-free alloy through aluminothermic reduction of the ore, but found this method unsuccessful. Investigations of the binary alloys, as well as ternary alloys, with copper, nickel, magnesium, and zinc appeared to show that there was no very great advantage to be gained by the use of molybdenum. The molybdenum appeared to exert no very great influence on the physical properties, while the alloys appeared difficult to cast and too brittle to roll. The alloys have no commercial applications.

(20) NICKEL.—As will be seen by comparing Figures 48 and 57, the nickel-aluminum system bears a marked similarity to that of copper-aluminum. Because of the higher cost of nickel and the greater difficulty of alloying it with aluminum on account of its higher melting point, nickel has been supplanted by copper as an alloying element for aluminum, although were no copper available the nickel-aluminum alloys would be useful.

(21) NIOBIUM.—Niobium-aluminum alloys are said to be more resistant to HCl and concentrated H_2SO_4 than pure aluminum (3d).

(22) PHOSPHORUS.—Phosphorus is claimed to increase the tensile strength of aluminum (3d) and the resistance to corrosion, but it is doubtful if either statement is correct.

(23) PLATINUM.—The platinum-aluminum system has been studied by Chouriguine (73a, b) whose diagram, with the addition of dotted lines as given by Corson, is given in Figure 58. The two intermetallic compounds formed are $PtAl_3$ and $PtAl_2$. An eutectic occurs at 9 per cent platinum.

(24) POTASSIUM.—Potassium, like sodium, is insoluble in aluminum. (Fig. 59.) The utility of these elements in the "modification" of the Al-Si alloys will be referred to under that system.

(25) SELENIUM.—The selenium-aluminum system has been studied by Chikashige and Aoki (75a),whose diagram is shown in Figure 60. The alloys are readily decomposed by moist air giving hydrogen selenide. Solid solutions are not formed but there are two eutectics.

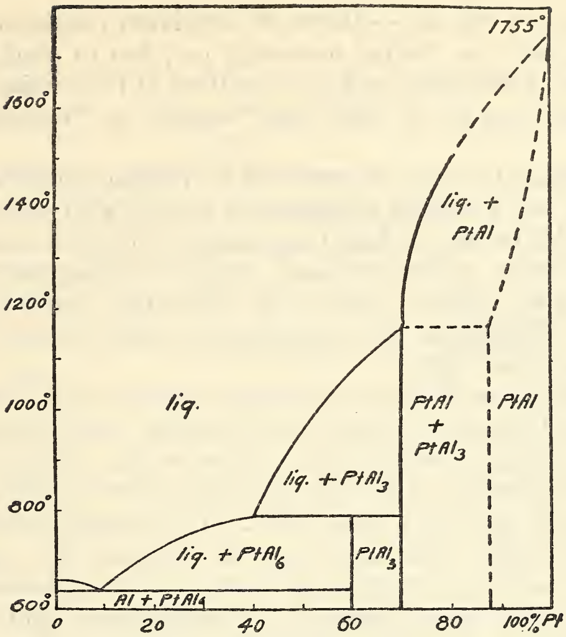

FIG. 58.—*Platinum-aluminum system.* (*Chouriguine, 73a, Corson, 2a*)

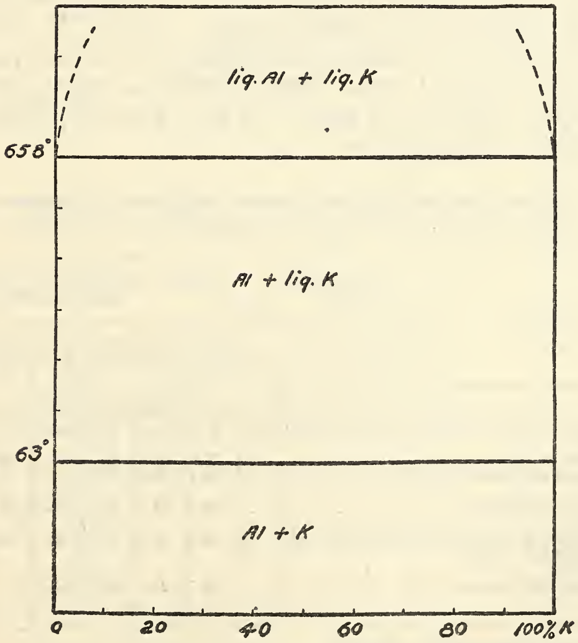

FIG. 59.—*Potassium-aluminum system.* (*Guillet, 68l*)

(26) SILICON (fig. 61).—Alloys of aluminum containing up to 15 per cent silicon are finding increasing use, due to their fluidity in pouring, small shrinkage, and the soundness of the casting produced. These alloys may be in either the "normal" or "modified" conditions.

The normal alloy may be produced by melting silicon with aluminum (76m) or by melting aluminum in contact with pure silica sand in the electric furnace at high temperatures (76v). An intermediate silicon-rich alloy is first produced, which is subsequently used for making up the alloys. The 50:50 silicon-rich hardener melts at 1,050° C. Castings of the normal alloys usually contain from 5 to 10 per cent silicon (76m).

The addition of silicon to aluminum makes manipulation easier, diminishes shrinkage, porosity, hot shortness, and increases fluidity (76j). In binary metals silicon improves the ultimate strength rapidly for additions up to 5 per cent, then slowly to a maximum of 22,000 pounds at 11 per cent silicon. The strength declines slowly but continuously. The alloys have a relatively low proportional limit and modulus of rupture in bending. The aluminum silicon alloys are lighter than aluminum and considerably lighter than the copper-aluminum or zinc-aluminum alloys (76k).

The densities of the normal alloys have been studied by Edwards (76bb) and range between 2.689 for the 0.11 silicon alloy at 20° to 2.631 for the 14.95 per cent silicon alloy. At 200° C. the 0.11 per cent silicon alloy has a density of 2.653, the 7.81 per cent silicon alloy 2.647 as compared with 2.680 at 20°, and the 11.63 per cent silicon alloy has a density of 2.661 to 2.663 at 20° C., 2.626 to 2.635 at 200° C. and 2.560 at 563° C.

TABLE 35.—*Chemical compositions and average coefficients of expansion of aluminum-manganese and aluminum-manganese-copper alloys*

Laboratory No.	Material	Composition					Average coefficients of expansion per degree centigrade						
		Al[1]	Mn	Cu	Si	Fe	20 to 100°	20 to 200°	20 to 250°	20 to 300°	20 to 400°	20 to 500°	20 to 600°
		P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
S845[2]	3 S sheet, rolled to ¼ inch.	97.78	1.05	0.19	0.41	0.57	23.8	25.7	26.1	25.9	26.5	27.5	28.6
S846	Duplicate of S845	-----	-----	-----	-----	-----	23.7	25.6	25.9	25.5	26.1	27.4	28.4
S837	Manganese alloy, sand cast.	96.73	1.80	.23	.40	.84	23.1	24.2	24.7	25.5	25.9	27.0	27.9
S838	Cut from same bar as S837.	-----	-----	-----	-----	-----	23.1	24.4	25.2	25.8	26.4	27.5	-----
S839[3]	Manganese, copper (McKinney) alloy, sand cast.	96.20	1.08	1.91	.30	.51	23.6	25.2	26.7	26.9	26.8	27.5	-----
S840[4]	Cut from same bar as S839.	-----	-----	-----	-----	-----	23.7	24.2	25.7	26.8	-----	-----	-----

[1] Per cent aluminum determined by difference.
[2] Brinell hardness No. 56.
[3] Used at the Washington Navy Yard to a considerable extent.
[4] Sample tested to 300° C. in an oil bath. All other samples of this series were heated in an air furnace.

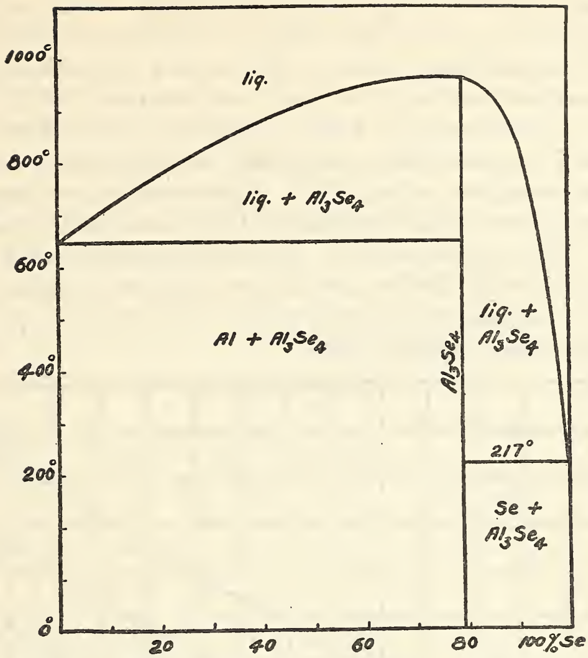

FIG. 60.—*Selenium-aluminum system. (Chikashige and Aoki, 75a)*

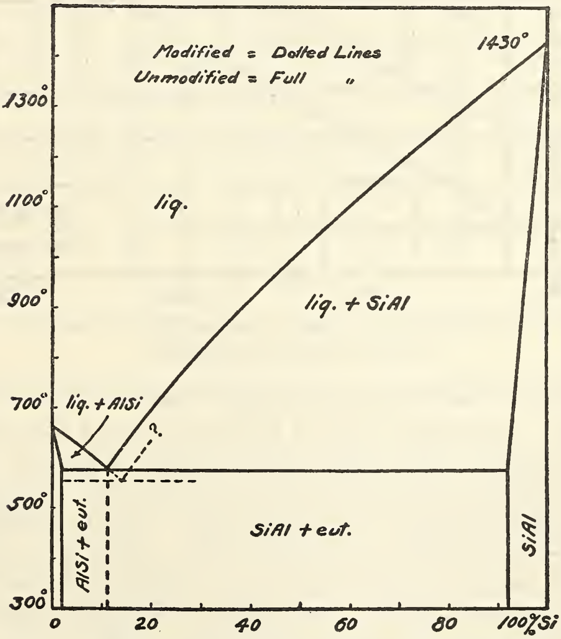

FIG. 61.—*Silicon-aluminum system. (Fraenkel, 76; Archer and Kempf, 76d)*
(The dotted lines represent in a qualitative way conditions when undercooling takes place, as in the presence of sodium)

As silicon contracts on melting and expands during solidification the shrinkage of many of these alloys is less than that of pure aluminum. The shrinkage of the 11.63 per cent (eutectic) alloy is 3.8 per cent as compared with 6.6 per cent for pure (99.75 per cent) aluminum. The shrinkage of the 7.8 per cent silicon alloys is 5.6 per cent. The 7 per cent silicon alloy may be cast around a steel liner and will not crack on cooling (76s). The coefficients of expansion of some silicon alloys as determined by this bureau (28c) are given in Table 36. (See figs. 62 to 64.) This freedom from cracking in the mold combined with the low specific gravity have brought the silicon alloys into prominence in recent years. The very low proportional limit is a drawback to these alloys.

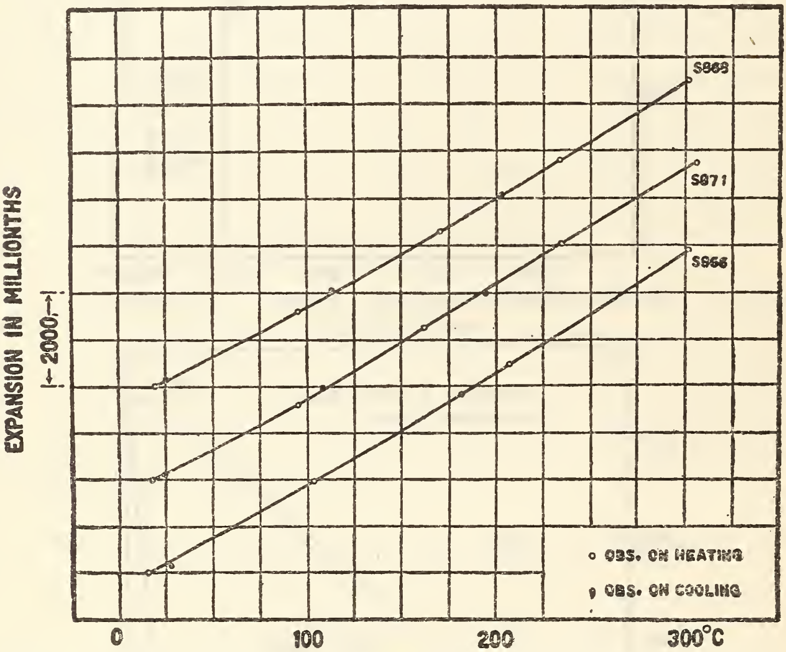

Fig. 62.—*Linear expansion of three aluminum-silicon alloys (4, 7, and 10 per cent silicon, respectively)*

The electrical conductivity of the 5 per cent silicon alloy is 35 (76k), of the 12 per cent silicon alloy 34 (76t), and the 13 per cent alloy 40 (76k) as compared with 56 per cent for pure aluminum (76k) when copper is taken as 100. The thermal conductivity is slightly higher for these alloys than for the No. 12 copper-aluminum alloy (76t).

The high-silicon alloys are brittle and can not be worked (76v). The 0 to 10 per cent silicon alloys are workable and ductile (76v), the 5 to 7 per cent silicon alloys being considered best for rolling (76s). The machining qualities are not so good as for the No. 12 alloy as the metal drags under the tool and excess of silicon tears out (76t).

The "modified" alloys first developed by Pacz in 1920, and described in patents (96a, k, l, o, n) have also been described by Jeffries (76u), Edwards and Archer (76n), Archer and Kempf (76d), Guillet (76r), Basch and Sayre (76w), Grogan (76e), Gwyer and Phillips (76f), Stockdale and Wilkinson (76h). These modified alloys may be produced electrolytically (76bb) by the addition of small percentages of sodium or potassium, or both, by the addition of the fluorides of the alkaline earths. Arsenic, antimony, and bismuth and cadmium also act as modifying agents (76f) and the use of antimony and bismuth for this purpose has been patented by Edwards. Usually, however, the sodium, potassium, or alkaline earth fluorides are used. The modification process is carried out almost entirely on the 13 per cent silicon alloy (76d). The process involves the suppression of the primary silicon, refinement of the structure of the "eutectic" and shifting of the apparent "eutectic" toward a higher silicon content (76d). X-ray studies of structures of the normal and modified alloys made by Jeffries (76u) and Edwards and Archer (76n) show

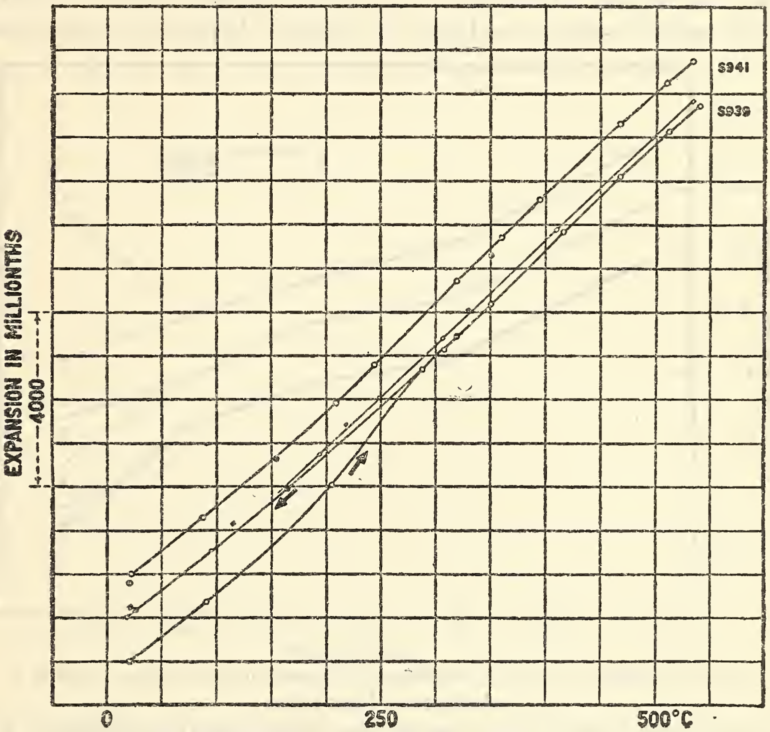

Fig. 63.—*Linear expansion of a normal and a modified aluminum-silicon alloy (12.5 per cent silicon)*

The observations on first tests are represented by circles and the observations on a second test by squares. The light symbols represent observations on heating and the dark symbols those on cooling.

that the same pattern is obtained for both the normal and modified alloys, the pattern of free silicon being superposed upon that of aluminum, no intermetallic compounds being formed. Obtani (76g) regards the modified alloys as ternary alloys of aluminum, silicon, and sodium.

Several theories have been advanced to account for the difference in structure (figs. 65 and 66) and properties produced by modification. One of these is based on the insolubility of sodium in solid aluminum, the sodium being precipitated out and being considered to offer mechanical obstruction to crystal growth (76n). Another theory regards sodium as being in colloidal dispersion in the alloy, being absorbed preferentially by the silicon nucleus and inhibiting its growth. The slow rate of crystallization of silicon relative to aluminum is considered to be retarded even more by the continual condensation of a film of sodium on the silicon nuclei (76n).

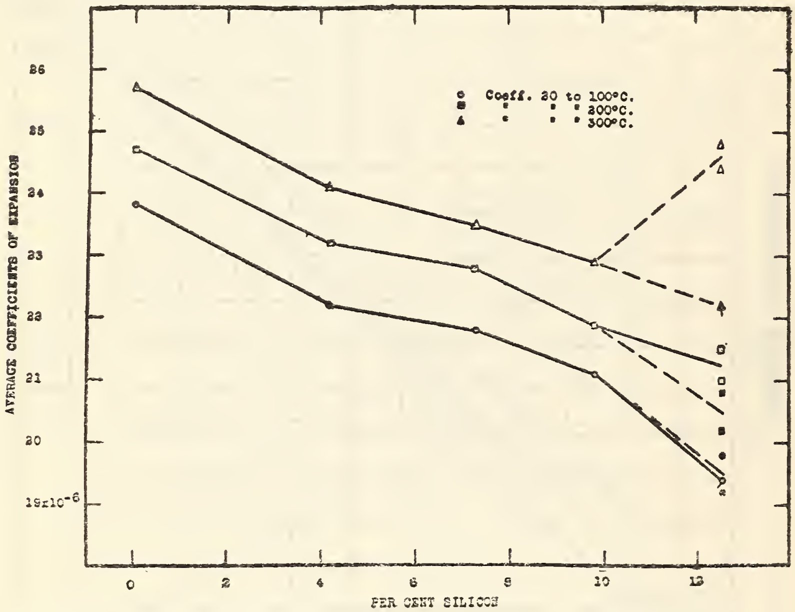

FIG. 64.—*Relations between coefficients of expansion and silicon content of aluminum-silicon alloys*

The light symbols represent values for normal alloys and the dark symbols for modified alloys. Where the values of two alloys are equal, a tagged symbol was employed as shown.

In the more recent work of Gwyer and Phillips (76f) it is suggested that at some stage during the modification process the silicon and aluminum aggregates will be of "colloidal dimensions." The rate of coalescence of these particles may be accelerated or diminished by the addition of appropriate reagents, and the authors believe the modifying agents to act as these colloid protectors. They do not consider the protector necessarily to be metallic sodium, the nature being regarded as unsolved.

FIG. 65.—*Structure of 13 per cent silicon alloy, unmodified. × 100—unetched*

Shows silicon-aluminum eutectic and primary particles of silicon in a 13 per cent silicon-aluminum alloy. Tensile strength, 20,000 lbs. per sq. in., elongation 2.5 per cent. (Aluminum Company of America)

FIG. 66.—*Structure of 13 per cent silicon-aluminum alloy, modified. × 100—unetched*

Refined silicon-aluminum eutectic and primary dendrites of aluminum solid solution in a 13 per cent silicon-aluminum alloy modified with Pacz flux. Tensile strength 29,500 lbs. per sq. in., elongation 9.5 per cent. (Aluminum Company of America)

Table 36.—*Average coefficients of expansion and length changes of aluminum-silicon alloys*

Laboratory No.	Material	Chemical analysis				Average coefficients of expansion per degree centigrade						Changes in length due to heat treatment received during test
		Aluminum[1]	Silicon	Iron	Copper	20 to 100° C.	20 to 200° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.	300 to 500° C.	
		P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	*Per cent*
S866 [2]	4 per cent silicon alloy, sand cast, heated to 400° C., and cooled in furnace	95.00	4.15	0.52	0.33	22.2	23.2	24.1	------	------	------	−0.01
S871 [2]	7 per cent silicon alloy, etc	91.98	7.28	.47	.27	21.8	22.8	23.5	------	------	------	+.00
S868 [2]	10 per cent silicon alloy, etc	89.47	9.81	.50	.22	21.1	21.9	22.9	------	------	------	+.00
S939	12.5 per cent silicon alloy cast in green sand	86.81	12.55	.56	.08	[4] 19.4 20.1	21.5 21.4	24.8 22.1	24.8 22.6	24.7 22.9	24.5 24.0	+.11 +.02
S940	Cut from same bar as S939					[4] 19.4 22.2	21.0 22.1	24.4 22.8	24.3 23.2	24.2 23.2	24.1 23.8	+.08 +.03
S941	Modified 12.5 per cent silicon alloy	Same as S939 except that it has had 0.1 per cent metallic sodium added to the molten metal just before casting.[3]				19.8	20.8	22.2	23.0	23.0	24.1	−.02
S942	Cut from same bar as S941					19.2	20.2	22.2	22.9	23.0	24.1	−.01

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[1] Aluminum by difference.

[2] Submitted by the engineering division, Air Service of the War Department, McCook Field, Dayton, Ohio. (Chemical analysis by Aluminum Co. of America.)

[3] This is according to the process described in United States Patent 1410461. J. D. Edwards, of the Aluminum Co. of America, states that this treatment results in giving the silicon particles a very high degree of dispersion. He also says that sample S939 (normal alloy) will show a rather coarse fracture, but sample S941 (modified alloy) will show a very fine fracture very much like that of steel.

[4] Values on this horizontal line were obtained on a second heating.

In the preparation of the modified alloys, when a fluoride reagent is used, the agent, consisting of an amount of flux equal to 3 per cent by weight of the metal treated, may be stirred into the molten aluminum-silicon alloy (76d). When metallic sodium is used, it is recommended by Archer and Kempf (76d) that the sodium be placed into the bottom of a preheated crucible and the molten metal poured onto it at a temperature of 775° C. These authors found that the amount of sodium required is definite for a given alloy and given casting conditions. The sodium requirement varies with the silicon content, rate of solidification, variation of temperature and time of standing before pouring. The tensile strength and elongation increase steadily to maximum values with time and then fall to values for the unmodified alloy, but the maximum tensile strength and maximum elongation do not occur at the same time, the elongation reaching its maximum before the tensile strength and decreasing more abruptly.

The effect of time after treatment on properties, effect of iron and effect of silicon on the physical properties are shown in curves (figs. 82 to 84) from the work of these authors. The effect of the modifying agent is lost if the molten metal stands too long before casting,

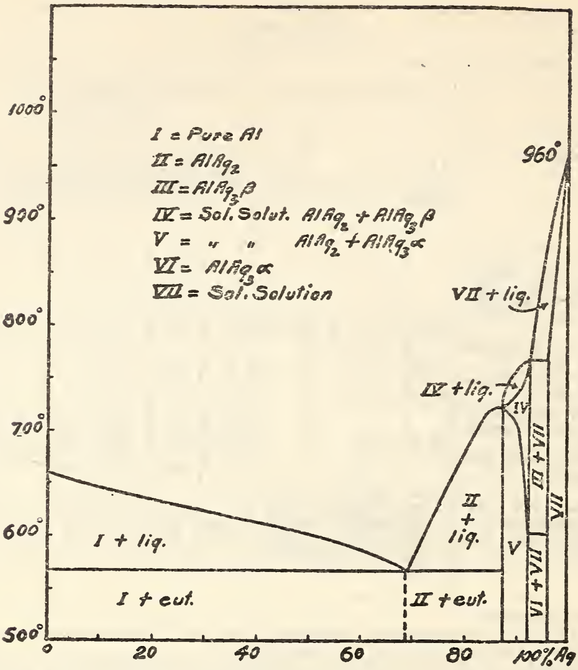

Fig. 67.—*Silver-aluminum system.* (*Petrenko, 77b, Corson, 2a*)

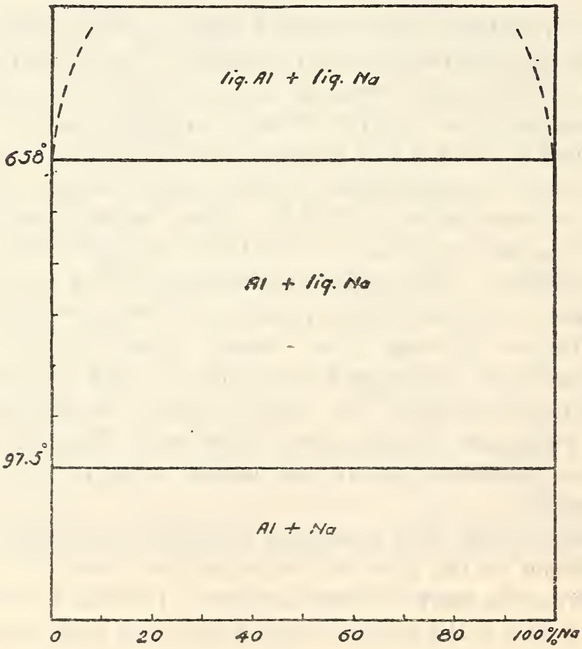

Fig. 68.—*Sodium-aluminum sustem.* (*Guillet, 68l*)

and it is lost on remelting. Pacz (96i) claims that manganese has a beneficial effect on the grain size of high-silicon alloys, and that by adding manganese during modification the effect is not lost on standing or remelting, while Parravano and Scortecci (76o) claim that the refinement obtained with copper, nickel, magnesium, and manganese is of a temporary nature.

(27) SILVER (fig. 67).—Silver gives aluminum greater hardness and tensile strength (3d), good working qualities, and chemical resistance. Kroll (77a) has studied the replacement of magnesium by silver in age-hardening alloys and found the effect of silver to be similar to that of magnesium due to the precipitation of $AlAg_2$, although the final hardness and strength is less because the initial strength is less. The strength of alloys containing both magnesium and silver is higher than that of magnesium-silicon-aluminum or silver-aluminum alloys because of presence of both $MgSi_2$ and $AlAg_2$. The alloys containing silver experience little improvement at room temperature, but must be aged at temperatures between 140 to 170° C. The maximum attainable strength of aluminum-silver alloys on aging is about 11,000 lbs./in.^{2} lower than the 5 per cent aged aluminum-copper alloys, while that of the aluminum-silver-magnesium alloys is about 7,000 lbs./in.^{2} lower than the strength of duralumin.

(28) SODIUM (fig. 68).—Sodium, like potassium, is insoluble in aluminum. Its use as a modifier has been discussed under the silicon-aluminum alloys.

(29) TANTALUM.—Tantalum-aluminum alloys are said to be more resistant to HCl and concentrated H_2SO_4 than pure aluminum (3d).

(30) TELLURIUM.—Although Chikashige and Nose (80a) have worked out an equilibrium diagram for the tellurium-aluminum system, Sisco and Whitmore (80b) have shown that aluminum forms a compound with tellurium which is entirely insoluble in liquid aluminum. The traces of telluride that remain are entrapped as segregations, and exert an exceedingly injurious effect upon the properties of aluminum.

(31) THALLIUM.—Like lead, thallium is not miscible with aluminum and forms no compounds with it. The diagram of the system as given by Doerinckel (81a) is shown in Figure 69.

(32) TIN (fig. 70).—Tin increases the tensile strength (3d) and gives sharp castings, decreasing piping (3d), but with too much tin the alloys are brittle and easily oxidizable so that a 15 per cent tin alloy falls to powder after a few days in the air (3d). The high-tin alloys have been studied by Losane and Carozzi (91z). Cold-rolling is successful up to 5 per cent tin (3a), hot-rolling is not successful above 200° C.

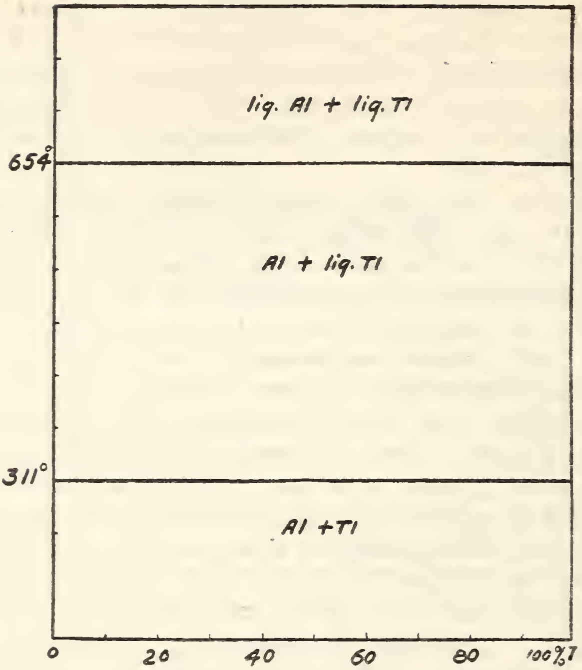

FIG. 69.—*Thallium-aluminum system.* (*Doerinckel, 81a*)

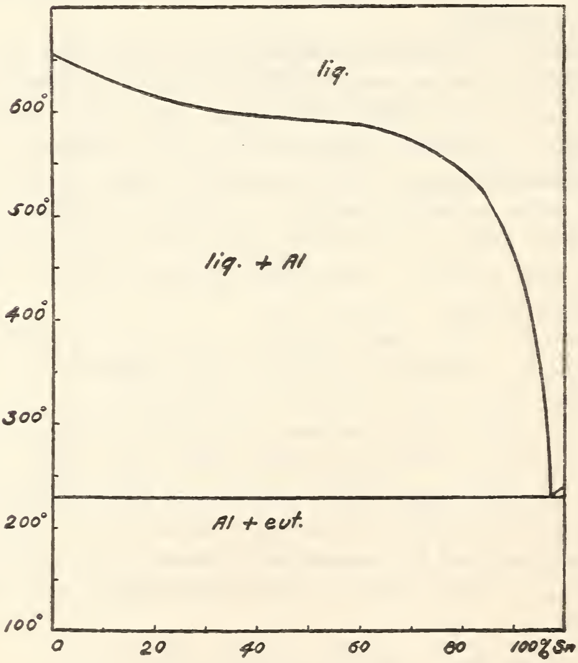

FIG. 70.—*Tin-aluminum system.* (*Gwyer, 82b*)

Tin in amounts below 2 per cent is used by some foundrymen in various casting alloys, such as those with copper, sometimes in an attempt to avoid cracked castings, sometimes to add ductility, or to give a whiter looking alloy. Some firms have used such an addition of tin in automobile crank-case castings, but the practice is generally discontinued. In view of the high price of tin, its use in aluminum alloys probably brings no advantage commensurate with the cost or which would not be obtained as readily by other means. On the other hand, a small amount of tin accidentally introduced by the use of scrap would ordinarily not be considered a very detrimental impurity.

Mortimer (82b) states that in England the alloy known there as 3–L–11, containing about 7 per cent copper, and practically identical with the American No. 12, may still contain up to 1 per cent tin, and the tin content was at one time specified, although "it is not quite clear why it was ever included."

(33) Titanium.—Titanium-aluminum alloys have been studied by von Erckelens (fig. 71) (83b), who states that alloys of over 0.5 to 1 per cent titanium show poorer tensile and working properties. Titanium used as a refining agent, he says, gives improved tensile strength and elongation, hardness, better workability, and increased resistance to corrosion. The electrical conductivity falls somewhat. The favorable effect of titanium is attributed by von Erckelens to reaction with the oxygen and nitrogen present. Manchot and Leber (83a) were unable to produce clean alloys with a titanium content of more than 37.3 per cent. They discuss the structure of the alloys and state that the hardness of the alloy increased with increasing titanium content.

Webster (3a) states that the alloys may be hot-rolled up to 6 per cent, and that the strength rises rapidly to 1 per cent and then slowly, the ductility falling in a similar manner.

(34) Vanadium.—Vanadium is said to improve the mechanical and chemical properties of aluminum (3d). Up to 4 per cent vanadium the alloys roll well at 500° C. (3a), the tensile strengths and hardness increasing up to 2 per cent, the ductility falling slowly. The diagram is shown in Figure 72.

Small amounts of vanadium have been used commercially in aluminum-copper alloys, with no appreciable effect one way or the other upon the properties.

(35) Zinc.—The constitution of the aluminum-zinc series has been studied by Rosenhain and Archbutt (85r), Shepherd (85t), Tanabe (85k), Isihara (85f, a), Hansen and Gayler (85m), and others.

In spite of the fact that this system has been studied by a large number of investigators, there is no close agreement as to the equilibrium diagrams determined by these workers. In practically all

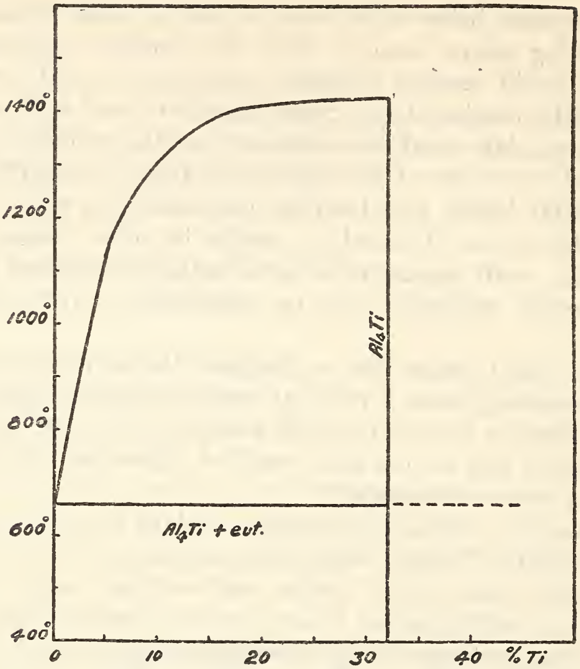

FIG. 71.—*Titanium-aluminum system.* (*von Erckelens, 83b*)

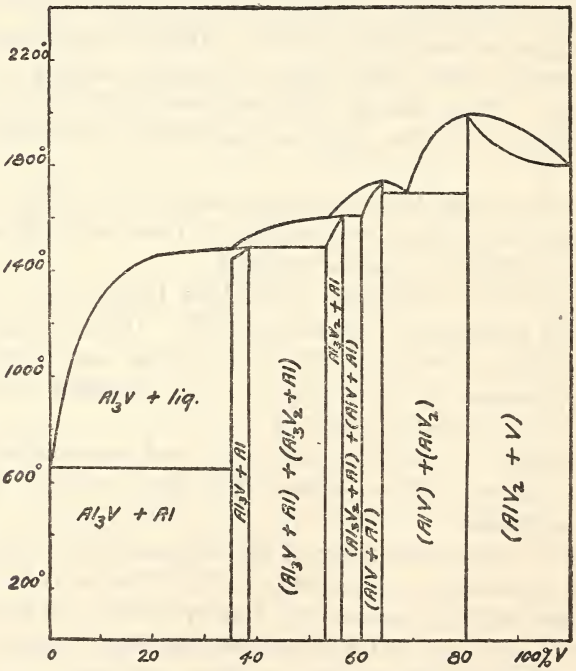

FIG. 72.—*Vanadium-aluminum system.* (*Corson's imaginary diagram, designed to represent facts found by Czako. This represents probabilities rather than actual data*)

of these diagrams there is a fair agreement on many points, but the exact shape and location of the limits of the field of solid solution of zinc in aluminum still remain a subject of controversy.

The diagram reproduced in Figure 73 is that of Isihara, who used the electro-resistance method to determine the diagram, making use also of microscopic examination, the dilatometric method, and X-ray analysis as supplementary methods. Tiedman (85d) states that the diagram of the aluminum-zinc system separates distinctly, between 2.5 and 5 per cent zinc, into two ranges which can be related to a "new solubility limit."

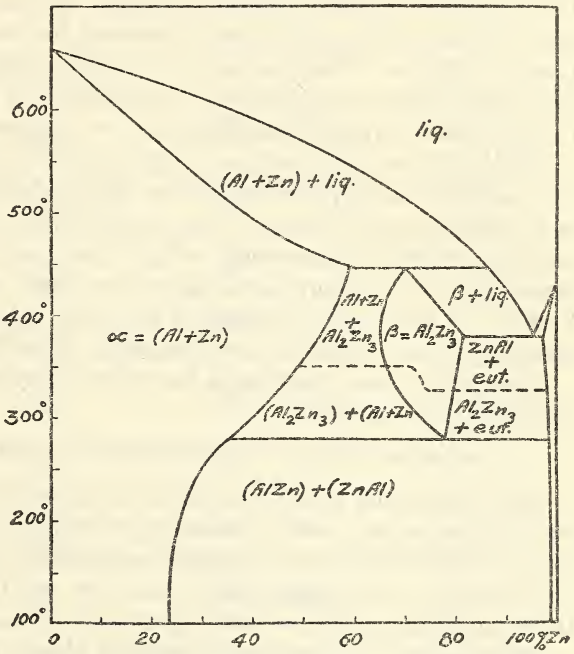

FIG. 73.—*Zinc-aluminum system.* (*Isahara, 85a*)

It is to be noted that the alloys from about 30 to 60 per cent aluminum are susceptible to heat treatment and age hardening.

(b) TERNARY ALLOYS OF ALUMINUM

Equilibrium diagrams for ternary alloys are often extremely complex, and most work upon the ternary and more complex alloys of aluminum has been confined to the alloys at the high aluminum corner of the triangular ternary diagram. The chief systematic work has been done by the National Physical Laboratory of England, which has studied the various ternary diagrams concerned in the complex alloys, duralumin (Al, Cu, Mg, Si) and "Y" alloy (Al, Cu, Ni, Mg, Si). Thus, the Al–Mg–Cu (43w, x), Al–Cu–Ni (89c, e, g), and the Al–Cu–Mg–Si (43v) diagrams for alloys high in aluminum are fairly well known. Other important diagrams that have been quite thoroughly studied are Al–Cu–Zn (86b) and (Al–Mg–Zn–Si (43u)).

Some work has been done on the Al–Zn–Sn (91z), Al–Cu–Sn (91y), Al–Cd–Zn (91ii), and the Al–Mo–Ni (91g) diagrams.

In all the cases the original articles (see bibliography sections on duralumin, page 365, and complex alloys, page 385) should be consulted, since the diagrams are too complex to be discussed in abstract.

II. TECHNOLOGY AND PROPERTIES

1. APPLICATIONS OF COMMERCIAL LIGHT ALLOYS

(a) COMPARISON OF DENSITY AND MECHANICAL PROPERTIES OF ALUMINUM ALLOYS, WITH OTHER MATERIALS OF CONSTRUCTION

In Table 37 are compared the tensile properties for several materials used for construction in relation to their densities. Steels have been chosen for comparison which have approximately the same ductility as the duralumin. Douglas fir has been included as representing the best wood available for aircraft wood construction. The values given bring out the fact that, weight for weight, duralumin and similar light alloys are as strong as the best steels and for the same strength give greater stiffness. There appears to be no doubt of the adequacy of such light alloys as substitutes for both steel and wood in construction in which both strength and lightness are a prime requisite.

While only two light alloys are given in the table, similar comparisons could be made for several other alloys of the same general type as duralumin and for some of the modern alloys of magnesium. In castings, as well as in wrought alloys, the alloys of aluminum and of magnesium show many advantages over steel, cast iron, brass, and bronze on the basis of strength per unit of volume. Many such comparisons are found in the literature. (See Bibliography, p. 393.)

Naturally, these advantages have been largely made use of in aircraft and automobiles.

(b) MAJOR USES OF CAST AND WROUGHT ALUMINUM ALLOYS

Pure aluminum, even in the hard-rolled condition, is a weak material of construction, and is chosen in preference to its alloys only when ease of fabrication, as in spinning household utensils; high electrical conductivity, as in transmission lines; or resistance to corrosion, as in chemical apparatus or cooking utensils; is sought.

Strengthening for castings is brought about by the use of alloying elements, such as copper, zinc, manganese, magnesium, silicon, iron, or nickel. Only these seven elements, or combinations of them, are used in the important commercial alloys of aluminum. The amount of alloying elements required to produce the optimum combination of properties seldom rises over a total of 10 per cent, except in the case of zinc, or, very rarely, in that of copper. Hence, the light alloys, containing 90 per cent or more of aluminum, have specific gravities under 3. Those with silicon may be lighter than pure aluminum.

Further strengthening of the alloys is brought about by cold working; that is, rolling, forging, drawing, etc. The alloys most suitable for cold-rolling more often approach 95 per cent of aluminum than 90 per cent, and, hence, have even lower specific gravities than the casting alloys.

TABLE 37.—*Comparison of mechanical properties of some materials of construction*

Material	Density	Tensile test						Ratios of some physical values of round bars of different materials of same length and of same weight to those of duralumin taken as unity					Ratios of some physical values of round bars of different materials of same length dimensioned to support the same working load to those of duralumin taken as unity (using values of allowable working stress given in column 8)				
		Modulus of elasticity	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area	Working stress [1]	Ratio of working load using value of working stress given in column 8	Ratio of diameter	Ratio of transverse stiffness (simple beam)[2]	Ratio of tensile stiffness [2]	Ratio of energy absorbed in deformation up to yield point	Ratio of weight	Ratio of diameter	Ratio of transverse stiffness (simple beam)[2,3]	Ratio of tensile stiffness [2]	Ratio of energy absorbed in deformation to yield point
	g/cm ^{3}	*Lbs./in.* $^2\times 10^{-6}$	*Lbs./in.* ^{2}	*Lbs./in.* ^{2}	*Per cent*	*Per cent*	*Lbs./in.* ^{2}										
Heat-treated alloy steel [4]	7.80	30	150,000	115,000	14	45	55,000	1.32	0.60	0.39	1.08	1.75	0.75	0.52	0.53	0.82	1.26
Rolled alloy steel sheet [5]	7.80	30	100,000	75,000	20	--------	37,000	.89	.60	.39	1.08	.74	1.12	.64	.88	1.22	.85
Rolled carbon steel sheet [6]	7.80	30	75,000	45,000	25	--------	23,000	.55	.60	.39	1.08	.27	1.82	.81	1.70	1.96	.50
Rolled and heat-treated duralumin	2.85	10	60,000	30,000	15	--------	15,000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rolled zinc-aluminum-copper alloy [7]	*3.29	10	71,000	61,000	21	38	30,000	1.74	.93	.74	.87	3.60	.58	.71	.39	.50	2.06
	†3.29	10	52,400	36,000	18	--------	18,000	1.04	.93	.74	.87	1.24	.98	.91	.77	.83	1.20
Douglas fir [8]	.47	1.64	6,100	4,400	--------	--------	1,200	.48	2.46	5.88	.99	.79	2.06	3.54	4.70	2.05	1.63

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[1] Using working stress equal to $\frac{\text{yield stress}}{2}$.

[2] Stiffness defined as $\frac{\text{total load}}{\text{deflection}}$, and is taken not of the material but of the bars themselves, which are of different dimensions for different materials.

[3] The comparisons in this column are made on the basis of bars of equal transverse working load, using working stress values of column 8.

[4] Commercial nickel, nickel-chromium or chrome-vanadium steel, according to specification 3S5 of the International Aircraft Standards Board, 1917.

Commercial nickel, nickel-chromium or chrome-vanadium steel, according to specification 3S28 of the International Aircraft Standards Board, 1917.

[6] Commercial carbon steel, of carbon content from 0.15 to 0.30 per cent, according to specification 3S27 of the International Aircraft Standards Board, 1917.

Containing 25 per cent zinc and 3 per cent copper in form (*) of one-half inch hot-rolled bar and (†) as rolled, 0.156 inch sheet, annealed (Rosenhain-Archbutt).

[8] Values given were adopted by American Railway Engineering Association. These values are determined in the transverse test.

Some alloy combinations are capable of still further strengthening by heat treatment. The heat treatable alloys do not respond as readily to heat treatment in the cast as in the worked condition. For quite a period the heat treatment of wrought alloys was common and that of cast alloys rare. As the details of heat treatment of cast alloys became better understood, heat treatment of castings became more common, and at present the tonnage of heat-treated aluminum alloys is about equally divided between castings and wrought products. The wrought heat-treatable alloys of the duralumin type are those in which the highest strength can be developed.

By alloying, working, and heat treatment it is possible to produce tensile strengths covering the entire range from 8,500 lbs./in.^{2} for annealed aluminum of the highest purity to 75,000 lbs./in.^{2} for a special wrought heat-treated duralumin, within a specific gravity range of 2.65 to 3.00.

The outstanding need for materials of such combinations of strength and light weight is in aircraft structures.

(1) Advantages of Light Alloys for Aircraft Structures.—Compared with wood, metal has the advantage of greater strength, and for a given metal the strength and other properties do not vary much from the average values for that material. It is therefore customary to use a smaller factor of safety in designing metal aircraft structures than in designing similar structures of wood.

If an aircraft member is subjected to tensile forces only, the material should be selected by choosing the one having the highest $\frac{\text{strength}}{\text{density}}$ ratio, if the price or difficulties in fabrication do not make its use impracticable.

If these ratios for metals are compared it is evident that heat-treated alloy steels are preferable to other materials.

For aircraft members subjected to compressive stresses, as in beams or struts, the resistance to secondary failure must be considered. For these members the light alloys have the great advantage over other metals, such as steel, which is stronger but heavier, that the thickness of a light alloy structural member is much greater than the thickness of equivalent steel section. The greater thickness offers much greater resistance to secondary failure, such as local buckling.

For the structures of dirigibles the light alloys are the only practicable material because the girders and other load-carrying members are fabricated from thin sheets of metal. Failure occurs in the longitudinals and lattices by buckling under compressive load.

For machinery having reciprocating parts, such as engines, the use of light alloys reduces the weight and, therefore, the inertia stresses. The high-thermal conductivity of the light alloys makes their use for cylinders and pistons highly desirable.

If castings are used, as in aircraft engines, it is impracticable to make the thickness less than the minimum which will give sound castings. In many cases light alloy castings are sufficiently strong and the weight is much less than for castings of other metals. About one-third the weight of the Liberty motor is made up of aluminum alloys.

The light alloys have rapidly replaced wood for aircraft propellers because these metal propellers are lighter and are more efficient. The higher efficiency of the metal propellers is due to the fact that it is practicable to fabricate metal propellers which more closely approximate the theoretical form. In addition, the higher modulus of elasticity of the metal propellers reduces the torsional vibration or "fluttering."

Propellers made from light alloys are more durable and the tip erosion is less than in wooden propellers, which often fail at the glued joints.

At the present time the light alloys are very extensively used for propellers and engines and for the structural portions of dirigibles. They are rapidly replacing wood for the structures of airplanes.

Table 38 gives some of the more common aircraft alloys.

(2) ADVANTAGES OF LIGHT ALLOYS FOR AUTOMOBILE CONSTRUCTION.—While light weight is not as vital for automobile use as for aircraft, the avoidance of unnecessary weight makes for high gasoline mileage and good acceleration. Cutting down on weight in one part of the machine by substitution of an aluminum alloy for a heavier one not only reduces the weight of that part alone but requires less heavy frame, springs, etc., to carry the total weight. Thus savings of weight are cumulative rather than merely additive.

The list of 1927 specifications for passenger-car engines (9a) includes materials of construction for about 100 different makes and models. The crank-case upper half is of cast aluminum alloy in 24 and the lower half in 18 of these, the others being cast iron or pressed steel.

Thirty-three of the 100 use aluminum alloy pistons, while the list of British, French, Belgian, Italian, German, and Austrian models show that the proportion using aluminum pistons abroad is fully twice as great as in the United States. Three American models use duralumin or similar aluminum alloy connecting rods. About 10 of the larger cars made in America use some aluminum in body construction.

The use of aluminum for crank cases and pistons is not as widespread in the United States as the above figures for the proportion of models using it would indicate because the cheaper cars produced in the largest quantities seldom use it.

TABLE 38.—*Principal alloys of aluminum used in aircraft* [1]

Alloying elements						Heat treatment							Physical properties						Uses
													As cast			Heat treated			
Copper	Nickel	Magnesium	Manganese	Silicon	Iron	Quenching temperature and time			Quenching medium	Aging temperature and time			Tensile strength	Elongation in 2 inches	Brinell, 500 kg	Tensile strength	Elongation in 2 inches	Brinell, 500 kg	
						° F.	° C.	*Hrs.*		° F.	° C.	*Hrs.*	*Lbs./in.^{2}*	*Per cent*		*Lbs./in.^{2}*	*Per cent*		
10.0	-------	0.25	-------	(2)	1.25	935	500	4	Boiling water	400	205	1	25,000	(3)	85	35,000	0.5	110	Pistons, bearings.
4.0	2.0	1.5	-------	(2)	(2)	950	510	4	do	400	205	1	25,000	1.0	80	35,000	.5	100	Pistons, air-cooled cylinder heads, bearings.
2.5	-------	.5	-------	(2)	1.25	950	510	2	do	300	150	2	19,000	1.5	65	28,000	3.0	70	Housings, brackets.
4.5	-------	-------	-------	1.0	(2)	925	495	24	do.[4]	300	150	2	21,000	2.0	60	[4] 30,000	[4] 3.0	75	Crank cases, water jackets, levers, wheel spiders.
WROUGHT FORMS																			
4.0	-------	0.6	0.6	(2)	(2)	950	510	(5)	Boiling water [6]	[6] 300	150	[6] 2	-------	-------	-------	[7] L-60,000	16	95	Propellers, connecting rods, miscellaneous forgings, and screw-machine products.
4.0	-------	-------	.6	0.75	(2)	970	520	(5)	do	300	150	[8] 2	-------	-------	-------	X-50,000	8	-------	

L=Parallel to flow lines.
X=Perpendicular to flow lines.

[1] After Johnson (Amer. Soc. Steel Treating, **9**, p. 517, 1926), but modified according to the latest recommendations of the Aluminum Co. of America.

[2] Present in small quantity as impurity.

[3] Less than 1 per cent.

[4] On room temperature aging 28,000 lbs./in.^{2} tensile, and 6 per cent elongation; and on full aging at elevated temperatures 36,000 lbs./in.^{2} tensile, with no elongation, may be obtained.

[5] The soaking time for the wrought material depends upon the dimensions of the piece which is tested. $\frac{3}{16}$-inch sheet will attain full hardness if soaked for about 30 minutes; 2-inch bar must be soaked 6 to 8 hours. The physical properties indicated are for a rolled propeller slab $\frac{3}{4}$ inch by 12 inches wide by 10 feet long.

[6] This alloy is usually aged at room temperature in commercial practice—not at elevated temperatures.

[7] These properties are for heavy forgings, not for sheet.

[8] Lower aging temperatures and longer times are generally used.

A moderate reduction in the price of aluminum would result in a largely increased use in automobile construction. Designs have been worked out for engines and cars in which far larger amounts of aluminum are required than is the normal practice, and such designs have many definite advantages. Construction of some of the higher-priced cars is tending toward the use of more aluminum, but the medium-priced cars use it sparingly and the lowest-priced cars avoid it almost entirely.

Pressed steel has made inroads on the use of aluminum for oil pans, but on the whole aluminum pistons seem to be gaining on cast-iron pistons. Individual manufacturers may use one material one year and another the next, but such changes are often ascribable to a desire to use an improved mechanical design which may be more readily worked out in one material than in the other.

(3) ALUMINUM ALLOYS FOR AUTOMOTIVE PISTONS.—Aluminum alloy pistons when used in automobile and aircraft engines have the advantages of lighter weight and better thermal conductivity and the disadvantage of higher coefficient of thermal expansion, more rapid wear or abrasion of the surfaces, and greater liability to sticking of piston rings.

The advantages noted above are common to all aluminum alloy pistons in somewhat varying degrees. The design may be modified to secure either a minimum weight with some sacrifice of heat distribution or to secure more uniform distribution of heat at the expense of greater weight. As engine speeds increase the use of alloy pistons becomes rapidly more important, being practically essential for very high engine speeds. For aircraft engines alloy pistons are practically universal, more for reduction of engine weight and to reduce bearing pressures than on account of high speed.

The disadvantages noted above are subject to wide variation with difference in the alloys used and in design of the piston. There are designs of alloy pistons which practically overcome the effect of greater thermal expansion by allowing sufficient flexibility in the piston structures. There are also composite pistons in which the diameter is controlled by sections of other metals such that the working expansion can be made almost anything desired.

Wear and scoring of the surface is largely a matter of alloy. If aluminum alloys can be used, which approach the rigidity and hardness of cast iron, it is probable that the rate of wear and danger of scoring will be comparable with the latter. Such alloys also should eliminate sticking of the rings which results from peening of the metal between the ring grooves by impact with the cylinder walls. Close fitting of the piston, which is possible when the difference in thermal expansion is minimized, will also assist in preventing sticking of the rings.

Gibson (10a) found that in a test on a particular engine the aluminum piston gave 18.10 horsepower as compared with 17.05 for cast iron, and used 7 per cent less gas per brake horsepower hour. The aluminum piston works at a much lower temperature than the cast iron (10b). Gibson (10a) states that the maximum temperature of a cast-iron piston is 200° higher than in an aluminum piston. Schapira (10c) gives the maximum temperature at the bottom of the aluminum piston as 450° C., a figure which is obviously in error, while Kerpely (10g) states that it does not rise above 250° C. Lea (8c) gives the maximum temperature of a 9 per cent Cu 2 per cent Ni–Al alloy piston as 233° C. Lea considers that burning occurs only after the pistons have been heated some time at 240° C., and afterwards heated to a temperature high enough to soften the $CuAl_2$ eutectic enough to allow it to be exuded. Gibson (10a) states that the tendency to burn appears to be greatest in cylinders fitted with inclined spark plugs. Excessive clearance admits hot gases and increases temperature, which probably breaks down the lubrication and allows friction, producing temperatures high enough to cause burning. Most of the burning occurred in engines in which the supply of lubricant was below normal.

While many of the pistons are produced from the 9 to 11.5 per cent Cu alloys there is no uniformity of practice. A variety of alloys has been recommended, the compositions and design of the pistons changing from year to year. In Table 39 are given the alloys used for pistons according to Johnson (8a) and Pannell (10k). Alloys ranging from 4 to 12 per cent copper have been recommended in English practice (10k, i, d, e).

The vast majority of aluminum pistons made in this country at present contain about 10 per cent copper, usually about 0.25 per cent magnesium with or without added iron.

Becker (10j) states that the lowest Brinell number to give good service life is 100. It may be noted that the alloys in the heat-treated condition mentioned by Johnson meet this requirement, whereas the hardness numbers of the copper-aluminum, Cu-Zn-Al alloys mentioned by Aitchison (10d) all fall far below 100. Aitchison gives data on the thermal conductivity, expansion, and high-temperature properties of the alloys he favors for piston use.

(4) ALUMINUM ALLOYS AS BEARING METALS.—Attempts have been made to use aluminum alloys as a bearing metal alloy, but without very marked success. Daniels (43z) reports that duralumin bearings compared to genuine babbitt bearings have less friction and show less wear under severe conditions. Duralumin forgings are used successfully for worm wheels in contact with hardened steel. The alloy may, accordingly, be suitable for some fairly heavy-duty bearings to be used in place of bronze. It should not be used in contact with soft steel.

TABLE 39.—*Aluminum alloys used for pistons* [1]

Kind or source	Chemical composition							
	Al	Cu	Zn	Mg	Mn	Ni	Sn	Fe
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Corbin	87.5	12.5						
Bergman	90.5	7	2.5					
German	93			7				
Curtiss	95.2	2.5		1.5				
Aerolite	86	12			2			
British [2]	89	10					1	
	88	12						
	85	14			1			
Benz Aviatek	80	6	12	Trace.	Trace.			1.5
British	94.8					5.5		
Magnalite	94.2	2.5	.5	1.3		1.5		
Magnalium	95			5				
N. P. L	92.5	4		1.5		2		
Lynite	88	10			.25			1.5
	90	8		.5				1.5
	88.5	10		.5				1.0

[1] According to Pannel

[2] British Air Board specification.

Experiments at the Royal Aircraft Factory (6e) on alloys containing 91 per cent Al, 7 per cent Cu, 1 per cent Zn, 1 per cent Sn, and 85 per cent Al, 14 per cent Cu, 1 per cent Mn, and 77 per cent Al, 3 per cent Cu, 20 per cent Zn indicated the frictional resistance of these alloys to be approximately twice that of white metal bearing alloys and the maximum bearing pressure to be only about a fourth. Complete film lubrication could not be maintained. The alloys showed a marked tendency to seize.

Tests in the main bearings of a 100 horsepower automobile engine (6b) of aluminum-copper and aluminum-zinc-tin alloys were unsuccessful. The shaft was badly scored in all cases presumably due to the $CuAl_2$ compound in the alloys. On the other hand, aluminum copper alloy castings, under light pressure, have in some cases shown good performance.

Risman (69a) has reported tests on bearings of aluminum containing 1 per cent of molybdenum with copper, magnesium, and nickel. His results tended to confirm others that aluminum is not suitable as a matrix for a bearing metal.

In general, aluminum alloys serve as bearings only when the pressure is light and the lubrication thorough and when the shaft is of hard steel.

2. PREPARATION OF COMMERCIAL LIGHT ALLOYS

(a) WROUGHT ALLOYS

(1) ROLLING, FORGING, ETC., OF ALUMINUM ALLOYS.—MECHANICAL WORKING.—The rolling and forging of aluminum alloys is carried out in a similar manner and with similar type of equipment to that used in the working of aluminum.

The temperatures used for the hot working of aluminum alloys are, in general, necessarily lower due to the lower melting point of the alloys. The approximate hot-working temperatures of some of the more common alloys are: For 98.5 Al, 1.5 Mn, 450° C.; duralumin, 450 to 480; Y alloy, 300 to 450. In some cases the "working" temperatures are quite critical, due to the tendency of these alloys toward "hot shortness" and the more rapid increase in hardness with lower temperatures. Consequently, greater care and more exact temperature control must be maintained. The alloys are, in general, more "tender" and require more careful handling in both hot and cold rolling. They also tend to "work harden" more rapidly in cold rolling. Accordingly, smaller pass reductions and more frequent intermediate annealing is required.

Rosenhain (2f) emphasizes particularly the necessity for obtaining a casting that is to be rolled or forged free from shrinkage, cavities, and surface defects in order to avoid cracking during working. He also emphasizes the importance of adequate lubrication of the rolls to prevent sticking of the metal to the rolls. This may be accomplished with kerosene or old machine oil.

Strauss (39g) has recently described forging practice in some detail.

Aluminum alloys may be drawn into rods, wires, tubes, and other shapes. At the present time, however, because of the greater advantages of the extrusion process, most of the rod, tube, and shapes are extruded rather than drawn.

The drawing is all done cold with suitable intermediate annealing. Anderson (43q) states that tallow is the most suitable lubricant. For very small sizes of wire diamond dies are used.

In the extrusion process it is particularly advantageous to work at as high a temperature as possible because of the greater plasticity of the metal and consequent saving in power. The temperature is, of course, limited by the melting point and other properties of the particular alloy to be extruded. One of the especial advantages of the extrusion process is the ability to extrude to a desired shape and size within quite close limits of tolerance.

Aluminum alloy forgings are, in general, made from hot-rolled forging billets or bar stock. Forging may be done in dies similar to those used in the manufacture of bronze forgings. Alloys of the duralumin type are used for forgings, such as the connecting rods of internal-combustion engines and as aircraft propellers. In general, alloys for forgings should be used the best physical properties of which can be developed by heat treatment after forging rather than to rely on finishing the forging at a relatively low temperature to obtain physical strength.

In the forming of many shapes used in aircraft construction by cold pressing in dies of sheet that has been stamped out into suitable shapes the Naval Aircraft Factory has used only one special die instead of two. The place of the die that would otherwise be used on the platen of the press is taken by a pad or thick sheet of rubber which conforms under pressure to the contour of the upper die. Since the sheet being formed is obviously shaped more gradually and with less restraint as the pressure increases than when matched dies are used, this method has been found to have many advantages beside the mere saving of the cost of one die. The method has been described by Weyerbacher (39b).

Aluminum alloy sheet may be spun similar to brass, but somewhat higher speeds are required. Both steel and wood forms and tools are used.

An increasing use for extruded shapes and for sheet is in motorbus bodies. An analagous use is in Pullman cars, and even in freight-car construction. In such uses wrought alloys used without heat treatment find some application, though the stronger, heat-treated wrought alloys are, perhaps, more commonly used.

Portable apparatus, such as vacuum cleaners and outboard motors, for example, obviously require very light construction and use much aluminum.

Automatic screw-machine products and drop forgings made from aluminum alloys are being used extensively to replace similar articles which were formerly made from other metals and subsequently nickel plated. This is also true of other parts in which the desired finish can be produced on the metal itself without the necessity of using a plated finish which wears off in use and exposes the base metal.

A myriad other uses can be found on every hand, many of which are cited by Anderson (39d) and in pamphlets published by the Aluminum Co. of America and the British Aluminum Co.

(2) Wrought Alloys used Without Heat Treatment.—Alloys for rolling or forging generally contain smaller percentages of the "hardener" metal than those for casting. Except when zinc is used, the total content of added metal to such alloys rarely exceeds 6 per cent and is usually less.

(*a*) *Aluminum-manganese alloy.*—An alloy (No. 3-S) containing about 1¼ per cent manganese is rolled by the Aluminum Co. of America, particularly into sheet, for use wherever a stiffer material than aluminum is desired. This alloy is superior in its resistance to corrosion to most other alloys of aluminum. The tensile properties of this alloy in sheet form average:

	Hard	Soft
Tensile strength........pounds per square inch..	30,000	15,000
Elongation in 2 inches........per cent..	2	25

The wrought 1¼ per cent Mn alloy (3–S) is used, like the 2 per cent Mn casting alloy, to reduce the tendency to electrolytic corrosion in pipe and tube. Streeter and Faragher (68e) state that the cold-worked alloys strain harden, the tensile strength, yield point, and hardness increasing in proportion to the amount of reduction up to a certain limit, beyond which the rate of hardening increases progressively. Sheet in hard temper is produced by reducing the thickness by cold rolling 12 or more gauge numbers after annealing (68e). The properties of hard-rolled 1.5 per cent Mn sheet are given by Anderson (68g) as tensile strength 31,000 to 47,000 lbs./in.^{2}, elongation 5 to 1 per cent, Brinell hardness 62 to 70 for No. 8 to 32 gauge, and for dead-soft annealed, tensile strength 18–20,000 lbs./in.^{2}, elongation 26 to 16 per cent, Brinell hardness 32 for No. 8 to 32 gauge.

The addition of manganese lowers the thermal and electrical conductivity. The effect of atmospheric exposure on electrical conductivity has been studied by Wilson (68f).

These alloys are also discussed under "casting alloys," page 185.

(*b*) *Alloys of aluminum, manganese, and copper.*—An alloy containing 1 to 2 per cent copper and 1 per cent manganese used at the Naval Gun Factory (35q) for small forgings may be readily forged at a temperature of about 525° C. If finished at a temperature of about 250° C., the forging is much harder. Forgings of this alloy give the following tensile properties:

	Finished cold	Finished hot
Tensile strength ---- pounds per square inch--	27, 500	21, 000
Yield point ---- do----	15, 000	12, 000
Elongation in 2 inches ---- per cent--	12	27
Reduction of area ---- do----	47	48

The alloy is said to be quite satisfactorily resistant to corrosion in sea air.

(*c*) *Aluminum-zinc alloys.*—An alloy of from 10 to 15 per cent zinc was formerly recommended for general forgings. This is said to flow well in the dies and to have useful physical properties. Compare Schirmeister's data for rolled material (p. 148).

(*d*) *Aluminum-silicon alloys* (*5 to 7 per cent silicon*).—These may be rolled. The hard-worked alloys may give the following properties:

Tensile strength ---- pounds per square inch--	35, 000
Elongation in 2 inches ---- per cent--	5

McAdam (39c, 46g) has studied the effect of cold working on commercial aluminum and on an alloy with 1 per cent manganese in sheet form, as well as of similar materials in bar form. His data are plotted against per cent increase in tensile strength due to cold working, but the base tensile strength is not given. More complete data will doubtless be given in a future paper.

Wrought alloys whose strength is obtained by cold working only, though applicable to many industrial uses, are inferior in properties to those whose strength is obtained by heat treatment; that is, duralumin and similar alloys. For aircraft construction the heat-treated alloys are used almost exclusively. These alloys will be discussed on page 212.

(*e*) *Other alloys.*—Nickel alloys, up to about 2 per cent nickel and copper alloys up to about 5 per cent copper have found slight commercial use in wrought form, in their natural state. The former is not now in use in this country and the latter is chiefly used in the heat-treated condition. It will be discussed in later sections.

(3) Schirmeister's Investigations of Wrought Binary Alloys.—A very comprehensive investigation of the mechanical properties of rolled binary light alloys of aluminum was carried out in 1915 by Schirmeister (1b).

Schirmeister rolled out several compositions of many binary alloys systems of aluminum and tested their hardness and tensile strength. His method of preparation for the alloys was the same for all series and was as follows:

About 900 g of the alloy were melted up in a small gas crucible furnace, poured into a chill mold to plates 25 mm thick. These were rolled in a 30-horsepower mill at the rate of 40 m per minute. The plates were first reheated after casting to from 400 to 500° C. and rolled with intermediate annealing, with reductions of each pass of from 1 to 3 mm, to a thickness of 4 mm. They were then annealed and rolled cold to from 1.3 to 1.5 mm thickness. Only those alloys of which the melting point was very considerably lowered by the additions were rolled at lower temperatures or cold. Specimens cut from these sheets were then annealed at from 300 to 350° in a muffle furnace, allowed to cool, and tested after several days.

His results are given in Table 40.

TABLE 40.—*Mechanical properties of rolled binary aluminum alloys* (*Schirmeister*) (*1b*)

Per cent composition	Tensile strength	Elongation in 5 cm	Brinell hardness (B. H. N.)[1]	Remarks
Antimony:	*Lbs./in.*^{2}	*Per cent*		
0.00	14,900	34	29	Rolled at 450 to 500° C., 8 m per minute, to 1.4 mm; it is only possible to roll these alloys up to 11 per cent of antimony; even at 8 per cent a certain amount of tearing and cracking takes place; antimony is seen to be an undesirable addition to aluminum.
0.4	14,600	37		
1.0	14,600	40	29	
2.0	14,600	38		
3.2	14,800	36	30	
4.5	14,900	32		
6.0	14,900	29		
8.0	15,400	23	27	
10.5	14,900	17		
Bismuth:				
0.0	16,300	32		Rolled cold, 8 m per minute, to 1.4 mm; the working properties, both hot and cold, are very unfavorably affected by the influence of bismuth; the physical properties attained indicate that bismuth is an undesirable addition to aluminum.
0.4	16,600	33		
1.2	17,800	31		
3.0	16,500	30		
4.8	15,800	30		
Cadmium:				
0.0	16,300	32	31	Rolled at 100 to 150° C., 8 m per minute, to 1.4 mm; these alloys may be rolled up to 6 per cent or more; results show that there is no advantage in the addition of cadmium.
0.4	16,500	33		
1.3	16,300	35	40	
1.8	16,300	36		
2.7	16,500	34	42	
4.0	16,500	32		
6.0	16,600	32	40	
Chromium:				
0.0	13,500	41	26	Rolled at 500° C., 8 m per minute to 1.4 mm; chromium may be added to aluminum in amounts as great as 5 or 6 per cent and can be rolled at 500° up to a content of 4 per cent; chromium does not seem to offer any advantages as an addition to aluminum, although it might be used to harden it in amounts up to 1 per cent.
0.3	17,600	26	37	
0.6	21,200	17	44	
0.9	22,100	17	47	
1.4	19,600	21		
1.9	17,500	22	38	
2.6	17,600	21		
3.7	18,300	19	42	
4.5	18,900	11		
Cobalt:				
0.0	14,900	34	29	Rolled 450 to 500° C., 8 m per minute, to 1.4 mm; these alloys may be rolled up to approximately 11 per cent of cobalt; 4 per cent of cobalt is about the most favorable composition.
0.6	15,500	35	32	
1.6	17,100	28		
2.3	17,500	25		
3.5	18,300	21	47	
5.5	22,100	18		
7.5	23,600	14	50	
9.4	23,500	11	51	
10.5	24,200	11		
12.0	26,300	6	61	
Copper:				
0.0	14,900	34	29	Rolled at 400 to 450° C., 8 m per minute, to 1.4 mm; these alloys may be rolled hot up to 12 per cent of copper; the author considers 3 to 4 per cent of copper to be the most advantageous composition.
0.5	19,200	30		
1.0	21,900	26	41	
2.1	24,300	23	46	
3.5	25,600	22	48	
5.1	25,300	21	49	
7.1	25,600	21	49	
8.9	26,600	19	52	
11.0	27,700	16		
Iron:				
0.9	14,900	34	29	Rolled at 450 to 500° C., 8 m per minute, to 1.4 mm; these alloys may be rolled up to a composition of 12 per cent, although it presents some difficulty in most of the alloys; the author considers that although the iron-aluminum alloys do not show properties which would make them of any utility it is shown by his work that 2 or 3 per cent of iron in aluminum alloys is not harmful.
1.3	15,500	36		
1.8	16,300	33	33	
2.7	17,500	31		
3.7	17,900	29	37	
5.0	17,800	25		
6.8	17,600	18	38	
8.8	17,100	12		
11.1	16,600	8	44	
12.5	16,200	7		

[1] The Brinell hardness numeral was determined with a 2.5 mm ball, using a pressure of 62.5 kg.

Table 40.—*Mechanical properties of rolled binary aluminum alloys* (*Schirmeister*) (*1b*)—Continued

Per cent composition	Tensile strength	Elongation in 5 cm	Brinell hardness (B. H. N.)	Remarks
Lead:	*Lbs./in.*	*Per cent*		
0.0	14, 900	34	----------	Rolled at 300° C., 8 m per minute, to 1.4 mm; these alloys can be rolled hot quite readily up to 4 per cent or more; the addition of lead in small amounts is not of any value; at the same time it has no marked ill effect upon the properties of the aluminum alloys.
0.4	14, 200	40	----------	
0.9	14, 100	37	----------	
1.5	14, 400	35	----------	
2.5	14, 500	34	----------	
4.0	14, 200	34	----------	
Magnesium:				
0.0	14, 900	34	29	Rolled at 450° C., 8 m per minute, to 1.4 mm; it is possible to roll these alloys up to approximately 6 per cent; above that the alloys crack and splinter; the author does not consider that magnesium is a valuable addition to aluminum for a rolling alloy.
0.3	15, 500	34	33	
0.6	16, 200	33	33	
1.2	15, 900	33	33	
1.6	16, 200	33	34	
2.6	21, 700	25	42	
4.0	30, 000	22	54	
6.0	41, 800	21	69	
Manganese:				
0.0	13, 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm; manganese-aluminum alloys may be rolled to approximately 5 per cent without much tearing; the author considers that 1 or 2 per cent of manganese might be added with advantage to aluminum.
0.4	14, 800	36	----------	
0.6	15, 300	33	31	
0.8	16, 200	34	----------	
1.3	17, 100	28	35	
2.4	18, 700	22	39	
3.2	19, 100	19	----------	
4.8	19, 500	18	46	
Molybdenum:				
0.0	13, 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm; these alloys can be rolled up to 5 per cent of molybdenum; the series shows, however, no improvement in properties.
0.4	15, 900	36	33	
0.7	16, 800	34	----------	
0.9	16, 800	33	34	
1.2	16, 400	29	33	
1.9	16, 500	25	----------	
3.7	16, 900	16	42	
4.9	17, 200	16	----------	
Nickel:				
0.0	13, 500	34	29	Rolled at 400 to 500° C., 8 m per minute, to 1.4 mm; these alloys can be rolled up to from 11 to 12 per cent nickel without very considerable tearing; the author considers those alloys containing approximately 4 per cent of nickel the best alloys of the series.
0.6	15, 900	33	----------	
1.0	16, 300	32	34	
1.9	18, 100	29	----------	
3.1	20, 900	27	44	
4.5	21, 600	25	----------	
6.2	21, 300	22	45	
8.1	21, 200	16	47	
10.3	23, 500	8	53	
Silicon:				
0.5	13, 500	41	26	Rolled at 450 to 500° C., 40 m per minute, to 1.4 mm; these alloys may be rolled up to 20 per cent of silicon; the author finds that the resistance to atmospheric corrosion of this series is fairly good in spite of the fact that it has been claimed that silicon causes a great corrodibility in aluminum; the author believes that an addition of silicon is of advantage, and that from 5 to 7 per cent of silicon may be added for rolling and forging alloys.
1.7	14, 900	41	----------	
3.1	15, 900	40	31	
4.9	17, 800	35	----------	
7.0	19, 300	32	38	
9.8	21, 600	27	43	
12.4	23, 800	23	46	
15.1	22, 300	17	47	
18.8	23, 300	11	----------	
Tantalum:				
0.0	13, 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm; only a few alloys were made of this series; results show that tantalum can not be considered as a technical utilizable constitutent for aluminum alloys.
0.3	14, 200	38	----------	
0.8	15, 100	38	30	
1.5	14, 600	38	----------	
2.2	14, 600	39	28	
3.5	14, 800	39	----------	
Tin:				
0.0	15, 500	37	31	Rolled cold, 40 m per minute, to 1.4 mm; tin diminishes the ease of working aluminum at higher temperatures; it is possible to roll these alloys only cold; tin is an undesirable addition to aluminum.
0.4	15, 400	33	----------	
1.0	15, 200	31	----------	
1.9	15, 300	29	31	
3.0	15, 600	27	----------	
4.8	15, 600	24	----------	
6.4	16, 100	26	32	
8.2	16, 600	20	----------	
10.3	17, 400	17	----------	
12.4	18, 500	15	31	

Table 40.—*Mechanical properties of rolled binary aluminum alloys* (*Schirmeister*) (*1b*)—Continued

Per cent composition	Tensile strength	Elongation in 5 cm	Brinell hardness (B. H. N.)	Remarks
Titanium:	*Lbs./in.*	*Per cent*		
0.0	13, 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm; these two metals are quite readily alloyed, although a high pouring temperature is necessary; up to 6 per cent of titanium the alloys of this series are readily rolled; the physical properties are not such that to the alloys may be attributed any technical importance.
0.4	15, 600	31	34	
0.8	16, 400	31	----------	
1.2	16, 100	31	----------	
1.6	16, 400	30	33	
2.1	16, 800	27	----------	
3.1	17, 400	23	35	
4.5	18, 500	19	----------	
6.2	20, 100	16	42	
Tungsten:				
0.0	13, 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm; the ease of rolling hot is not unfavorably affected by tungsten, which can be added to aluminum up to 6 per cent; tungsten does not seem to offer any advantages as an addition to aluminum.
0.3	14, 200	42	29	
0.6	14, 800	42	----------	
1.1	15, 500	40	32	
2.0	15, 400	36	34	
3.5	15, 500	33	----------	
6.0	15, 400	32	33	
Vanadium:				
0.0	13, 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm; the addition of vanadium to aluminum presents some difficulty, but it can be added and rolled up to 4 per cent; the author states that for a rolling alloy 1 or 2 per cent of vanadium might well be used.
0.4	15, 500	38	----------	
0.8	16, 100	36	33	
1.2	16, 800	34	34	
2.0	17, 800	28	38	
2.8	17, 800	27	----------	
3.7	17, 500	29	39	
Zinc:				
0.0	14, 900	34	29	Rolled at 8 m per minute, 350 to 400° C., to 1.4 mm; can be rolled up to 30 per cent; most suitable compositions are from 12 to 14 per cent, these alloys can be rolled up to 30 per cent of zinc; the author considers that the most suitable of them are those with from 12 to 14 per cent of zinc.
0.6	16, 400	32	----------	
1.3	17, 900	24	----------	
3.0	17, 800	27	34	
4.0	17, 800	27	----------	
5.7	18, 800	26	37	
7.8	20, 200	28	----------	
10.3	24, 200	32	42	
12.7	29, 000	33	----------	
16.0	25, 600	26	60	
18.5	41, 000	20	----------	
23.0	50, 100	17	----------	
25.3	53, 500	15	124	
Zirconium:				
0.0	13, 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm; zirconium acts much as does titanium as an alloy constituent of aluminum; alloys may be rolled up to 6 per cent of zirconium, do not show any remarkable good physical properties, however.
0.4	15, 100	34	----------	
0.8	15, 200	34	31	
1.2	15, 100	34	----------	
1.6	15, 400	34	31	
2.4	15, 800	34	----------	
3.2	16, 100	33	33	
4.5	16, 900	28	----------	
6.0	17, 800	25	37	

(b) COMMERCIAL CASTING ALLOYS, NOT HEAT-TREATED

(1) Sand, Die, and Permanent Mold Casting.—(*a*) *Melting practice.*—Pure aluminum is but rarely used in the cast form, owing to its softness, high shrinkage, and poor machining qualities. Its alloys, however, with copper, silicon, magnesium, or zinc, or combinations of these, give, with proper care, excellent castings.

In general, casting practice for aluminum alloys follows that for brasses and bronzes. The alloys are melted, in commercial practice, in reverberatory or open-flame oil or gas furnaces, upon a refractory hearth; in iron pots heated by oil or gas; in crucibles heated by oil, gas, coke, or coal; and to a small extent in electric furnaces of various types. The reverberatory type of furnace is used for remelting the metal taken from the reduction pots and for making up alloys to be sold in ingot form and in reclaiming scrap to be poured direct into castings or to be sold as ingot. This type is commonly used only when rather large tonnage is dealt with. Appreciable contamination of the melt by silicon reduced from the fire clay or fire brick hearth occurs in such practice only at unnecessarily high temperatures. The hot furnace gases are in direct contact with the melt, hence, the opportunity for solution of these gases in the metal is greatest with this type of furnace.

Most castings are made from alloys melted in cast-iron pots. Contamination by iron dissolved from the pot, and the introduction of hard, undissolved particles of the iron-aluminum alloy which forms on the inside of the pot, and which, if knocked off into the melt may appear as hard spots in the casting, have to be guarded against in this type of furnace.

Crucible melting is generally resorted to only when small amounts are to be melted. In any method of melting care should be taken not to overheat the metal, as it then oxidizes, absorbs gases, and is more likely to absorb impurities from the hearth, pot, or crucible.

(*b*) *Recovery of secondary aluminum.*—Perhaps 30 per cent of the metal used for the production of aluminum castings to-day is derived from recovered metal (5b) (see Table 4). Old castings from junked automobiles, old cooking utensils, sheet clippings, borings, turnings and millings from machining operations, and dross skimmed from melting pots all serve as sources of secondary metal.

Since the vast majority of castings used in this country have been made from the alloy of 8 per cent Cu, 92 per cent Al, and the balance chiefly from alloys which do not differ greatly from that alloy, reclaimed metal from miscellaneous heavy scrap castings generally approximates the composition and properties of that alloy. Since some alloys containing zinc are likely to be present in any lot of junk aluminum castings, and since steel studs, etc., may have to be left in the scrap until melted and then taken out, which as well as a mere second melting in an iron pot tends to raise the iron content of the melt, secondary metal is likely to contain small amounts of zinc and a higher iron content than would be found in new metal. If the amount of the various hardening elements, such as copper, zinc, and iron, is kept low enough by adding pure aluminum to compensate for the extra iron, etc., picked up, castings whose properties are quite suitable for most uses can be obtained. In fact, some producers prefer the alloy with high iron and a little zinc but with lower copper (S. A. E. 33) to the No. 12 alloy, and would use such a composition even if it were to be made entirely from new metal.

As the silicon-aluminum alloys come into wider use the composition of miscellaneous junk castings will vary still more widely. But alloys of 8 per cent Cu, 12 per cent Zn, 2 per cent Mn, 5 per cent Mg, 6 per cent Si, 6 per cent Ni, 7½ per cent Cu+1 per cent Zn, 6 per cent Cu+5 per cent Zn, 4 per cent Cu+10 per cent Zn, 7 per cent Cu+2 per cent Sn, 7 per cent Cu+1½ per cent Fe, 3 per cent Cu+1½ per cent Mn, 7 per cent Cu+½ per cent Mg, 4 per cent Cu+4 per cent Si, 3½ per cent Cu+1½ per cent Fe+4 per cent Si, all have tensile strengths which do not differ materially, say, from 18,000 to 21,000 lbs./in.^{2}, and mixtures of such alloys in almost any proportion would fall in the same range of tensile strength and would be usable for most purposes for which castings are required. Hence, miscellaneous aluminum junk castings make better castings when remelted than would be the case with most any other class of alloys. Such heterogeneous scrap would doubtless give more trouble to the foundryman than would a single composition made up of new metals, but the finished castings, after passing rigid inspection for cracks, shrinks, and other flaws, would be serviceable for most automobile uses, and will in many cases be cheaper than when new metal is used. The reason why such a wide range of compositions, varying to some extent in physical properties, are interchangeable from the engineering point of view in castings is that in order to make possible the molding of most automobile castings the cross section of the casting usually has to be larger than would be required from considerations of the stresses the castings must withstand in service, so that there is a margin of safety due to the inability of the foundryman to produce castings in quantity with as thin walls as would satisfy the engineer. Stiffness, rather than strength, is often what the engineer really seeks. If sections are used which are stiff enough, they may often be strong enough even if a relatively weak alloy is used.

For aeronautic work, or for automobile work where there is no comfortable margin of safety between calculated stresses and the minimum strength of the casting, the use of metal reclaimed from miscellaneous junk is inadvisable and the strict specifications can only be met by the use of new metal.

The amount and character of machining to be done on castings may govern the amount of scrap that can be safely used. While the slightly greater proportion of hardening elements normally present as a result of using scrap may improve the average machining quality, yet the uniformity of the product from scrap is not as good and the danger of hard spots is increased, so that the lower cost of castings due to the use of a high proportion of scrap may be partly or wholly balanced by higher machine-shop costs. In balancing the two factors it is usually found that some proportion of scrap is economically used.

In any case the use of a charge containing a large proportion of ingot reclaimed from borings or drosses requires great care. The aluminum is oxidized in remelting to a larger extent than the alloying elements are, so that unless suitable amounts of scrap unalloyed aluminum are added to the melt before ingoting the ingot will usually be so high in alloying elements that too hard, brittle castings will result. When the ingot is used in mixtures calculated to give a correct balance of the various constituents on the basis of chemical analysis the results may be satisfactory, but the reclamation process is liable to produce material that is not as clean, contains more entangled oxide and more dissolved gases than material made from new metals or from the remelting of heavy scrap.

The remelting of scrap aluminum alloy in coarse form offers no particular difficulty, but that of borings and chips is extremely difficult (5d), owing to the fact that each particle is covered with an extremely tenacious coating of Al_2O_3, which effectually prevents its coalescence with its neighbor. Two remelting methods are in commercial use. In one the chips are puddled in iron pots until a pasty mass of metal accumulates, which is then heated to a red heat until the dross and dirt rises, leaving clear metal. In the other the chips are mixed with a chloride and fluoride flux and melted in a crucible until the metal collects at the bottom. In a modification of this method (5d) a low melting point chloride-fluoride flux is melted down in a crucible and the aluminum chips fed into it. The oxide is fluxed off of the chips, which melt and collect at the bottom.

By these methods from 50 to 95 per cent recovery of metal is accomplished, depending on the cleanliness of the chips. The metal should not be used as a large part of the charge, except for unimportant castings of which the mechanical properties are not a prime consideration. Chips of magnalium, remelted by a method described by Coulson (100r) gave much lower tensile strength than the original virgin metal and practically no ductility. The use of a deoxidizer, such as metallic calcium, is claimed to have caused a partial recovery of the former mechanical properties. It is doubtful if any deoxidation practice can be relied upon for this purpose.

A more recent development has been the practice of briquetting light scrap of aluminum alloy (5c). Tests made by Hirsh (5e) indicated a shorter melting time and a lower melting loss for remelted briquetted "aluminum" than for remelted chips (8.1 per cent as against 13.8 per cent melting loss), but other experience indicates that briquettes disintegrate on heating, so that when the melting temperature is reached the condition is the same as if the chips were charged in loose form, so that briquetting would offer notable advantage only through convenience in handling, storage, and shipment.

(c) *Gases in aluminum alloys.*—The solubility of gases in aluminum has been studied and described by Czochralski (94e), who found that the absorption of gases by aluminum seems to start at 900° C. It is the least for nitrogen and increases in the following order: Carbon monoxide, air, oxygen, sulphurous acid, carbonic acid, illuminating gas, hydrogen. The temperature at which the metal begins to take up gas lies comparatively high for all these gases, so that in ordinary practice no considerable amount is taken up, such absorption occurring only with great overheating of the metal. Bircumshaw (94a), however, states that there is evidence of a considerable solubility of hydrogen in aluminum just above the melting point; he found that aluminum which has been heated to expel the gas, on introduction of hydrogen, continued to absorb the gas for a long period, the metal not being saturated after a period of 20 hours. Grogan (35b) finds that Charpy impact tests on chill cast material showed reduced values as the result of overheating in an atmosphere of N and CO, and further reduction by passing gas through the metal while still overheated, the reduction being practically independent of the gas used. The notched bar impact figure is partially restored by remelting the gassed material in air, and still more in vacuo. Hydrogen passed through molten aluminum at casting temperatures lowers the test figure very appreciably; CO_2 is less harmful; N appears to be beneficial, though the evidence for this is somewhat contradictory. Overheating or repeated melting of aluminum in an electric furnace did not injure its properties after rolling if the metal was allowed to cool to the normal pouring temperature before casting (35m, 94f).

Lobley (35n) pointed out that while this agreed with general experience it did not appear to hold for reverberatory melting where products of combustion might be absorbed. Norton (34f) described an apparatus for studying the hot-shortness of aluminum casting alloys. On such a test an alloy of 8 per cent Cu, 92 per cent Al made from aluminum severely overheated in an open-flame oil furnace would withstand only about one-eighth the stress without cracking that the alloy would withstand when made from aluminum of essentially identical chemical analysis but never overheated.

Archbutt (35h) finds that metal containing dissolved gases which tend to be given out on solidification and produce pinholes in the casting (which, while not necessarily especially detrimental to the strength of the casting, are to be avoided both for the sake of the appearance of a polished surface and from their effect in increasing corrosion difficulties) can be improved by allowing it to solidify very slowly in the crucible or the hearth in which it was melted, so that the gas may escape from the melt and remelting at once. Rapid cooling, as in an ingot mold, did not give a marked improvement.

Bubbling nitrogen through the melt before slow solidification appeared to sweep out the gas held by the melt. Lyon (35rr) had previously found that bubbling air through a melt of piston alloy did not injure the properties of the metal and in some cases slight improvement was noted.

The tests made by Archbutt did not show entirely consistent results, but, on the whole, the slow solidification method gave higher density, freedom from pinholes, and slightly improved physical properties. Corson (2a) has corroborated Archbutt's findings. Similar methods have been applied to copper by Edwards and Prytherch (61x). It has for a long time been common practice at the Bureau of Standards, in making up alloys by fusion in vacuo which are then allowed to solidify in the crucible, to remelt after the first solidification in order to produce alloys free from blowholes.

(*d*) *Temperature control.*—Good practice favors keeping the temperature of any aluminum alloy during melting practically at its melting point by the continuous addition of solid metal. Pouring should be done at the lowest temperature at which the metal will completely fill the mold. A low-pouring temperature is particularly important for aluminum castings because of the high specific heat of the metal. If poured at a high temperature, the metal in cooling heats the mold so hot that the rate of cooling is very slow. A coarse grain and weak metal result.

(*e*) *Effect of casting section and pouring temperature on mechanical properties.*—Gillett (38c) has studied the effect of pouring temperature on the mechanical properties of aluminum alloy castings.

A heat of No. 12 alloy (8 per cent Cu) was poured at 703° C. into test bars of different sizes, the test results of which are given in Table 41. It is seen that the greater the cross section of the casting the lower is the resulting tensile strength.

TABLE 41.—*Tensile properties of No. 12 casting alloy* (*Gillett, 38c*)

A. EFFECT OF CASTING SECTION

Dimensions of section in inches	Area of section	Tensile strength
	Square inches	*Lbs./in.²*
0.9 by 0.4	0.36	16,000
0.75 by 0.25	.188	18,000
0.40 round	.126	20,000
0.45 round	.159	19,000
0.50 round	.196	18,000
0.75 round	.442	16,000
1.00 round	.785	13,500

B. EFFECT OF POURING TEMPERATURE

Temperature in degrees Fahrenheit	Tensile strength	Temperature in degrees Fahrenheit	Tensile strength
	Lbs./in.²		*Lbs./in.²*
1,200	20,000	1,450	17,800
1,250	19,500	1,500	17,500
1,300	19,200	1,550	17,000
1,350	18,500	1,600	16,000
1,400	18,000		

In part B of the same table are given Gillett's results on the effect of pouring No. 12 alloy into a (S. A. E.) cast-to-size test bar (0.5 inch diameter) in green sand from different temperatures. The strength decreases with increasing pouring temperature. Gillett tested the effect of pouring temperature on 53 alloys in all (see Table 42), and concludes that, in general, the alloys are weaker by approximately 20 per cent when poured hot (1,550 to 1,600° F.) than when poured cold (1,225 to 1,250° F.). An exception was noted in the case of the 5 per cent magnesium and of the 2 per cent manganese alloy.

TABLE 42.—*Effect of pouring temperature on the tensile strength of light aluminum alloys* (*Gillett, 38c*)[1]

Chemical composition	Lower pouring temperature		Higher pouring temperature	
	Pouring temperature	Tensile strength	Pouring temperature	Tensile strength
	°C.	*Lbs./in.*^{2}	°C.	*Lbs./in.*^{2}
Pure aluminum	760	10,500	871	8,000
Copper-aluminum alloys:				
2 per cent copper	663	13,800	871	11,500
4 per cent copper	663	15,500	871	13,000
6 per cent copper	663	17,600	871	14,500
8 per cent copper	663	20,000	871	15,500
10 per cent copper	663	21,000	871	16,000
12 per cent copper	663	22,500	871	17,500
Zinc-aluminum alloys:				
4 per cent zinc	663	13,000	843	10,000
8 per cent zinc	663	17,000	843	12,700
12 per cent zinc	663	21,000	843	14,000
16 per cent zinc	663	24,000	843	17,000
20 per cent zinc	663	27,000	843	20,000
24 per cent zinc	663	30,000	843	24,500
28 per cent zinc	663	33,000	843	27,500
32 per cent zinc	663	35,000	843	30,000
36 per cent zinc	663	37,000	843	33,000
Copper-zinc-aluminum alloys:				
8 per cent copper and 0.25 per cent zinc	663	20,000	843	17,000
8 per cent copper and 0.5 per cent zinc	663	20,500	843	17,000
7.5 per cent copper and 1 per cent zinc	663	18,000	843	14,000
7 per cent copper and 3 per cent zinc	663	19,500	843	15,500
7 per cent copper and 9 per cent zinc	663	25,000	843	18,000
6 per cent copper and 5 per cent zinc	663	20,000	843	15,000
5 per cent copper and 10 per cent zinc	663	24,000	843	18,500
4 per cent copper and 8 per cent zinc	663	23,500	843	17,000
4 per cent copper and 15 per cent zinc	663	32,000	843	23,000
3 per cent copper and 3 per cent zinc	663	17,000	843	13,000
3 per cent copper and 6 per cent zinc	663	19,000	843	13,500
3 per cent copper and 12 per cent zinc	663	26,000	843	18,500
3 per cent copper and 15 per cent zinc	663	28,500	843	19,500
3 per cent copper and 25 per cent zinc	663	37,500	843	29,500
2.5 per cent copper and 19 per cent zinc	663	33,000	843	25,000
2 per cent copper and 10 per cent zinc	663	23,000	843	15,500
2 per cent copper and 22 per cent zinc	663	36,000	843	28,000
2 per cent copper and 25 per cent zinc	663	37,000	843	33,000
1.75 per cent copper and 30 per cent zinc	663	42,000	843	34,000
3 per cent copper, 15 per cent zinc, and 0.50 per cent manganese	663	30,000	843	20,000
Miscellaneous:				
2 per cent manganese	649	19,000	843	18,500
5 per cent magnesium	676	20,500	760	20,000
8 per cent copper and 0.25 per cent manganese	649	20,000	814	17,500
7 per cent copper and 0.33 per cent manganese	649	19,000	814	16,000
6 per cent copper and 0.5 per cent manganese	676	18,500	814	16,500
4 per cent copper and 1 per cent manganese	676	16,000	814	15,000
8 per cent copper and 2 per cent tin	657	18,000	802	15,750
5 per cent copper and 3 per cent tin	657	16,800	814	15,000
6 per cent copper and 1 per cent nickel	703	18,200	871	14,500
8 per cent copper and 0.25 per cent titanium	676	19,000	814	18,400
8 per cent copper and 0.25 per cent chromium	649	19,500	814	15,900
8 per cent copper and 0.25 per cent antimony	676	20,000	814	17,400
8 per cent copper and 0.25 per cent vanadium	676	20,000	814	18,500
8 per cent copper and 0.25 per cent cadmium	676	18,600	814	15,800
8 per cent copper and 0.25 per cent bismuth	676	18,000	814	14,000
4 per cent copper and 4 per cent silver	703	19,700	843	15,400
8 per cent copper, 1.5 per cent iron, and 0.75 per cent silicon	676	21,000	814	18,000

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[1] The bars were poured into the S. A. E. cast-to-size test bar in greensand. Aluminum containing 0.3 per cent iron and 0.2 per cent silicon was used in the preparation of the alloys.

Rosenhain and Lantsberry (87n) have studied the effect of pouring temperature on the tensile properties of a chill-cast aluminum-manganese-copper alloy No. 10 and find the following results:

Pouring temperature in degrees centigrade	Tensile strength	Elongation in 2 inches
	Lbs./in.^{2}	*Per cent*
775 to 737	12,900	2
687 to 675	26,000	8
650	25,300	8

Other tests have been made by Donaldson (85q, discussion), who finds a falling off in tensile strength and elongation for an alloy of 19 per cent zinc and 1 per cent copper when poured between 800 and 850° C.

Pouring temperature in degrees centigrade	Tensile strength	Elongation in 2 inches
	Lbs./in.^{2}	*Per cent*
850	20,400	1.8
800	29,300	4.0
700	22,000	2.5

Tests by Carpenter and Edwards (61u) give the following results for chill castings of an alloy of 4.63 per cent copper, balance aluminum:

Pouring temperature in degrees centigrade	Tensile strength	Elongation in 2 inches
	Lbs./in.^{2}	*Per cent*
650	21,700	8.5
724	15,700	5.5
707	10,900	3.0

Tests by Rosenhain (85q discussion), contribute the following values for chill castings of an alloy of 20 per cent zinc and 1 per cent copper:

Pouring temperature in degrees centigrade	Tensile strength	Elongation in 2 inches
	Lbs./in.^{2}	*Per cent*
850	24,000	2.5
800	30,800	4.0
750	31,500	3.0
700	31,700	4.0
650	30,900	5.0

Pyrometric control of pouring temperatures is not difficult and is in vogue in all modern foundries making aluminum castings. (38a, d.)

Hurren (35r) examined several English aluminum-zinc-copper alloys as well as an 11 per cent Cu piston alloy and "Y" alloy. He found that all these classes of aluminum alloys gave better mechanical properties the lower the casting temperature, down to the point where mis-runs and cold shuts appear. The results of the repeated impact test were very markedly affected by the pouring temperature. (See p. 273.)

(2) SAND CASTINGS.—(*a*) *Fluxes.*—No flux should be used in melting down, and the surface should not be covered with charcoal, as this may be included in the casting. Just before pouring, however, a small amount of zinc chloride is sometimes added to clean the surface and thus prevent dross from entering the casting. Skimming will accomplish the same result without the flux. Anderson (5a) discusses very fully the fluxes used for smelting secondary aluminum and aluminum alloys, giving the types of flux for different purposes, requirements, and characteristics of each.

(*b*) *Sand molds and cores, pattern-makers' shrinkage.*—In molding castings to be poured in aluminum alloys the characteristics of the particular alloy to be used should be borne in mind. Some of the alloys are quite brittle or "hot-short" and fragile at temperatures just below the melting point, while the silicon alloys are quite free from this trouble. In casting most other alloys extreme care should be taken that the mold should not be too hard. Ordinary green-sand, not too fine, is used, and hard ramming is to be avoided. A large percentage of bad castings is probably due to nonadherence to this principle. Albany 00 sand is generally used for molds (35l). No special facing is used, additions to make a smooth surface tending to make the sand impervious to steam and gases. Cores should be soft to give to the shrinkage of the metal. A core sand composed of sharp sand and molding sand is held together by the minimum possible amount of a binder, such as rosin, flour, or core oil. More trouble from cracked aluminum castings has its origin in the core room that produces too hard cores than from all other sources put together.

The mold should be poured carefully and not too rapidly, as the metal may otherwise fail to fill finer parts of the mold. The casting should be stripped as soon as set in order to prevent cracking. Owing to the lightness of the alloys, chaplets are rarely needed in anchoring cores.

For the usual alloys 0.156 inch per foot is accepted as the pattern maker's allowance for shrinkage; for commercially pure aluminum this is 0.203 inch per foot. The shrinkage of a number of alloys of aluminum as given by Anderson (35s) is shown in Table 43.

(*c*) *Porosity and methods for treating porous castings.*—Aluminum castings may have internal defects which are not visible from the outside and are not located by ordinary means when it is not desirable to cut into the castings. In such cases X rays may be used to locate defects (35d). Such methods have been used to show the difference in quality of die-cast and permanent mold-cast material, showing the permanent mold-cast product to be uniformly sound while die castings are porous and have blowholes beneath the surface skin. Sand castings are often porous due to intercrystalline shrinkage cavities or dross films. Porosity may also be tested for use by methylene blue in gasoline (35e), water pressure, air pressure, or steam pressure, the test being chosen according to the service for which the aluminum is to be used.

TABLE 43.—*Linear contraction of light aluminum alloys* (*Anderson* (*35s*))

Nominal composition	0.5-inch bar, poured at 700° C. in sand molds			0.5 by 1.0 inch bar, poured at 700° C. in sand molds			1.0 by 1.0 inch bar, poured at 700° C. in sand molds			1.0 by 1.0 inch bar, poured at 900° C. in sand molds			Excess of per cent linear contraction of 1.0 by 1.0 inch bars poured at 700° C. over those poured at 900° C.
	Linear contraction[1]												
	Inch per foot	Patternmaker's scale	Per cent	Inch per foot	Patternmaker's scale	Per cent	Inch per foot	Patternmaker's scale	Per cent	Inch per foot	Patternmaker's scale	Per cent	
100 Al	0.201	1/59	1.68	0.197	1/60	1.64	0.202	1/59	1.68	0.192	1/62	1.60	+0.08
98.5:1.5 Al-Mn	.201	1/59	1.68	.202	1/59	1.68	.210	1/56	1.75	.216	1/55	1.80	−.05
97:2:1 Al-Cu-Mn	.196	1/60	1.63	.198	1/60	1.65	.198	1/60	1.65	.192	1/62	1.60	+.05
92:8 Al-Ni	.193	1/61	1.61	.190	1/62	1.58	.192	1/62	1.60	.192	1/62	1.60	.00
90:10 Al-Zn	.184	1/64	1.53	.185	1/64	1.54	.189	1/62	1.58	.186	1/64	1.55	+.03
Duralumin	.180	1/66	1.50	.184	1/64	1.53	.184	1/64	1.53	.179	1/66	1.49	+.06
95.3:3:1:0.5 Al-Cu-Fe-Mg	.180	1/66	1.50	.182	1/65	1.52	.185	1/64	1.54	.184	1/64	1.53	+.01
90:2:8 Al-Cu-Zn	.179	1/66	1.49	.179	1/66	1.49	.179	1/66	1.49	.180	1/66	1.50	−.01
92:8 Al-Sn	.179	1/66	1.49	.180	1/66	1.50	.184	1/64	1.53	.178	1/67	1.48	+.05
90:8:2 Al-Cu-Mn	.178	1/67	1.48	.173	1/68	1.44	.185	1/64	1.54	.178	1/67	1.48	+.06
95.5:1.5:1.5:1.5 Al-Cu-Mg-Ni	.178	1/67	1.48	.178	1/67	1.48	.177	1/67	1.48	.179	1/66	1.49	−.01
96:4 Al-Mg	.176	1/67	1.47	.179	1/66	1.49	.179	1/66	1.49	.180	1/66	1.50	−.01
97:3 Al-Si	.174	1/68	1.45	.172	1/69	1.43	.175	1/67	1.46	.166	1/71	1.38	+.08
86.5:7:1:1.5:4 Al-Cu-Mn-Ni-Zn	.172	1/69	1.43	.169	1/70	1.41	.172	1/69	1.43	.173	1/68	1.44	−.01
90:8:2 Al-Cu-Fe	.172	1/69	1.43	.178	1/67	1.48	.170	1/69	1.42	.172	1/69	1.43	−.01
90:10 Al-Si	.172	1/69	1.43	.170	1/69	1.42	.172	1/69	1.43	.162	1/73	1.35	+.08
96:4 Al-Cu	.172	1/69	1.43	.176	1/67	1.47	.188	1/63	1.57	.178	1/67	1.48	+.09
92:8 Al-Cu	.170	1/69	1.42	.164	1/72	1.37	.172	1/69	1.43	.168	1/70	1.40	+.03
80:20 Al-Zn	.170	1/69	1.42	.165	1/72	1.38	.167	1/71	1.39	.171	1/69	1.43	−.04
85:14:1 Al-Cu-Ni	.169	1/70	1.41	.171	1/69	1.43	.167	1/71	1.39	.167	1/71	1.39	.00
91:7:1:1 Al-Cu-Sn-Zn	.169	1/70	1.41	.168	1/70	1.40	.173	1/68	1.44	.173	1/68	1.44	.00
90:10 Al-Cu	.168	1/70	1.40	.167	1/71	1.39	.168	1/70	1.40	.164	1/72	1.37	+.03
88:8:4 Al-Cu-Fe [2]	.168	1/70	1.40	.169	1/70	1.41	.170	1/69	1.42	[3] .168	1/70	1.40	+.02
90:8:2 Al-Cu-Ni	.168	1/70	1.40	.168	1/70	1.40	.173	1/68	1.44	.166	1/71	1.38	+.06
90:8:2 Al-Cu-Sn	.167	1/71	1.39	.165	1/72	1.38	.170	1/69	1.42	.165	1/72	1.38	+.04
90:8:2 Al-Cu-Zn	.164	1/72	1.37	.160	1/74	1.33	.170	1/69	1.42	.171	1/69	1.43	−.01
85:14:1 Al-Cu-Mn	.163	1/73	1.36	.161	1/74	1.34	.165	1/72	1.38	.165	1/72	1.38	.00
88:12 Al-Cu	.162	1/73	1.35	.164	1/72	1.37	.168	1/70	1.40	.152	1/78	1.27	+.13
77:3:20 Al-Cu-Zn	.162	1/73	1.35	.160	1/74	1.33	.166	1/71	1.38	.162	1/73	1.35	+.03
92.5:4:1.5:2 Al-Cu-Mg-Ni	.161	1/74	1.34	.164	1/72	1.37	.164	1/72	1.37	.165	1/72	1.38	−.01
85:3:12 Al-Cu-Zn	.161	1/74	1.34	.156	1/76	1.30	.171	1/69	1.43	.175	1/67	1.46	−.03
88:8:4 Al-Cu-Sn	.157	1/75	1.31	.162	1/73	1.35	.160	1/74	1.33	.162	1/73	1.35	−.02
86:14 Al-Cu	.156	1/76	1.30	.160	1/74	1.33	.160	1/74	1.33	.158	1/75	1.32	+.01
91.5:8:0.5 Al-Cu-Mg	.156	1/76	1.30	.156	1/76	1.30	.166	1/71	1.38	.167	1/71	1.39	−.01
85:5:10 Al-Cu-Sn	.156	1/76	1.30	.154	1/77	1.28	.163	1/73	1.36	.158	1/75	1.32	+.04
76:3:0.5:0.5:20 Al-Cu-Mg-Mn-Zn	.156	1/76	1.30	.162	1/73	1.35	.162	1/73	1.35	.161	1/74	1.34	+.01
66:1:33 Al-Mn-Zn	.155	1/77	1.29	.155	1/77	1.29	.156	1/76	1.30	.150	1/79	1.25	+.05
67:33 Al-Zn	.153	1/77	1.28	.152	1/78	1.27	.152	1/78	1.27	.152	1/78	1.27	.00
90:8:2 Al-Cu-Si	.149	1/80	1.24	.152	1/78	1.27	.159	1/74	1.33	.147	1/81	1.23	+.10
92:8 Al-Mg	.147	1/81	1.23	.146	1/81	1.22	.147	1/81	1.23	.152	1/78	1.27	−.04
90:8:2 Al-Cu-Mg	.146	1/81	1.22	.147	1/81	1.23	.149	1/80	1.24	.148	1/80	1.23	+.01

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[1] Alloys are arranged in order of decreasing contraction for 0.5 inch bar.
[2] Poured at 850° C.
[3] Poured at 950° C.

In cases where the castings are sufficiently porous to require treatment, several methods have been used, including application of bakelite sprayed under pressure, bakelite and aluminum powder, boiled linseed oil applied under pressure and baked, sodium silicate solution, zinc chloride solution, ammonium chloride solution, aluminum powder and sulphur, peaning, welding, or soldering (35f). Of the methods utilizing the application of solutions the ones chiefly used are the sodium silicate solution and the bakelite method. The sodium silicate used is the ordinary commercial water glass. In America the casting is soaked in the silicate at least 1 hour or treated under pressure, immersed 1 to 2 minutes in 3 to 5 per cent HCl or 10 per cent H_2SO_4, washed in cold water, then baked above 100° C. for at least 1 hour (96f). The British process differs somewhat from the American process. In either case the effect is probably due to deposition in the holes of a corrosion product from the aluminum, of silica or some other solid. The specification given by the Bureau of Aeronautics, United States Navy Department, for sodium silicate to be used for castings treatment is—alkalinity (calculated as NaO) 14 per cent, water not more than 45 per cent, specific gravity at 65° F., not less than 1.7. In using bakelite it may be used as a dip, or may be poured in, brushed on, or sprayed. The casting is then air-dried and baked about 2 hours at 150° C. In using more than one coat each coat is allowed to cool before applying the mixture. Welding is suitable, and soldering may be used in a limited number of cases.

(3) Die Casting.—The term "die casting" is used in England to connote the casting of metal in metallic molds either with or without the mechanical application of pressure (gravity and pressure die castings), but in this country it is customary to use the term "die casting" to apply to casting in metal molds with the application of pressure, and to refer to casting in metal molds without pressure as "permanent mold" casting.

Die castings may readily be made of aluminum alloys; the aluminum silicon alloys are especially suitable (96b), the copper-aluminum alloys are also suitable for this class of work. Aluminum-zinc alloys are difficult to handle because of their hot-shortness (Norton, 35ss). Norton describes the use by the Aluminum Castings Co. of No. 12 alloy for permanent mold castings. This metal gives die castings which are of smooth surface, dense, and dimensionally true within a very small margin (±0.005 inch). Mechanical properties for die castings of No. 12 average:

	Sand castings	Die castings
Tensile strength....pounds per square inch..	20, 000	25, 000
Yield point (stress for 0.01 inch elongation in 2 inches)....do....	13, 000	13, 000
Elongation in 2 inches....per cent..	1. 7	3. 1
Density....	2. 84	2. 87

Many articles are now die cast in this alloy, such as parts of cash registers, typewriters, and adding machines.

Pack (36c) describes an aluminum-copper alloy which is being commercially die cast under pressure. The chief commercial difficulty with the die casting of aluminum is the cracking, or heat checking, of the iron or steel molds used (36b). Cracks appear in the mold after a few thousand castings have been made in it.

An extensive investigation of aluminum die casting alloys by the American Society for Testing Materials is now under way. The following compositions are under test.

TABLE 44.—*Compositions of aluminum die-casting alloys under test by A. S. T. M. B-2-VIII Section*

[List of aluminum alloys agreed on for die-casting investigation]

Number	Copper	Silicon	Nickel	Iron [1]	Aluminum [2]
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	4			1½–2	Balance.
2	10			1½–2	Do.
3	14			1½–2	Do.
4		5		1½–2	Do.
5		13		1½–2	Do.
6	2	3		1½–2	Do.
7	4	5		1½–2	Do.
8	1½	¾	2¼	1½–2	Do.
9	4	1½	4	1½–2	Do.
10		2	5	1½–2	Do.
11	2	8		1½–2	Do.
12	8	1		1½–2	Do.

[1] The iron content represents a minimum below which it would probably be difficult to go, due to the nature of the die-casting process and molds.

[2] The alloys are preferably to be free from manganese and magnesium (max. each, 0.05 per cent).

Table 45 gives the specifications of the Army Air Service for aluminum die castings.

TABLE 45.—*Specifications for aluminum die castings*

Specification	United States Army Air Service, No. 11302, September 15, 1926.		
Chemical requirements	Copper	per cent	3.5 to 4.5
	Silicon	do	4.5 to 5.5
	Other impurities	do	1.0
	Aluminum		Remainder
Physical properties	Tensile strength (minimum)	lbs./in.^{2}	28,000
	Elongation in 2 inches (minimum)	per cent	2.5
	Brinell hardness (minimum)		60
Permissible variations	Permissible variations per inch of diameter or length shall be plus or minus 0.0025 inch. This may be further reduced when a dimension amounts to several inches, as stated in the contract or purchase order.		

(4) PERMANENT MOLD CASTINGS.—Automotive pistons from light aluminum alloys are now more commonly made, in this country, in chill molds (permanent cast-iron molds) than in sand. The advantages are the better physical properties of the product, due to the finer grain of the chilled casting, to the freedom from pinholes if the mold has been properly designed and gated, and to the smaller amount of machining, due to the ability to produce castings close to

the desired dimensions. On repetition work, where very large numbers of identical piston castings are desired, the cost of production is probably somewhat less than in sand casting, even though the making of the mold is an expensive matter.

Other castings of fairly regular outline, even though somewhat larger and more complex than pistons, are also produced in permanent molds, but very large or very complex castings are not thus made commercially in the United States. In Europe, especially in the case of the "Cothias" castings made in France, permanent molds are often used for quite complex and quite large castings which American foundrymen find to be more cheaply made in sand.

In order to allow a permanent mold casting to be separated from the mold before contraction causes cracking, the cores must be so made as to be instantly collapsed or withdrawn. The design of such a mold is a task requiring much experience.

Permanent mold castings in No. 12 alloy show 25 per cent higher tensile strength and double the elongation that the same alloy would give in sand. While there is difficulty in designing the mold, cores, and gate so as to avoid trapped air and consequent blowholes, once the proper design is obtained, and care taken in pouring, the permanent mold castings are free from the porosity found under the skin of die castings made under air pressure.

The subjects of die castings and permanent mold castings are quite fully discussed by Anderson (2d) in his book, and more fully in a number of articles by Anderson and others, references to which will be found in Anderson's bibliography. Mortimer (36a) has also given a very full discussion of die-casting problems.

(c) THE MORE IMPORTANT COMMERCIAL LIGHT CASTING ALLOYS

(1) TESTING CAST ALLOYS.—The physical properties of light casting alloys with which one is concerned are the tensile properties and the resistance to alternating stresses. The tensile properties of commercial alloys are, of course, well known. Little data on the resistance to alternating stresses of these alloys are published, although such data are of the utmost importance in view of the use of such castings for machine parts subject to vibration, such as motor crank cases.

Some confusion exists with respect to the description of tensile properties. In this country a test specimen cast to size in green sand is usually used to determine these properties. This is usually 0.5 inch in diameter over the reduced section. In Great Britain a specimen cast to size in a chill is often used. Experience has shown that the tensile strength of chill-test castings of light alloys will usually average from 3,000 to 5,000 lbs./in.^{2} higher than for sand-cast ones. This should always be borne in mind in comparing tests of these alloys.

It should also be noted that standard test bars, whether attached to the casting (35s) or cast separately, do not give the properties of the casting itself. Skillman (35t) points out that attached test bars of 92 per cent aluminum, 8 per cent copper, will show a tensile strength of 18,000 to 20,000 lbs./in.^{2} if the casting is poured at the proper temperature, while sections of the casting itself ½ inch thick might have a tensile strength of 12,000 lbs./in.^{2} and those $\frac{3}{16}$ inch thick might have one of 22,000 lbs./in.^{2}.

Jeffries (35c) also points out that parts of the casting that are about ¼ inch in section approximate the properties of the ½-inch diameter test bar, while the heavier sections may have as low as 70 per cent and lighter sections over 100 per cent of the strength shown by the test bar.

Dix and Lyon (35u) found similar differences in specimens cut from large crank cases of several different aluminum alloys. These variations and those between sand and chill castings are caused by the difference in rate of crystallization during freezing, which depends on the chilling effect of the mold. (See effect of casting section, p. 153.)

Not only is the tensile strength of chill castings higher than that of sand castings, but (with the exception of the modified silicon alloys), the elongation also. In general, any variation of casting condition which increases the tensile strength of a casting alloy increases also its ductility (elongation) and a double gain of hardness and toughness is thereby obtained.

Satisfactory results are obtained either on a cast-to-size test coupon, poured horizontally in sand with gate and riser, or with the Webbert type of cast-to-size coupon, cast in core sand and fed along its whole length by a gate and pouring head. The Naval Gun Factory (Washington) uses the latter form with a gate five-eighths inch thick.

(2) ALLOYS OF ALUMINUM AND COPPER.—Among the copper alloys, the one most commonly used is the No. 12 alloy (8 per cent copper, 92 per cent aluminum). The preparation of the No. 12 alloy has been studied in detail by Anderson (61n). The alloy may be prepared by the direct addition of copper to molten aluminum, by use of the 33:67 copper-aluminum alloy and by use of the 50:50 copper-aluminum alloy. The last method is the one most favored as the melting temperature can be held down, the 50:50 alloy melting at a temperature lower than that of aluminum. The 50:50 alloy is prepared by the direct addition of molten copper to molten aluminum. In the preparation of these alloys there is an increase of temperature usually amounting to about 40 to 250° C., and sometimes even higher. This rise of temperature may be due partly to the heat of formation of the copper-aluminum compounds, to the interaction of aluminum and copper oxides or of aluminum and oxygen or to both. Carpenter and Edwards (61t) concluded that the rise of temperature was not

due to the combination aluminum-copper, but aluminum and oxygen. Other investigators find that if sufficient aluminum is added to reduce all the copper oxide in a melt of oxidized copper, subsequent additions of aluminum will not produce any further considerable rise in temperature.

Although the composition of No. 12 alloy is usually given as 8 per cent copper, 92 per cent aluminum, it frequently contains a high percentage of iron, sometimes up to 1.75 per cent. In die castings the iron content may be as high as 3 per cent. Small amounts of magnesium, zinc, manganese, or tin are sometimes intentionally added or may be unintentionally added through the use of scrap.

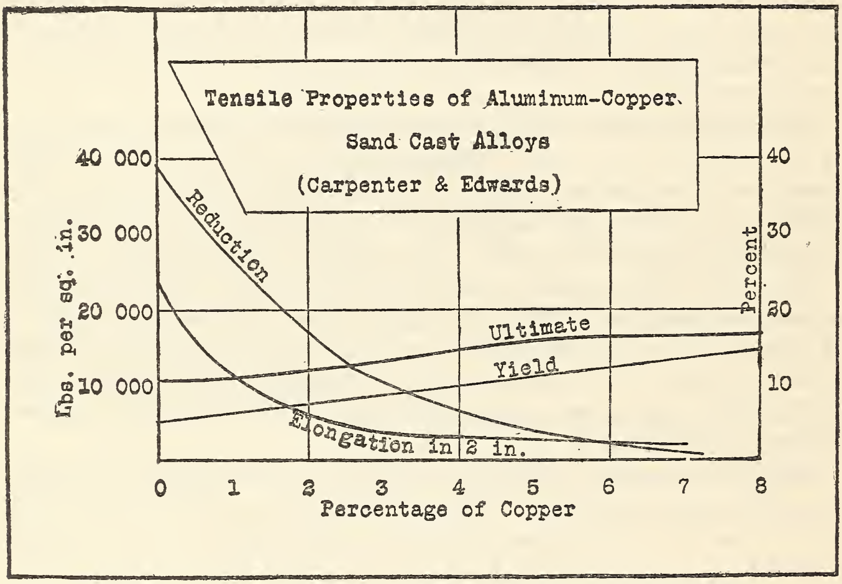


FIG. 74.—*The tensile properties of aluminum-copper sand-cast alloys.* (*Carpenter and Edwards, 61u*)

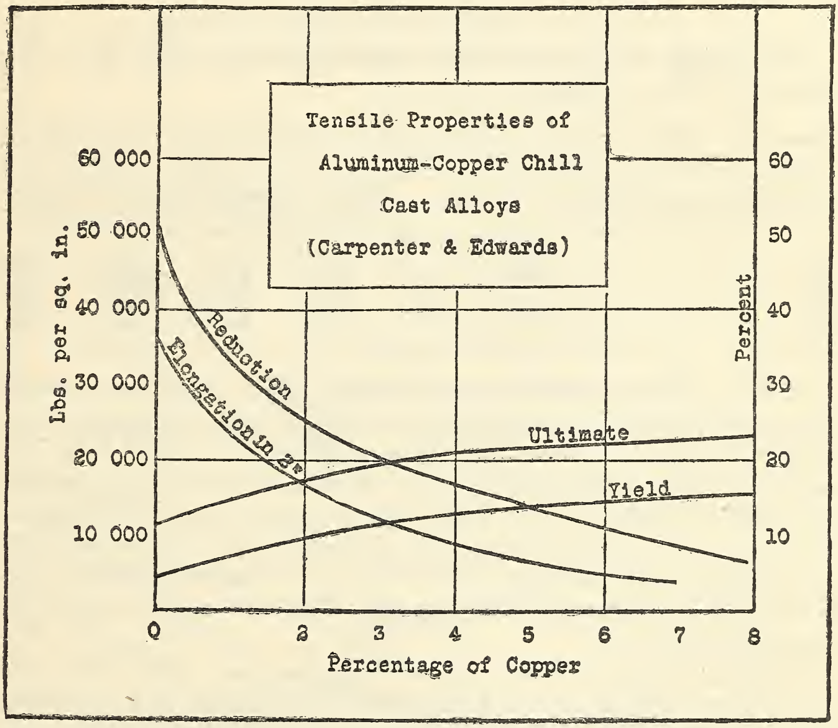
The text specimens were cast to size, 0.564 inch in diameter

The tensile properties of aluminum-copper alloys have been studied by Carpenter and Edwards (61u) and are shown in Figures 74 and 75. From this curve it is to be noted that the tensile strength of the alloy increases with increase of copper content, although Anderson (61n) states that the increase of ultimate strength ceases at 6 per cent copper, after which there is a decrease.

The following properties for the No. 12 alloy are given by Anderson (61n).

TABLE 46.—*Properties of "No. 12" aluminum-copper alloy*

Property	Westinghouse Electric Manufacturing Co.	Bureau of Mines	Lumen Bearing Co.
Ultimate strength, chill cast			20–24,000
Ultimate strength, sand cast	19,800		16–20,000
Poured hot		15,500	
Poured cold		20,000	
Elastic limit, lbs./in.^{2}	5,000		
Elongation in 2 inches, per cent	0.8	1.5	1.0–2.0
Reduction of area, do	4.9		
Brinell hardness	50		
Specific gravity	2.83	2.84	2.80
Shrinkage in 12-inch bar, inch	0.175		$\frac{3}{16}$
Coefficient of expansion, °C	0.000024		



FIG, 75.—*The tensile properties of aluminum-copper chill-cast alloys. (Carpenter and Edwards, 61u)*

Test specimens were cast to size, 0.564 inch in diameter

Jeffries[6] finds that this alloy when properly cast to give from 20,000 to 24,000 lbs./in.^{2} tensile strength will withstand 1,000,000 alternations of stress between 0 and 12,000 lbs./in.^{2} tension without failure. The alloy is not as strong in impact test as No. 31.

Broniewski (61r) finds the electrical resistance of an alloy of this approximate composition to be 5.75 μ–cm.

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[6] Private communication from Z. Jeffries.

Figures for specific gravity are given by Carpenter and Edwards (61t) as follows:

TABLE 47.—*Specific gravity of aluminum-copper alloys*

Composition		Condition of alloys		
Al-Cu	Sand cast	Chill cast	Rolled bars	Drawn bars
99.14	2.72	2.73	2.73	2.73
1.90	2.73	2.75	2.75	2.75
2.77	2.75	2.77	2.77	2.77
3.76	2.77	2.79	2.79	2.79
4.97	2.78	2.81	2.81	------------
6.15	2.81	2.83	2.83	------------
6.91	2.82	2.85	2.85	------------
8.09	2.85	2.88	2.88	------------

The density of alloys at higher temperatures are given by J. D. Edwards (61k) as follows:

TABLE 48.—*Density of aluminum-copper alloys at temperatures up to 1,000° C.*

Temperature in degrees centigrade	Condition	Copper 0 per cent	Copper 7.84 per cent	Copper 30 per cent	Copper 59.9 per cent
20	Solid	2.706	2.857	3.433	4.680
700	Liquid	2.373	2.524	3.068	4.345
800	do	2.345	2.494	3.032	4.300
900	do	2.318	3.464	2.997	4.254
1,000	do	2.291	2.434	2.962	4.208

In the work of Carpenter and Edwards (61t), tests were made upon sand castings to ascertain the effect of heat treatment, consisting of quenching from 450° C. and annealing at 450° C. The alloy containing 8.08 per cent copper showed, as sand cast, a tensile strength of 16,600 lbs./in.^{2} with approximately 2 per cent elongation; as sand cast and annealed, a tensile strength of 15,900 lbs./in.^{2}; as sand cast and quenched, 18,000 lbs./in.^{2}. Quenched alloys were consistently higher in tensile strength than the cast or cast and annealed alloys.

Ingots 3 inches in diameter and 20 inches long were heated to 400° C. and rolled in round grooves to a diameter of 1¼ inches. From this rod, portions were both hot-rolled to $\frac{13}{16}$ inch in diameter and drawn after annealing to $\frac{13}{16}$ inch diameter. From 0 to 8 per cent of copper all of the alloys rolled well, and from 0 to 4 per cent of copper they could be drawn sound. In Figures 76 and 77 are shown the results of the tests of 0.05-inch sheets and 1¼-inch diameter hot-rolled bars. The bars rolled to $\frac{13}{16}$-inch diameter showed throughout a higher tensile strength than those rolled to 1¼ inches, amounting to 2,000 to 3,000 lbs./in.^{2} The bars drawn with and without annealing showed a higher tensile strength, but also a smaller elongation. In Table 49 are shown the test results of an alloy containing 3.76 per cent of copper in different conditions.

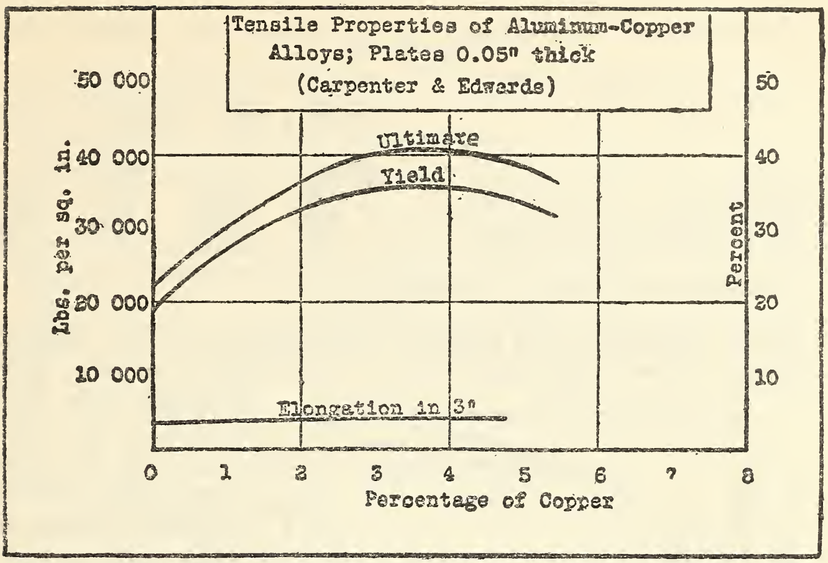

FIG. 76.—*The tensile properties of aluminum-copper alloys in the form of sheet, 0.05 inch thick. (Carpenter and Edwards)*

The ingots were cast ⅝ inch thick, hot-rolled to ⅜ inch, cold-rolled to ¼ inch, annealed, cold-rolled to 0.1 inch, annealed, cold-rolled to 0.05 inch

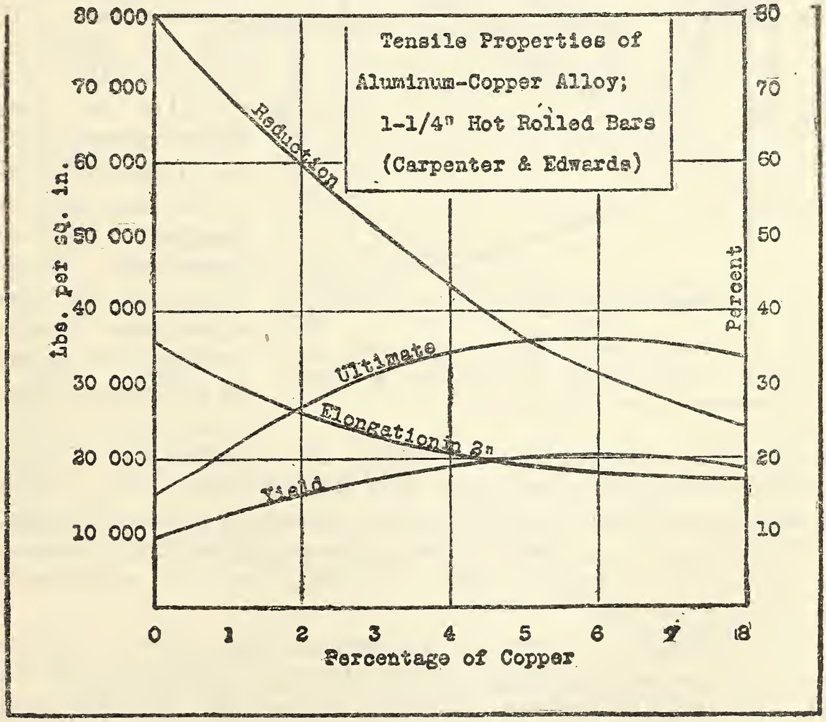

FIG. 77.—*The tensile properties of aluminum-copper alloys. (Carpenter and Edwards)*

These results were obtained on 1.25-inch diameter bars hot-rolled from 3-inch ingots to size

TABLE 49.—*Tensile properties of an aluminum-copper alloy (Carpenter and Edwards, 61t)*[1]

	Tensile strength	"Yield point"	Elongation in 2 inches	Reduction of area
	Lbs./in.^{2}	*Lbs./in.*^{2}	*Per cent*	*Per cent*
Chill casting	21, 500	12, 100	10. 5	21. 46
1¼ inch hot-rolled bar	37, 700	20, 100	20. 0	38. 21
$\frac{13}{16}$ inch hot-rolled bar	38, 000	26, 000	21. 0	49. 76
$\frac{13}{16}$ inch bar drawn with annealing	37, 900	34, 600	8. 0	21. 79
$\frac{29}{32}$ inch bar cold drawn, without annealing	44, 900	41, 500	7. 5	20. 84

[1] Alloy containing 3.76 per cent copper, in different forms.

Sheets were rolled from an ingot 6¾ by 9¾ by ⅝ inches by hot-rolling to ⅜ inch, allowing to cool and cold-rolled to ¼ inch. The resulting slab was then cut into portions, and the portions rolled down to different thicknesses with intermediate annealing. In Figure 76 are shown the results of tests upon a sheet rolled to 0.05 inch in thickness. The tensile test results on these sheets are very similar to those obtained on the same alloy in the form of rolled or drawn bars. The authors draw the conclusion that there is nothing to be gained by adding more than 4 per cent of copper for a rolling or forging alloy, as well as for a casting alloy. Their conclusion as regards the casting alloy is not in accord with modern practice which favors the use of an alloy containing 8 per cent copper.

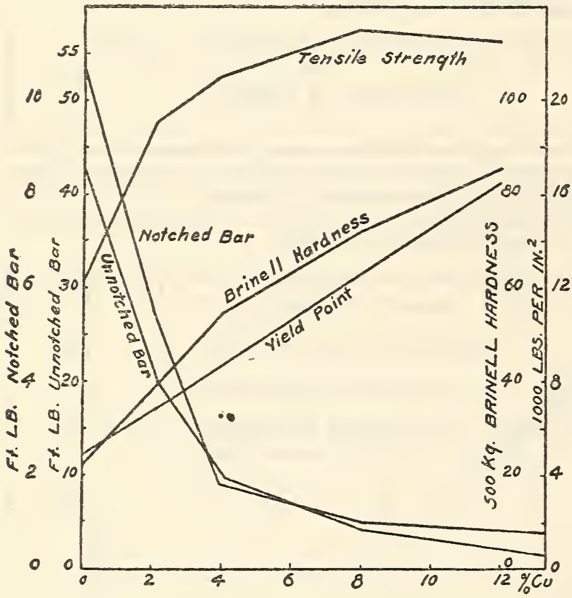

FIG. 78.—*Comparison of Charpy impact with yield point, tensile strength, and hardness of copper-aluminum alloys. (Dix, 45f.)*

The Charpy impact resistance of copper-aluminum alloys decreases with increase of copper content within the limits of experiments performed (fig. 78).

The coefficient of expansion of copper-aluminum alloys as determined at the Bureau of Standards are shown in Table 50 and Figure 79. The relation between the copper content and the coefficients of expansion of the alloys is shown in Figure 80.

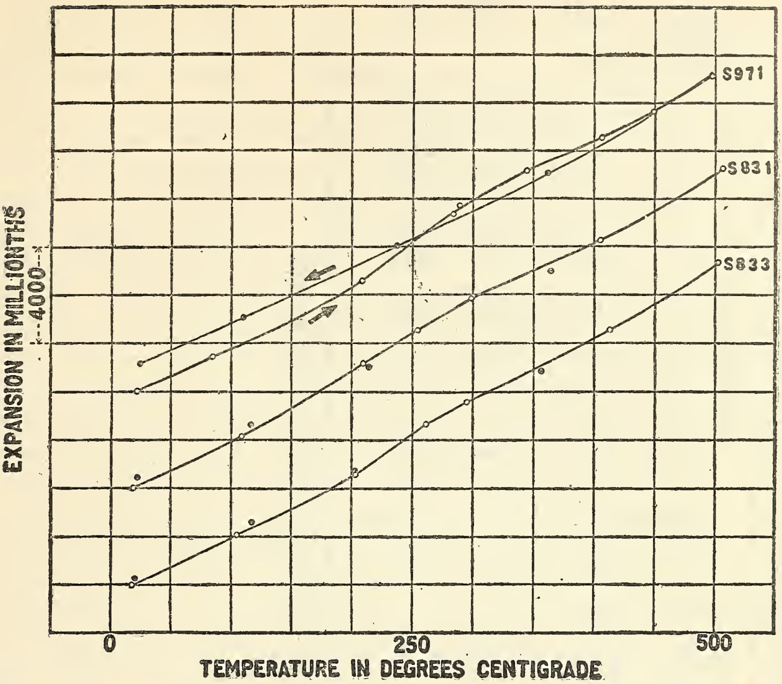

Fig. 79.—*Linear expansion of three aluminum-copper alloys (approximately 4, 8, and 12 per cent copper, respectively)*

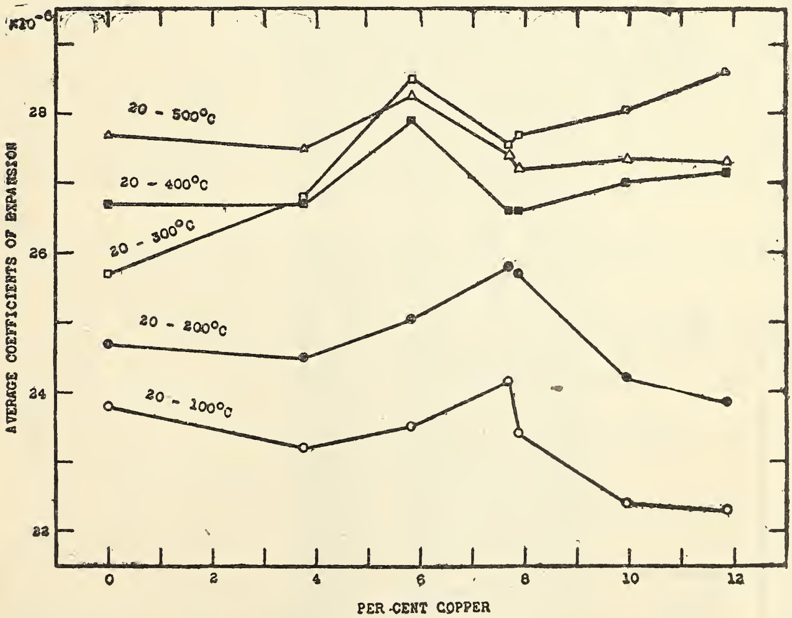

Fig. 80.—*Relations between the copper content and the coefficient of expansion of aluminum-copper alloys*

TABLE 50.—*Average coefficients of expansion and length changes of aluminum-copper alloys*

Laboratory No.	Material	Chemical analysis					Average coefficients of expansion per degree centigrade						Changes in length due to heat treatment received during test
		Aluminum [1]	Copper	Silicon	Iron	Manganese	20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.	
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	*Per cent*
S833	Approximately 4 per cent copper alloy, sand cast	95.41	3.75	0.30	0.36	0.18	23.7	24.6	27.0	27.2	26.7	27.5	+0.02
S834	Cut from same bar as S833						22.7	24.4	25.4	26.4	--------	--------	+.04
S967	Approximately 6 per cent copper alloy, cast in green sand	93.41	5.81	.36	.42	--------	23.8	24.9	26.5	27.8	27.8	28.0	+ [3].07
S968	Cut from same bar as S967						23.2	25.2	28.1	29.2	28.0	28.5	+ [3].09
[2] S829	Approximately 8 per cent copper alloy, cast in green sand	91.14	7.68	.39	.46	.33	24.6	25.3	26.1	27.1	--------	--------	--------
S830	Cut from same bar as S829						23.7	26.3	27.8	28.0	26.6	27.4	+.05
[2] S831	Approximately 8 per cent copper alloy, cast in green sand, different melt.	91.13	7.87	.33	.45	.22	23.4	26.8	27.7	28.0	26.6	27.2	+[3].04
S832	Cut from same rod as S831						23.4	24.6	26.4	27.4	--------	--------	+[3].08
S969	Approximately 10 per cent copper alloy, cast in green sand	89.22	9.95	.39	.44	--------	22.4	24.2	26.1	28.3	27.3	27.7	+[3].11
S970	Cut from same bar as S969						22.4	--------	27.8	27.8	26.7	27.0	+[3].07
S971	Approximately 12 per cent copper alloy, cast in green sand	87.30	11.88	.39	.43	--------	22.4	24.1	26.8	28.6	27.5	27.6	+[3].11
S972	Cut from same bar as S971						22.2	23.6	28.5	28.6	26.8	27.0	+.07

[1] Per cent aluminum determined by difference.

[2] This composition for No. 12 alloy, the most widely used casting alloy of aluminum in the United States, meets S. A. E. specification No. 30. These percentages of Si, Fe, and Mn are permissible but not required.

[3] At any given temperature above room temperature the variation between the expansion curves on heating and cooling did not exceed this value.

Carpenter and Edwards (61t) studied the corrosion of alloys containing up to 6 per cent copper in fresh water and sea water. Plates exposed to fresh water were slightly corroded, but gained in weight due to the coating of aluminum hydrate formed. Those exposed to sea water were badly corroded and pitted, the loss of weight ranging from 0.008 lb./ft.^{2}/month for 0.00 per cent copper, 0.93 per cent copper and 1.57 per cent copper to 0.003 lb./ft.^{2}/month for 5.34 per cent copper. The loss of weight is considerable; for the first three alloys about three and one-half times that which would be experienced by mild steel under the same conditions. It is concluded that these alloys are not suitable for construction which will be exposed to sea water. More recently the corrosion of a variety of aluminum alloys, including copper-aluminum, was reported by Hewlett and Basch (61h) and by Sayre and Basch (61c) and the results would appear to uphold those obtained by Carpenter and Edwards.

Carpenter and Edwards also studied the corrosion of copper-aluminum alloys of the same compositions in boiling tap water, 1 per cent aqueous acetic acid, 1 per cent aqueous citric acid, and 1 per cent aqueous oxalic acid. The losses in weight were 0 for tap water, from 0.0002 lb./ft.^{2}/hr. to 0.0003 lb./ft.^{2}/hr. for 100 per cent aluminum to 5.34 per cent copper in the acetic acid; 0.0001 to 0.0003 for the same alloys in nitric acid, and 0.0010 to 0.0023 in oxalic acid.

The 96 Al, 4 Cu alloy is used for sand-cast cooking utensils, the 90:10 and 88:12 for die and permanent mold castings. The 1 to 6 per cent Cu alloys may be rolled. The 96:4 alloy is suitable for sheets and shapes. (Commercial production of these forms is chiefly in the "25S" alloy, containing about 4 per cent Cu plus Mn and Si, which will be described under heat-treatable alloys.) The Cu-Al alloys can be hammered up to 10 per cent Cu, but above 10 per cent Cu they are brittle (61i). The binary light aluminum copper alloys, without addition of other elements, are chiefly used in the cast condition.

Liberty motor crank cases averaged from 8.06 to 8.21 Cu, 0.92 to 1.04 Fe, 0.28 to 0.40 Si, and balance aluminum.

Copper alloys containing from 8.5 to 14 per cent copper are used for castings which are to be subjected to high temperatures, such as manifolds, pistons (see Table 28), and also for castings to withstand pressure, such as for pumps, etc.

The 8.5 to 11 per cent alloy is generally used for pistons, and the 11 to 14 per cent alloy used for pressure castings.

These alloys will ordinarily give the following physical properties:

Tensile strength, lbs./in.^{2}	18,000–19,000
Elongation in 2 inches	Usually less than 1 per cent.
Density 8.5 to 11 per cent copper	2.95
Density 11 to 14 per cent copper	3.00

Certain of the casting alloys which were manufactured by the Aluminum Castings Co. and sold under the trade name "Lynite" are almost identical with the alloys mentioned above. The composition and physical properties of the "Lynite" alloys as guaranteed by the company were as follows:

Lynite No. 122 (for castings for use at higher temperatures, pistons, etc.) (or S. A. E. No. 32):

Copper	per cent	9.25–10.75.
Other elements	do	Not over 2.
Aluminum	do	Balance.
Density		Not over 2.95.
Permanent mold—tensile strength	lbs./in.^{2}	About 28,000.

Lynite No. 109 (for pressure castings):

Copper	per cent	11.5–13.5.
Other elements	do	Not over 1.7.
Aluminum	do	Balance.
Density		Not over 2.97.
Sand cast—tensile strength	lbs./in.^{2}	19,000.

(3) ALLOYS OF ALUMINUM AND SILICON.—Some points in regard to these alloys, such as the fact that by "modification" there can be produced a condition of unstable equilibrium, in which the eutectic composition appears to be higher in silicon than in the normal or unmodified alloys, and the freedom of these alloys from hot shortness and shrinkage cracks have been previously mentioned under the silicon aluminum equilibrium diagram, page 122. (See figs. 62 to 64, p. 124, 125, and 126, for thermal expansion.)

The chief drawback of these alloys is their very low proportional limit (fig. 81). Where this is not an important objection, the alloys are very useful and are coming more and more into commercial use, especially where lightness is of major importance. Silicon has a lower specific gravity than aluminum, and hence the alloys are slightly lighter than pure aluminum. They are more resistent to corrosion than most other alloys suitable for castings and are being employed for outdoor exposure (76c). Their most notable advantages are their ductility, and their superior casting properties, which include relative freedom from cracking and leaking, and a degree of fluidity which makes possible the casting of unusually thin sections and fine details.

The alloys containing up to about 13 per cent silicon may be cast in the "normal," or the "modified" condition. The "modified" condition is the more common for the alloys of the higher silicon content, but the unmodified or normal alloy with 5 per cent silicon is probably used more widely in this country at present than the higher silicon type. The "Alpax" alloys, which belong to this class, may be considered as having the following properties:

Tensile strength	lbs./in.²	25,600–32,700
Elongation in 2 inches	per cent	5–10
Brinell hardness		52
Specific gravity		2.60–2.65

Daniels (76j) gives the physical properties of aluminum-silicon alloys as follows:

Table 51.—*Properties of normal Al-Si alloys*

Silicon	Ultimate strength	Elongation in 2 inches	Brinell hardness	Specific gravity
	Lbs./in.²	*Per cent*		
0.14	11, 050	29. 2	20	2. 68
0.50	12, 240	18. 0	23	2. 66
0.64	12, 270	12. 8	24	2. 67
1.20	13, 830	12. 5	28	2. 66
2.80	16, 370	10. 2	31	2. 64
4.80	18, 310	7. 8	34	2. 62
AS QUENCHED AND AGED				
0.50	12, 850	25. 3	22	2. 67
0.64	13, 690	19. 7	24	2. 67
1.20	16, 270	17. 2	29	2. 66
2.80	18, 160	13. 8	30	2. 64
4.80	19, 990	17. 0	32	2. 63
AS ANNEALED 550 TO 1,025° F.; 96 HOURS, FURNACE COOLED				
0.50	11, 630	26. 0	19	2. 67
0.64	11, 210	19. 2	23	2. 67
1.20	11, 210	19. 5	21	2. 68
2.80	11, 180	9. 8	22	2. 59
4.80	10, 800	6. 0	22	2. 62

The properties were obtained on normal (unmodified) alloys cast to size (0.505 inch diameter) in green sand. The iron content of the alloys was about 0.32 per cent. Up to 2.8 per cent silicon the alloys piped like pure aluminum. From 2.8 to 4.8 per cent they piped less and were sounder. Quenching and aging effected little improvement in ultimate strength and hardness of the alloys. The 4.80 per cent silicon alloys showed an increase in ductility on heat treatment without loss of strength or hardness.

Grogan (76e) has given data for modified aluminum-silicon alloys of higher silicon content than those described by Daniels. Table 52 gives his results. All his data for the various properties studied may be plotted as straight lines against silicon content. The data of Archer and Kempf (76d) (fig. 82) are averages of many tests and are more representative than the data of the tables. Archer and Kempf's tests were made on specimens cast to size (0.505 inch diameter) in green sand. The copper content of the alloys was less than 0.05 per cent and, unless noted, the iron content was about 0.35 per cent.

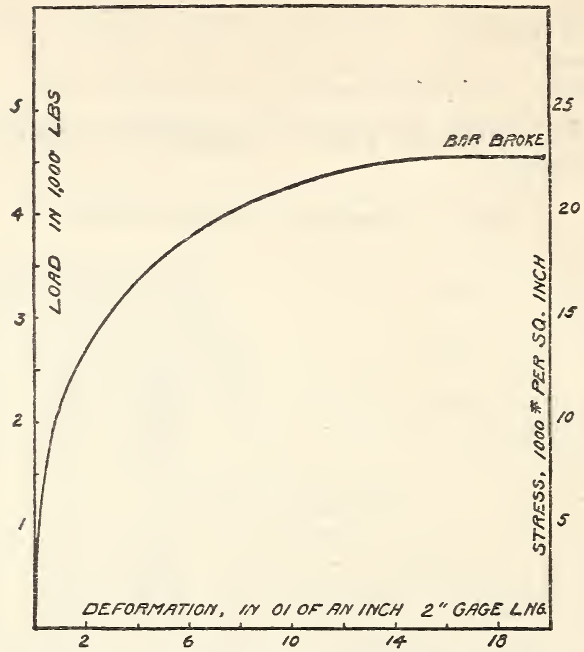

Fig. 81.—*Load deformation curve of modified alloy containing 10 per cent silicon. (Archer and Kempf, 76d)*

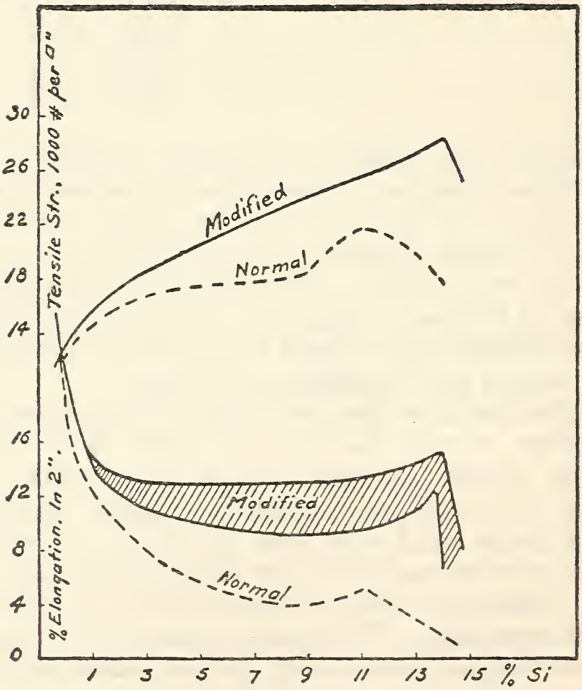

Fig. 82.—*Physical properties of normal and modified aluminum-silicon alloys containing about 0.35 per cent iron. (Archer and Kempf, 76d)*

TABLE 52.—*Mechanical tests of silicon-aluminum alloys, "flux" modified*

CHILL

Analysis		Density	Brinell hardness[1]	Proof stress[2]	Ultimate stress	Elongation in 2 inches	Charpy[3] foot-pounds
Silicon	Iron						
				Lbs./in.^{2}	*Lbs./in.*^{2}	*Per cent*	
7.8	0.3	2.682	50.4	12,500	27,000	19.0	1.34
9.8	.3	2.673	55.3	14,500	28,500	13.5	1.01
12.0	.4	2.663	60.5	17,000	30,000	11.0	.89
13.5	.45	2.658	61.5	[4] 16,800	30,500	11.0	.56
14.1	.45	2.655	65.0	17,500	31,000	10.0	----------
SAND. MOLDED HORIZONTALLY							
7.8	0.3	2.680	43.9	11,000	23,500	16.5	0.80
10.0	.3	2.671	46.9	12,500	24,000	15.0	.66
12.0	.4	2.661	50.8	14,000	26,000	9.5	.45
13.0	.5	2.651	55.1	16,000	27,000	10.5	.44
14.3	.65	2.651	56.8	14,500	26,500	8.0	----------

[1] Brinell hardness, ball, 10 mm.; load, 500 kg.

[2] The proof stress is that stress which will produce a permanent deformation of 0.5 per cent in a length of 2 inches.

[3] Charpy test-piece dimensions: Cross section =5 by 5 mm.
Bottom of notch=5 by 3.5 mm.
Form of notch= "V" angle 45°, root radius =0.25 mm.

[4] Proof stress on a 13 per cent chill cast alloy for permanent deformation of 0.15 per cent in 2 inches instead of 0.5 per cent, is only 11.500 lbs./in.^{2}.

Grogan tried the addition of about 5 and 10 per cent zinc and of 0.4 to 0.7 per cent magnesium to each of the 8 and 12 per cent silicon alloys and obtained inferior physical properties, especially in elongation, in all.

The mechanical properties of normal sand-cast silicon aluminum alloys of varying silicon contents as given by different writers are listed below.

TABLE 53—*Properties of normal Al-Si alloys of 5, 8, and 13 per cent Si*

Silicon	Ultimate strength	Proportional limit	Elongation	Brinell hardness	Specific gravity	Reference
	Lbs./in.^{2}		*Per cent*			
5	18,000	----------	5-6	----------	----------	(76t)
5	18,100	3,200	7.8	34	2.62	(76x)
5	17,800	----------	5.3	40	2.63-2.68	(76k)
5	17,850	3,000	5.3	40	----------	(76w)
8	18,500	----------	5.5	40	----------	(76k)
13	21,000	----------	2	----------	----------	(76t)

Modification may be brought about by sodium or potassium fluoride, according to the method of Pacz (96l) or by metallic sodium or potassium, according to the method of Edwards, Frary, and Churchill (96a). The latter method is now the more generally used.

The properties of the modified aluminum-silicon alloys have also been discussed by Stockdale and Wilkinson (76h). The "modified" alloys include those known as "Alpax," and "Silumin." These alloys have a specific gravity of 2.60 to 2.65 (76y, w, z, k). The thermal coefficient of expansion is slightly under 20×10^{-6} (88g). The thermal conductivity is stated to be 0.386, electrical conductivity 40 (76z), but the thermal conductivity is probably higher than the figure stated. The Alpax alloys have a tensile strength of 25,600 to 32,700 lbs./in.^{2}, elongation 5 to 10 per cent (76r), Brinell hardness 52 at 18° C., 45 at 100° C., and 18 at 350° C. (76r). Tapsell (76l) states that the tensile strength falls steadily with rising temperature, being much lower at 250° C. than that of "Y" alloy as cast. The alloys are primarily casting alloys but the mechanical properties of rolled Alpax are superior to those of rolled aluminum up to 300° C. (76r). For a comparison of high temperature properties of various alloys, see page 77. Rolled annealed Alpax has a tensile strength of 22,800 lbs./in.^{2}, elongation 28 to 30 (76r); hard worked Alpax has a tensile strength of 35,000 lbs./in.^{2}, elongation 5 per cent. Wear under friction is said to increase with increasing per cent of silicon (76r) although this is the opposite of what would be expected. Iron may be present as $FeAl_3$, FeSi or iron-aluminum silicide. The iron content has an influence on the properties of the modified alloys as shown in curves (figs. 83 and 84) and should be kept low. The refinement exerts only a small effect on the size and distribution of the iron silicide grains so that presence of iron results in a sudden loss of elongation (76k). The iron content that can be present without effect varies with the silicon content, the more silicon being present, the less iron should be present.

The improvement attainable by modification of sand castings is shown in Figure 82. Chill casting tends toward modification (fig. 85). The alloys lose strength at elevated temperatures much as the copper aluminum alloys do (fig. 86). (See also figs. 31 and 32.)

The amount of modifier must be sufficient, and varies with the amount of silicon in the alloy (figs. 87 and 88). If the modified melt is held long enough for the sodium to "burn" out partly, the remaining amount of sodium may not be sufficient (fig. 89).

Heat treatment by quenching and aging is said by Swan (76aa) to have no effect on the alloys, but this statement does not agree with the data of Daniels (76j). Long annealing at low temperatures (300 to 350° C.) produces little effect. As the temperature increases, coalescence of the silicon grains in the eutectic commences, reaching a maximum at 550° C. (76aa) and causing a softening. Prolonged heating just below the melting point of the eutectic decreases tensile strength and increases the elongation (96p); also Archer (76d).

The cast Alpax alloys are more resistant to concentrated nitric acid than other aluminum alloys (76r), but the loss of weight of rolled Alpax is greater. Investigations of the General Electric Co. showed that after eight weeks in nitric acid the 5 per cent silicon alloy was not appreciably attacked, and the 8, 10, and 13 per cent silicon alloys were in good condition throughout (76k).

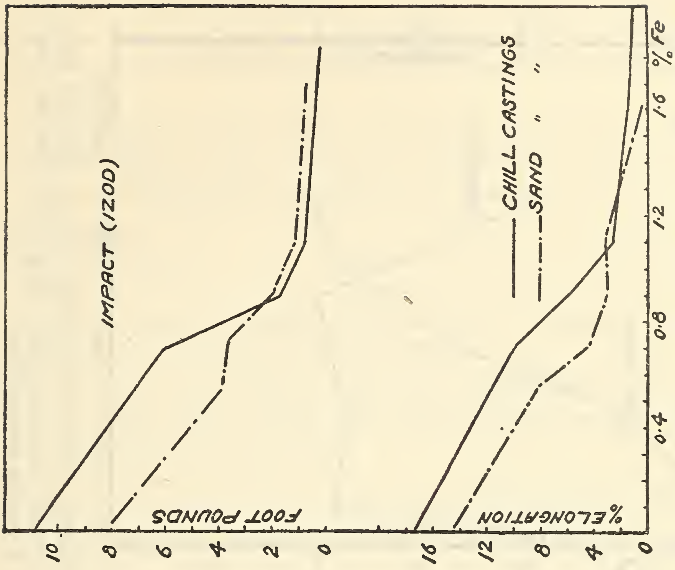

FIG. 84.—*Influence of iron on elongation and resistance to impact of alloys containing 10 and 11 per cent silicon.* (*Gwyer and Phillips, 76f*)

FIG. 83.—*Effect of iron content on physical properties of modified alloys containing 11 to 14 per cent silicon.* (*Archer and Kempf, 76d*)

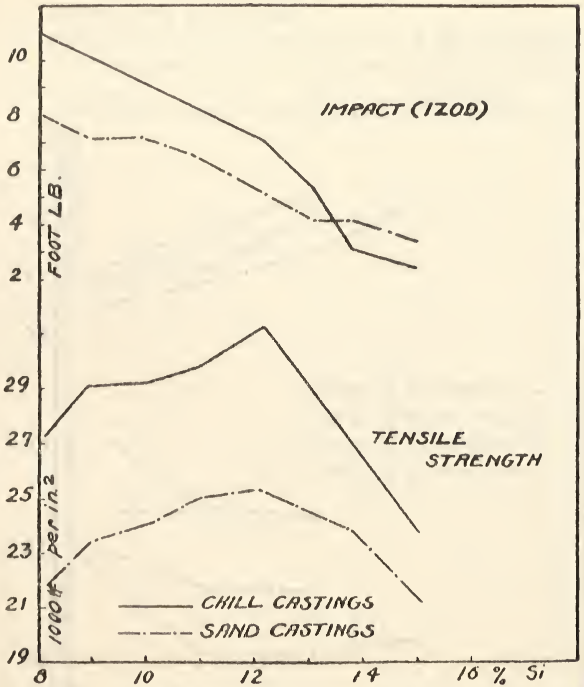

FIG. 85.—*Influence of silicon on tensile strength and resistance to impact in chill and sand casting.* (*Gwyer and Phillips, 76f*)

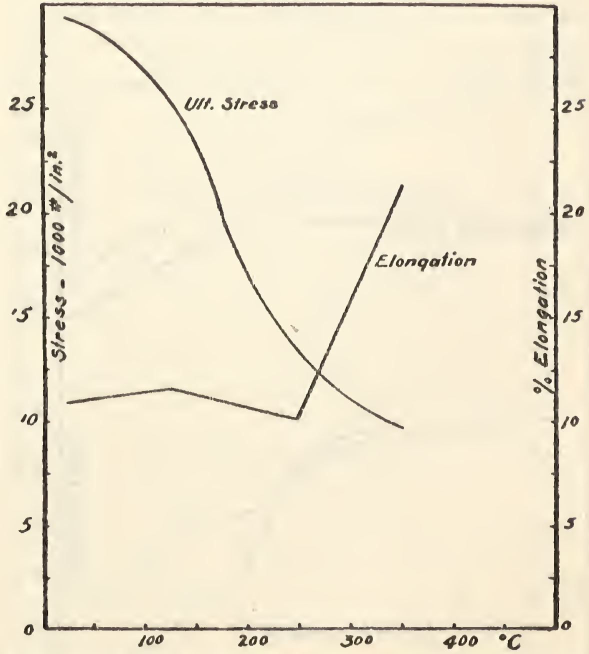

FIG. 86.—*Tensile tests of chill cast bars* (1⅛*-inch diameter*) *of aluminum-silicon alloy of 12.7 per cent silicon at varying temperatures.*

(4) Alloys of Aluminum and Magnesium.—This alloy is one of the earliest commercial alloys. The term "Magnalium" originally connoted an alloy of aluminum containing from 5 to 30 per cent of magnesium but was later extended to cover a variety of commercial alloys containing magnesium and also small quantities of copper and nickel.

A "magnalium" used at one time by the Westinghouse Electric & Manufacturing Co. (61q) contained 5 per cent of magnesium. This alloy may be depended on to give the following tensile properties:

Tensile strength	lbs./in.^{2}	20, 000
Elongation in 2 inches	per cent	0. 5–2
Specific gravity		2. 63

With care a tensile strength of 25,000 lbs./in.^{2} and an elongation of 5 per cent may be obtained on this alloy.

Such alloys, up to about 10 per cent magnesium, were formerly used when ultra-light castings were needed but have been superseded by the aluminum-silicon alloys.

(5) Alloys of Aluminum and Zinc.—Although binary aluminum-zinc alloys formerly found extensive use in England, other alloys are coming into use there (85c), and the zinc alloys have never found extensive use in this country. The 67 : 33 Al-Zn alloy was formerly used to some extent for castings in this country (85g), and while the 80 : 20 Al-Zn alloy, which may be cast, rolled, or extruded (85g) has been said to have the best combination of mechanical properties, present practice seldom exceeds 15 per cent in the binary alloys, and even these are very little used. The 5 to 10 per cent zinc alloys may be drawn.

The alloys are prepared by the direct combination of aluminum and zinc, no intermediate alloy being necessary. Iron-pot practice should be carried out with care as the alloys dissolve iron rapidly (85g).

The principal investigation of this alloy series is that of Rosenhain and Archbutt (85q) who, besides their study of the constitution of the alloy series, carried out tensile, impact, and alternating stress tests of cast and wrought alloys. The tensile properties were studied at higher temperatures and corrosion tests made on castings.

For sand cast Al-Zn alloys, there is a gradual increase in tensile strength with increasing zinc to a maximum at about 50 per cent zinc. The strength of chill castings is slightly greater at all compositions than that of the sand castings. The strength of the sand cast alloy (fig. 90) rises from 12,000 lbs./in.^{2} for the 5 per cent zinc alloy to 42,000 lbs./in.^{2} for the 50 per cent alloy, the yield point rising from 6,000 lbs./in.^{2} to 29,000 lbs./in.^{2}, and the elongation dropping from 16 to 2 per cent. With the chill cast alloy (fig. 91) the strength rises from 15,000 lbs./in.^{2} for the 5 per cent zinc alloy

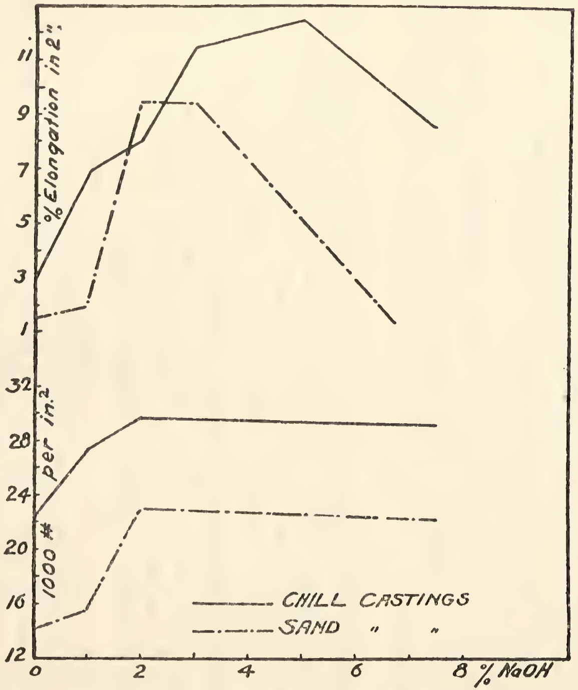

FIG. 87.—*Influence of quantity of modifier on tensile strength and elongation of 11 per cent silicon alloy. (Gwyer and Phillips, 76f)*

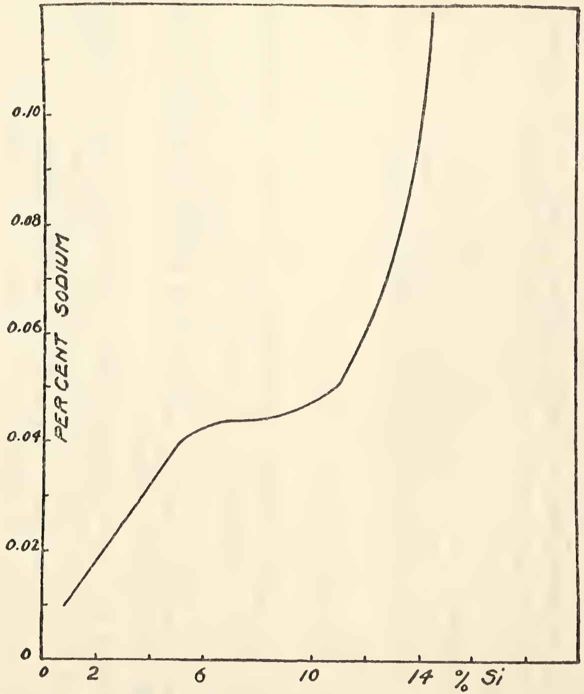

FIG. 88.—*Effect of silicon content of alloys on quantity of sodium required for modification. (Archer and Kempf, 76d)*

to 48,000 lbs./in.^{2} for the 50 per cent alloy, the "yield point" rising from 6,500 lbs./in.^{2} to 12,000 lbs./in.^{2} and the elongation falling from 29 per cent to 1 per cent (85g, 85q). The specific tenacity of the sand cast alloys is shown in Figure 92.

Tests for possible spontaneous disintegration of cast alloys containing 9 to 75 per cent zinc over a period of 15 months showed no disintegration (85q), the conclusion being that this type of aging process must be of an extremely gradual character. It was found, however, that in every case there had been an increase of tensile strength, varying from 500 to 4,000 lbs./in.^{2} accompanied in some cases by decrease, in others by increase of elongation. This agrees with practical experience with these alloys in that immediately after casting they are not readily machined, but "drag." After aging for a few weeks a marked improvement in machineability occurs. For the effect of a variety of heat treatments on the properties of alloys containing up to 20 per cent zinc, reference is made to the extensive investigation of Tiedmann (85d).

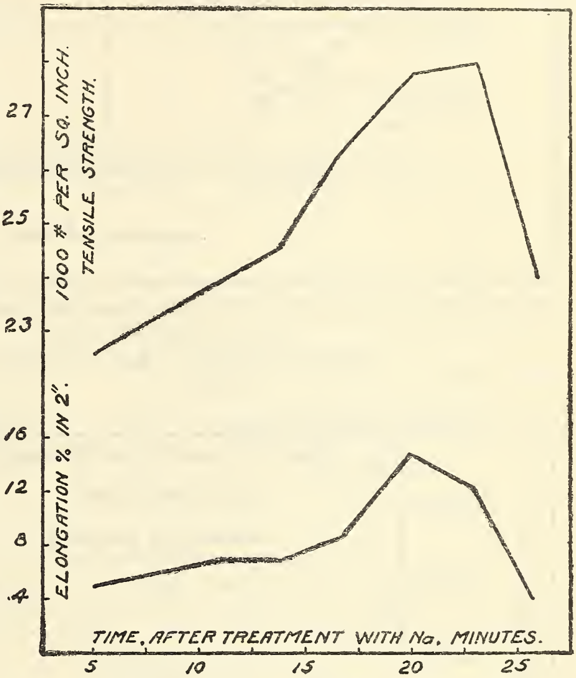

Fig. 89.—*Effect of time of holding after addition of sodium on physical properties of modified aluminum-silicon alloy 13.7 per cent silicon.* (*Archer and Kempf, 76d*)

Recent work of Fraenkel and Goez (85e) on the decomposition of the compound Al_2Zn_3 showed a definite evolution of heat on breaking up of the compound accompanied by a contraction of volume of about one-third per cent. The authors give the range of stability of Al_2Zn_3 as extending from 256 to 460° C., the melting point. Below 256° C. the compound breaks up. Bauer and Heidenhain (85h) have also studied the limits within which Al-Zn alloys tend to instability. Between 0 and 15 per cent aluminum, and 40 to 100 per cent aluminum following quenching at 320° C., there is an increase in

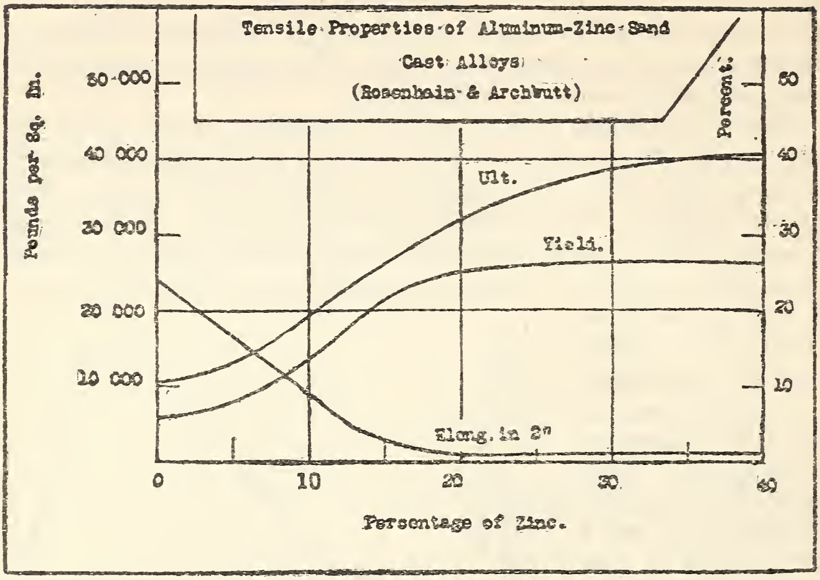

FIG. 90.—*The tensile properties of aluminum-zinc sand-cast alloys. (Rosenhain and Archbutt, 85q)*

Test specimens were cast to size, 0.564 inch in diameter

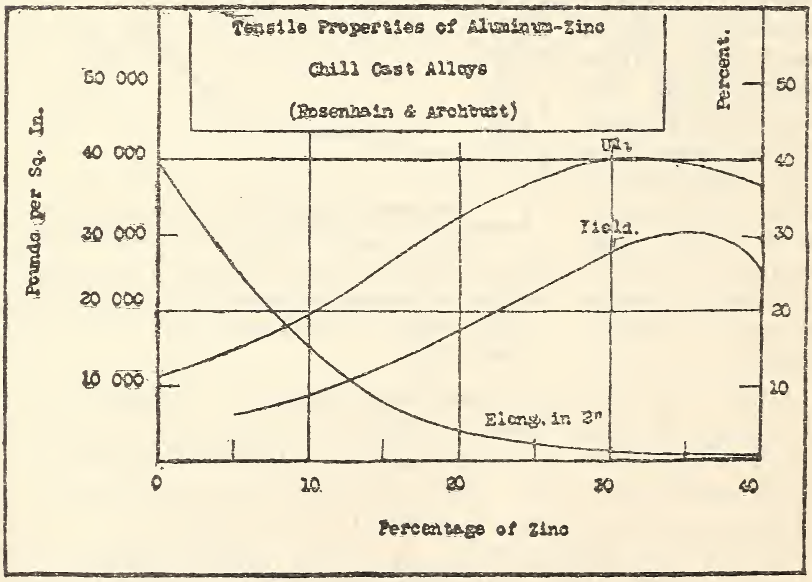

FIG. 91.—*The tensile properties of aluminum-zinc chill-cast alloys. (Rosenhain and Archbutt, 85q)*

Test specimens were cast to size, 0.564 inch in diameter length, between 15 and 40 per cent aluminum a decrease; the compound Al_2Zn_3 breaks up immediately after quenching with an evolution of heat accompanied by a decrease in length. The authors attribute the change of length to the breaking up of Al_2Zn_3 to alpha and gamma crystals which have a different volume. They advise avoiding alloys containing 0.75 to 83 per cent aluminum for chill castings.

In the investigation of Rosenhain and Archbutt (85p) the 25 per cent zinc-aluminum alloy was rolled fairly readily, but the 30 per cent alloy cracked considerably, so that 25 per cent may be looked upon as the maximum composition which can be rolled. Experiments showed that the malleability increases with increase of temperature up to 400° C., but at 450° C. the test specimens cracked, and at 500° C. broke into coarse powder. Alloys containing up to 15 per cent zinc stood cold drawing well.

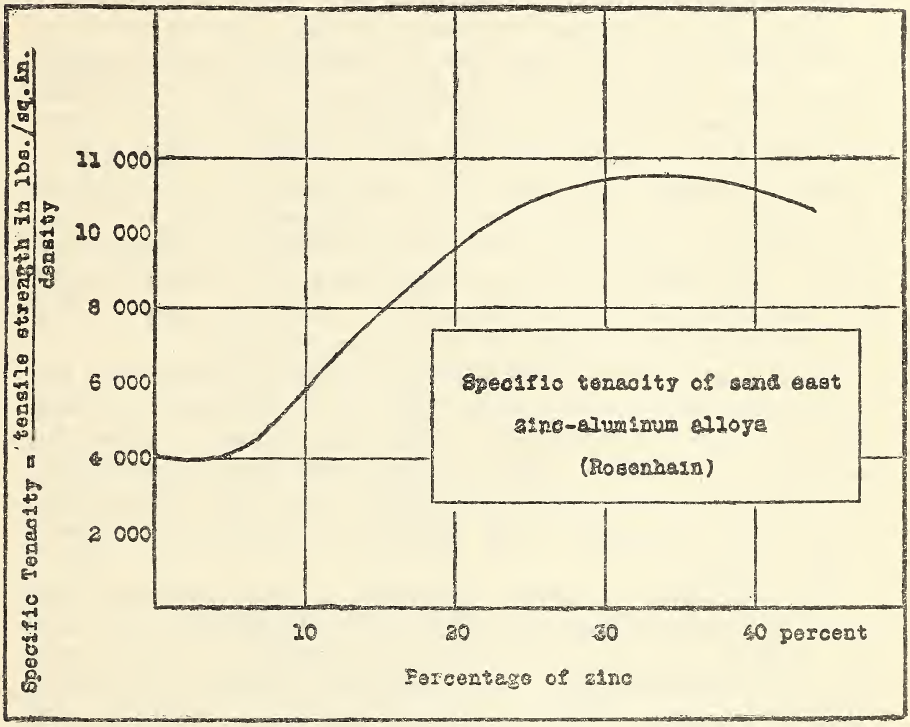

Fig. 92.—*The specific tenacity of sand-cast zinc-aluminum alloys.* (*Rosenhain and Archbutt, 85q*)

There is a general tendency of Al-Zn alloys containing more than 15 per cent zinc to deteriorate with work, the greater the amount of work and the higher the zinc content, the greater the deterioration in strength. In considering the strength of cold-drawn bars drawn to thirteen-sixteenths inch diameter from the hot-rolled 1¼-inch diameter rods it is remarkable that the ultimate strength of the cold-drawn bars is very little higher than that of the original hot-rolled bars from which they were drawn. Alloys higher in zinc (above 15 per cent) show a lower ultimate strength in the cold-drawn than in the hot-rolled state. No amount of further work, whether applied to the metal when hot or cold, increases the tensile strength of the 25 per cent aluminum alloy beyond that which is attained in the form of 1¼-inch hot-rolled bars, the only marked effect of cold-work being to bring about some reduction in the ductility of the alloy.

Tensile tests at elevated temperatures on the 13 per cent alloy, as seven-eighths-inch rolled bars, showed a decrease in tensile strength from 32,100 lbs./in.^{2} at 18° to 11,900 lbs./in.^{2} at 200°. The yield point increased from 15,700 lbs./in.^{2} at 18° to 18,350 lbs./in.^{2} at 50°, and then fell to 11,100 lbs./in.^{2} at 200°. A yield point so near to ultimate strength is surprising, and since Rosenhain and Archbutt do not state their criterion for yield point, seems open to doubt. The figure for proportional limit would probably be considerably lower. The elongation fell from 31 per cent at 18° to 29 per cent at 75°, and then rose to 48 per cent at 200°. As shown on page 82, the zinc alloys are not desirable for high temperature use.

These alloys and any of the alloys of considerable zinc content are much more liable to crack in the mold, due to hot-shortness (34-f) than the aluminum copper alloys, and very much more so than the aluminum-silicon alloys. This, combined with their poor resistance to corrosion and their high specific gravity, has in this country outweighed the advantage of high strength of the binary or ternary alloys with zinc.

The coefficient of thermal expansion of three-sixteenths inch diameter rolled bar between 0 and 18° C. is 0.0000227 for 5 per cent Zn, 0.0000231 for 15 per cent Zn, and 0.0000234 for 20 per cent Zn (seven-eighths-inch bar). An investigation of Schulze (85o) of the thermal expansion of aluminum-zinc alloys showed that between 250 and 280° the values obtained for alloys containing up to 62.5 per cent aluminum are smaller when determined with rising temperature than with falling temperature, indicating a chemical transformation. The irregularities in the curves are attributed to the formation and decomposition of Al_2Zn_3. Since, however, this compound is only present in the approximate region 1 to 70 per cent aluminum, the measurements indicate that a hysteresis phenomenon is first manifested in the expansion in the alloy containing 62.5 per cent aluminum. Measurements of the coefficients of expansion of aluminum-zinc alloys containing approximately 12, 77, and 95 per cent zinc have been made at the Bureau of Standards and the results are shown in Table 54.

TABLE 54.—*Average coefficients of expansion and length changes of aluminum-zinc alloys*

Laboratory No.	Material	Chemical analysis						Average coefficients of expansion per degree centigrade						Changes in length due to heat treatment received during test
		Aluminum	Zinc	Copper	Silicon	Iron	Manganese	20 to 100°C.	20 to 200°C.	20 to 250°C.	20 to 300°C.	20 to 400 C.	20 to 500°C.	
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	*Per cent*
[1] S841	Zinc alloy, rolled and drawn to hexagonal shape	85.83	12.17	1.47	0.21	0.31	0.01	24.3	28.1	28.3	27.9	27.6	28.6	+0.01
S842	Cut from same bar as S841 [2]							25.5	27.3	28.5	28.3	----------	----------	----------
[3] S389	Approximately 77 per cent zinc alloy	22.57	[4] 77.22	.05	.05	.11	Nil.	[5] 27.5	29.6	----------	----------	----------	----------	+.02
								26.0	28.3	30.5	----------	----------	----------	−.01
[3] S388	Approximately 95 per cent zinc alloy	5.29	[4] 94.66	.02	.01	.02	Nil.	[5] 33.3	35.7	----------	----------	----------	----------	+.02
								32.0	37.2	40.7	----------	----------	----------	+.02

[1] Moderately high zinc rolling alloy sold mostly in the form of rod and wire.

[2] Aluminum by difference.

[3] Submitted by the metallurgical division of this bureau (chemical analysis by Aluminum Co. of America).

[4] Zinc by difference.

[5] Values given on this horizontal line were obtained on a second heating.

Corrosion tests on sand and chill castings in sea water showed the chill castings to be superior to the sand castings in this respect. The investigation of Bauer and Heidenhain (85h) with 1/50 *N* HCl, 1/50 *N* caustic soda and 1 per cent salt solution showed the greatest solubility in the HCl at the Al_2Zn_3 composition (21.65 per cent aluminum) from which the solubility fell regularly to that of pure aluminum. The results for 1 per cent salt solution were similar, while those for the caustic soda showed the reverse, the minimum attack occurring at Al_2Zn_3 composition and rising to the solubility of pure aluminum.

The hardness of the 15 per cent and 30 per cent zinc alloys at low temperatures has been given by Guillet and Cournot (85l), the hardness of the 15 per cent zinc alloy falling from 55 at 20° to 47 at −20°; 48 at −80°, and then rising to 76 at the temperature of liquid air. For the 30 per cent zinc alloys, the hardness rises from 129 at 20° to 137 at −20°, falls to 121 at −80°, and then rises to 192 at the temperature of liquid air.

The linear shrinkage of the 15 per cent zinc alloy may be taken as 17/100 inches per foot (10e). The density of the 5 per cent zinc alloy is 2.76 (85j), of the 16 per cent zinc 2.99, of the 23 per cent Zn 3.15.

The work of Rosenhain and Archbutt may be summarized as follows:

(1) It has been found possible to roll out bars and even draw into wire an alloy containing as much as 26 per cent zinc. This alloy attains its maximum tensile strength when in the condition of hot-rolled bar 1¼ inches in diameter, the maximum strength being 61,000 lbs./in.^{2} This alloy has a density of 3.24 when hot-rolled.

(2) Further rolling down of this alloy does not improve, but diminishes the tensile properties of the material.

(3) Both the binary and ternary alloys referred to differ from the majority of nonferrous alloys in the fact that in the rolled condition they exhibit a definite and well-marked yield point similar to that of mild steel.

(4) A great defect of this group of alloys is their great sensitiveness to rise of temperature in relation to their tensile strength. Thus, the alloy containing 25 per cent zinc loses 26 per cent of its tensile strength at 20° C. when the temperature is raised to 100° C. The highest tensile strength of the cast alloys determined was 42,000 lbs./in.^{2} for an alloy containing 50 per cent of zinc. The highest for the wrought alloys was that of the 1¼-inch hot-rolled bars of 26 per cent zinc content and having a tensile strength of 61,000 lbs./in.^{2}, a yield point of 56,000 lbs./in.^{2}, and an elongation of 16.5 per cent on 2 inches.

(5) Single-blow impact tests made on the Izod machine showed that the work absorbed by fracture reaches a maximum for a zinc

content lying between 15 and 20 per cent. This, for an alloy containing 15 per cent of zinc, is 5.8 foot-pounds. Under the Arnold alternate bending test the resistance of the alloys falls rapidly with the increase of zinc content.

(6) ALLOYS OF ALUMINUM AND MANGANESE.—A 2 per cent manganese alloy is used for small castings that are resistant to the corrosive attack of salt water and weak organic acids (68b) or for cases where ductility is desired and a low proportional limit can be endured. Above 1 per cent, manganese additions increase shrinkage and porosity, little strength and elongation being gained by adding more than 2 per cent manganese (68c). The 4.6 per cent manganese alloy machines like cast iron (68c) and the 9.6 per cent manganese alloy is subject to internal stresses sufficient to cause exudation of the liquid eutectic (68c). A homogeneous metal can not be obtained above 12 per cent manganese (68j).

Manganese makes aluminum at first harder and stronger, but less ductile, and then decreases the strength (68i). The alloys have been studied by Daniels (68c), who gives the following figures for properties of the sand-cast and quenched and aged alloys. (See Table 55.)

TABLE 55.—*Tensile properties of Al-Mn alloys*

SAND CAST

Manganese	Ultimate strength	Elongation	Brinell number	Specific gravity
	Lbs./in.^{2}	*Per cent*		
0.54	11,750	38.5	20	2.68
1.02	13,930	27.2	25	2.691
2.88	14,900	2.6	36	2.713
4.56	16,860	3.0	39	2.720
9.60	12,560	0	46	2.765
QUENCHED AND AGED				
0.54	13,960	35.8	24	2.690
1.02	15,430	23.3	27	2.697
2.88	15,300	3.3	35	2.715
4.56	16,930	2.3	40	2.723
9.60	11,300	0	48	2.768

Streeter and Faragher (68e) give properties of 16,000 to 20,000 lbs./in.^{2} tensile, 3.5 to 6.5 per cent elongation, 6,000 lbs./in.^{2} approximate yield point, and 40 Brinell hardness for the alloy No. 106 (2 per cent manganese).

Daniels (68c) states that the extent of corrosion of the manganese alloys was about the same as for pure aluminum, but less for the 8 per cent copper alloy. An increase in manganese over 1 per cent and heat treatment did not alter the behavior. The alloys are more resistant to salt spray than to distilled water. All are superior to the 8 per cent copper alloy and compare favorably with the aluminum-silicon alloys. The resistance to corrosion is thought to be due to a film of manganese oxide which forms and retards further corrosion (68g).

The 25:75 manganese-aluminum alloy is used to some extent in adding manganese to aluminum or other alloys. This alloy is subject to disintegration. It may be made by adding solid manganese to liquid aluminum, the temperature of the aluminum being kept low to avoid excessive oxidation (68g). The 1.5 per cent manganese alloy may be made by adding part of the calculated amount of the 25:75 alloy to molten aluminum, the remainder being added alternately with the remainder of the aluminum. An excess of the intermediate alloy is required to make large heats of specified composition, the manganese content being made higher than desired and then reduced by adding aluminum.

Measurements of the coefficients of expansion of some manganese-aluminum and copper-manganese-aluminum were made by the Bureau of Standards (68d) and the average coefficients are given in Table 35, page 122.

The effect of manganese in causing retention of strength at high temperatures of various alloys in which it is used, has already been commented on. A small amount added to the light copper-aluminum alloys appears to give them a whiter and smoother surface. Most foundrymen consider that up to, say, 0.25 per cent at least, manganese is a welcome addition in most cast alloys, and it is used in various heat-treatable alloys probably because it tends toward a smaller grain size. While these small amounts do have a definite strengthening effect of their own, the benefits in the foundry itself are difficult to evaluate, but seem generally acknowledged.

(7) ALLOYS OF ALUMINUM AND NICKEL.—Although nickel produces about the same effect on aluminum as is produced by copper, and the nickel alloy was one of the earliest to be used commercially in this country for castings (70f), no alloys of this class are used commercially to-day, the alloys being more expensive (70f) and more difficult to make.

The alloys may be made by the direct addition of nickel in the form of thin sheet scrap, or electrolytic nickel, to the molten aluminum, or by the use of intermediate alloys, preferably containing about 20 per cent nickel (70c). Although strips of electrolytic nickel will go into solution in molten aluminum fairly readily at 800° C., it is probably preferable to use the intermediate alloy. The 20 per cent nickel alloy is preferable to the 50 per cent nickel alloy, as the latter is subject to rapid disintegration on standing (70c).

For casting the percentage of nickel should not exceed 5 per cent. Up to 5 per cent nickel the strength and yield point of chill castings increase, the 1.11 per cent nickel alloy having a strength of 14,900 lbs./in.^{2}, "yield point" 5,800 lbs./in.^{2}, elongation 20.8 and reduction of area 36.2 per cent, while for the 5 per cent nickel alloy the tensile strength is 21,700 lbs./in.^{2}, "yield point" 9,000 lbs./in.^{2}, the elongation and reduction of area falling to 9.0 and 11.1 per cent, respectively (70g). Above 5 per cent nickel the addition of nickel decreases the elongation (70b). Reiman (69d) investigated the effect of small percentages of molybdenum (up to 1 per cent) on a low nickel series of alloys and found it had little influence on ductility, rolling, or hardness, but appeared to decrease the impact strength. Regelsberger (70e) states that the 5 per cent nickel alloy is not resistant to weathering, while Hewlett and Basch (70d) found the nickel alloys failed to meet the salt-spray test.

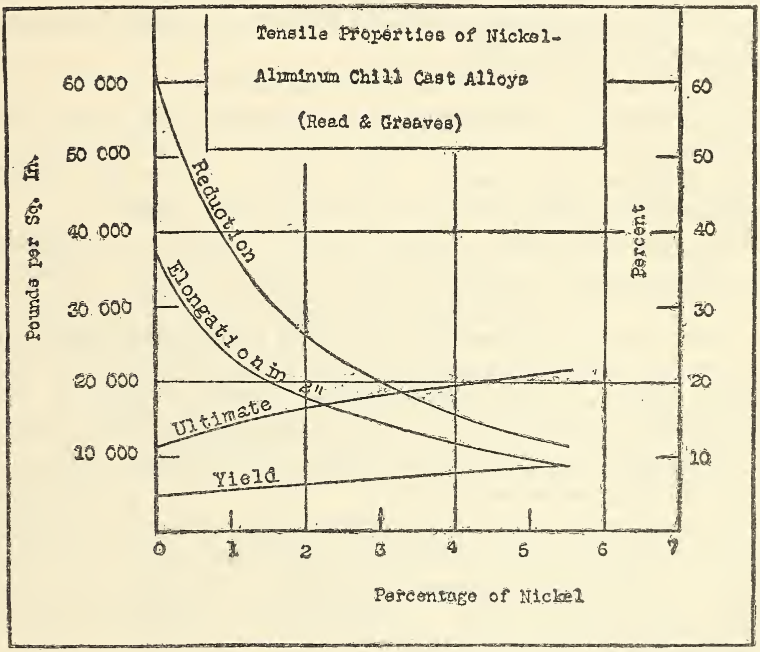

FIG. 93.—*The tensile properties of nickel-aluminum chill-cast alloys. (Read and Greaves, 70g)*

Specimens were cast to size 0.564 inch in diameter

Pannell (70a) states that the addition of magnesium to nickel-aluminum alloys makes them capable of responding to heat treatment.

Some of the results of the influence of nickel on the properties of chill-cast aluminum are shown in curves in Figure 93.

The chief present use of nickel in light aluminum alloys is as a constituent of the heat-treatable "Y" alloy used to some extent in England.

(8) Alloys of Aluminum, Copper, and Zinc.—The S. A. E. No. 30 alloy (A. S. T. M. alloy C) (Aluminum Co. of America No. 12), specified to contain 7 to 8½ per cent copper, and not over 0.2 per cent zinc, is sometimes replaced by S. A. E. "No. 33" (A. S. T. M. "D") (Aluminum Co. of America No. 112) in which the copper is not allowed to rise above 8 per cent, and may fall to 6 per cent, and up to 2½ per cent zinc is allowed, together with a nominal iron content of 1.25 ± 0.25 per cent.

This recognizes the fact that an alloy of 7½ per cent copper, 1 per cent zinc, or one of 7 per cent copper, 2 per cent zinc, has almost identical properties with those of the 8 per cent copper alloy. Only when service at high temperatures is concerned, would the difference in properties be noteworthy.

Such alloys were originally hardly to be considered as intentionally of the ternary Al–Cu–Zn group, since the presence of zinc generally came from the use of scrap which contained a small proportion of alloys of higher zinc content. Now that the use of this alloy has become common (86c) zinc is often intentionally added.

When the advantages of higher tensile strength are sought and the disadvantages of greater specific gravity, greater tendency to hot shortness and marked loss of strength at high temperatures can be borne, recourse is generally had to the alloy containing 12 to 15 per cent zinc and 2 to 3 per cent copper, which gives 25,000 to 30,000 lbs./in.^{2} tensile strength with a specific gravity of about 3. With the addition of one-half of 1 per cent manganese, this is the Aluminum Co. of America's "No. 31" alloy which is now seldom used, having been practically superseded by the "No. 145" alloy which contains 10 to 12 per cent zinc and 2 per cent copper with the intentional addition of iron to bring the iron content to about 1½ per cent, since iron improves the physical properties. This alloy, cast to size in greensand, gives 25,000 to 37,000 lbs./in.^{2} tensile strength with an elongation of 3 to 6 per cent.

An alloy of 2½ to 3 per cent copper, 19 to 20 per cent zinc, specific gravity 3.10 to 3.15 gives 30,000 to 35,000 lbs./in.^{2} tensile, with an elongation of only about one-half of 1 per cent in sand castings and has had some commercial use. This alloy has also been suggested by Rosenhain for wrought material. (86f.)

Another alloy, formerly quite extensively used, was "No. 31" (zinc 15 per cent, copper 3 per cent, aluminum balance, with or without one-half per cent of manganese): Melting range, 625 to 440° C.; shrinkage, 0.156 inch per foot.

Alloys of this type have been used more extensively abroad, particularly in Great Britain and in Germany, than in this country. Its higher tensile strength as compared with No. 12 has not in this country outweighed the doubt in the minds of many as to its liability to crack in service or to deteriorate upon aging.

This type of alloy is decidedly "hot-short" and will not crush hard cores without cracking. It has a tendency toward shrinks and draws. Complicated castings of variable cross section are more difficult to make from this alloy than from alloys that contain only negligible amounts of zinc. If the patterns are properly filleted, if the alloy is poured at the lowest possible temperature, and if soft cores are used, it is usually possible to make good castings, free from cracks. The poor reputation of this type of alloy in service is due more to poor foundry practice and lax inspection, whereby undetected cracks were present in castings before they were put in service, than to the properties of the alloy itself. A perfectly sound casting of this alloy should be as dependable in service under stresses for which it would be chosen by a designer as one of any other casting alloy.

This alloy can usually be depended on to give the following properties:

Tensile strength	lbs./in.^{2}	22, 000–25, 000
Elongation in 2 inches	per cent	0. 5–3
Specific gravity		3

When poured properly and at a low temperature a tensile strength of 30,000 lbs./in.^{2} may be obtained with this alloy.

This alloy is tougher in impact than the copper alloys.

Another alloy of this type, containing 2½ per cent copper, 19 per cent zinc, balance aluminum, has a density of 3.1, tensile strength 33,000 lbs./in.^{2}, elongation in 2 inches, 0.5 to 1 per cent, and has the highest strength per unit weight of any of the nonheat-treated casting alloys.

An English alloy of this class designated as 2–L–5 by the British Engineering Standards Association contains 13.5 per cent zinc, with an allowed variation of ±1 per cent, and 2.75 per cent copper, with an allowed variation of ±0.25 per cent. Mortimer (85c) says this is less hot short than the alloys higher in zinc and free from copper. The British specifications call for chill-cast specimens, and results of such tests are not exactly comparable to those obtained on sand-cast bars. Jeffries (85b) points out that there is a small amount of "aging" in this alloy at room temperature.

Only rarely are the alloys used that are still higher in zinc, such as those with 1½ to 3 per cent copper and 25 to 30 per cent zinc, with specific gravities of 3.30 to 3.35, tensile strengths of 37,000 to 42,000 lbs./in.^{2} with elongation almost zero.

The tensile strengths of 20 different Al-Cu-Zn alloys are given in Table 43, page 157.

Rosenhain (86d) has studied the properties of the ternary alloy containing 3 per cent copper and 20 per cent zinc. In this alloy the "yield point" for hot-rolled rod of ⅞ inch to 1⅝ inches diameter varies from 39,000 to 41,400 lbs./in.^{2}, tensile strength 59,100 to 61,400 lbs./in.^{2}, elongation 17 to 30 per cent, reduction of area 29.8 to 36.5 per cent. For hot-rolled sheet the "yield point" varied between 27,700 and 60,500 lbs./in.^{2}, tensile strength 49,700 to 73,900 lbs./in.^{2}, elongation 13 to 28 per cent. Cold-rolled sheet had a yield point of 58,200 lbs./in.^{2}, 66,300 lbs./in.^{2}, tensile strength, 11 per cent elongation. Reference should be made to the tables given in this work for more exact figures for the alloy in different conditions. Reference should be made to the table given by Anderson (86c) for the tensile strength and elongation of chill-cast alloys which contain copper and zinc in varying proportions.

Rosenhain has also described the properties of other Cu-Zn-Al alloys (86f). For use at ordinary temperatures he recommends a 2 to 3 per cent Cu, 25 to 30 per cent Zn alloy, which has a strength of about 42,500 lbs./in.^{2} in sand-cast condition and 45,000 lbs./in.^{2} in chill-cast condition. Alloy "L5," having a strength of 24,500 lbs./in.^{2} and 4 per cent elongation on 2 inches, may be improved by aging, showing an increase of 30 per cent in strength during the first 10 months. It contains 12½ to 14½ per cent Zn and 2½ to 3 per cent Cu.

Among the wrought alloys are those containing 3 per cent Cu and 20 per cent Zn, and 3 per cent Cu and 25 per cent Zn. It is possible to produce thin sheet 0.0035-inch thick from these alloys having a tensile strength of over 50,000 lbs./in.^{2} The increase of strength of the first alloy on aging is most marked in the thin sheet. Immediately after rolling the strength is 60,000 to 65,000 lbs./in.^{2} and after five years it rises to 72,000 lbs./in.^{2}.

The effect of various contents of copper and zinc have been studied by Waehlert (86g). He finds that in casting the piping is less with the addition of copper and zinc than with copper alone. The addition of zinc to Cu-Al alloys does not appreciably influence the hardness up to 3 per cent zinc. From 3 per cent on the hardness increases slowly at first and reaches a maximum at 6 to 7 per cent zinc, and then decreases again. The effect of the addition of copper to Zn-Al alloys is similar. The strength increases with Cu and Zn, the elongation decreasing.

With regard to corrosion, Anderson (86c) states that, in general the Cu-Zn-Al alloys corrode less than the Zn-Al alloys and more than the Cu-Al alloys. The rate of corrosion may be said to increase with increasing zinc and decrease with increasing copper.

The constitution of the alloys of aluminum, copper, and zinc have been studied by Levi-Malvano and Marantonio (86h) and Hanson and Gayler (86b), and constitutional diagrams are given for alloys containing 5, 10, 15, 20, and 25 per cent Cu and Zn from 0 to 100.

Since, as has been pointed out (p. 131), no one equilibrium diagram for the Al-Zn series as yet finds universal acceptance among metallurgists, that for the Cu-Zn-Al series is also in doubt.

In an investigation of the effect of small amounts of Mg on Cu-Zn-Al alloys, Dix and Lyon (86e) concluded that the use of Mg in the alloys is not advisable. The tensile strength and elongation of a 2 per cent Cu, 10 per cent Zn alloy containing 0.5 per cent Mg is less than for the same alloy containing 1 per cent Fe and without the Mg, while the hardness is increased. The tensile strength and hardness of alloys in the Mg-Zn series may be increased at the expense of the elongation by suitable heat treatment, but have low ductility and higher specific gravity, and are inferior to duralumin.

(9) ALLOYS OF ALUMINUM, COPPER, AND MANGANESE.—Rosenhain and Lantsberry (87n) have carried out some tests on light alloys of the manganese-copper-aluminum series. Their investigation was primarily concerned with the alloys rich in copper. Only a few tests were made of the strength of the alloys at the aluminum end of the diagram. Table (56) shows the results of tests of sand and chill castings of different compositions of alloys up to about 4 per cent of copper and 2 per cent of manganese.

The specimens were machined from castings and immersed for 121 days. The resistance to corrosion in sea water of the alloys was reported to be superior to that of commercially pure aluminum. These results are contrary to usual experience with relative corrosion resistance of aluminum and its light alloys (87p) and are open to considerable question.

Tests of resistance to corrosion by sulphuric acid and nitric acid of alloys of from 1 to 10 per cent manganese showed that these alloys were less resistant to the attack of these acids than pure aluminum.

The 1 per cent manganese, 2 per cent copper alloy is used for sand castings (87g). This alloy is soft and has low strength, but is corrosion resistant (87b). It is not suitable for castings subject to vibration (87a). The 2 per cent copper, 1.50 per cent manganese alloy is used for casting and forging at the United States Naval Gun Factory (87m).

TABLE 56.—*Tensile properties of cast aluminum-copper-manganese alloys* (*Rosenhain and Lantsberry, 87n*)

No.	Chemical composition		Tensile properties					
			Sand cast			Chill cast		
	Copper	Manganese	Tensile strength	Yield point	Elongation in 2 inches	Tensile strength	Yield point	Elongation in 2 inches
	Per cent	*Per cent*	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Per cent*	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Per cent*
022	2.15	0.88	13,800	10,500	5	19,100	12,400	6
023	3.11	.57	15,400	11,300	4	18,500	11,300	5.5
024	3.28	.98	14,000	11,300	4	18,800	14,200	5
025	1.27	2.06	15,300	12,600	4.7	13,900	13,800	6
026	2.02	1.90	14,300	13,200	3	21,900	13,900	7
026A	2.15	1.91	18,100	15,000	5	22,400	17,500	5
027	2.89	1.76	17,100	14,300	3.5	15,200	13,600	5
028	4.13	1.92	3,200	3,200	2.5	18,600	14,300	3.5

This alloy is described by McKinney (35q) and is suitable both for casting and for forging. Cupromanganese may be used in preparing it, and it is apparently not too difficult an alloy to handle in the foundry, although it has very marked piping qualities. This alloy will usually have the following tensile properties or better:

Tensile strength	lbs./in.^{2}	18, 000
Elongation in 2 inches	per cent	8
Specific gravity	about	2. 80

The proportional limit is very low. With care this alloy may be cast to have a tensile strength of 20,000 lbs./in.^{2}, with an elongation in 2 inches of 10 per cent. This alloy is quite largely used by the Naval Gun Factory, Washington, D. C., but not by many other foundries.

The 2 per cent manganese, 3 per cent copper alloy is used for forgings (p. 144). The 6 per cent copper, 3 per cent manganese alloy is known as United States Naval N alloy and has been said to be used for general casting purposes, but is too high in manganese to work well in the foundry (87i). It has an ultimate strength of 20,000 lbs./in.^{2}, elastic limit 4,500 lbs./in.^{2} and 8 per cent elongation. The 8 per cent copper, 1 per cent manganese alloy is sometimes used for cylinders (87f). The 5 per cent copper, 1 per cent manganese alloy is said to be suitable for pistons (87h, j), but is much lower in copper than the usual piston alloys. The 12 per cent copper, 2 per cent manganese alloy is a piston alloy known as Aerolite (87l), and has a tensile strength of 22,000 lbs./in.^{2}. This also is so high in manganese that it would be difficult to handle.

The copper-manganese-aluminum alloys possess high ductility and corrosion resistance, but are difficult to cast (87c). Rosenhain (87k) states that the addition of 1 per cent manganese to the 8 to 14 per cent copper alloys causes an increase in tensile strength with rise in temperature up to 250° C. where it is 2,200 lbs./in.^{2} greater than at normal temperature. Above 250° C. the strength decreases, but at 350° C. is still better than that of the simple copper-aluminum alloy. The effect of deformation on the copper-manganese-aluminum alloys has been discussed by Guillet (87e), who states that the smallest amount of drawing produces noteworthy hardening which increases progressively with the amount of drawing. The elastic limit approaches the breaking load and the percentage of elongation diminishes after drawing. No change of microstructure accompanies these changes.

The alloy containing 14 per cent copper, 1 per cent manganese has been suggested for permanent-mold cast pistons (87g). The manganese acts as an agent to increase the strength at moderately elevated temperatures (87b), Rosenhain (87k) stating that the strength of this alloy rises from 20,000 lbs./in.^{2} to 22,500 at 250° C.

and then falls to 14,300 lbs./in.^{2} at 350° C. The difference between sand and chill castings disappears at 350° C. Annealing at 450° C. improves the alloy. Haas (87b) states that there is a loss of thermal conductivity of the 1 per cent manganese, 14 per cent copper alloy after quenching from 450° C., but the thermal conductivity may be restored by annealing at 454° C. (87a). The alloy has an ultimate strength of 22,000 lbs./in.^{2}, 1 per cent elongation and 75 Brinell. It is sometimes termed the N. P. L. alloy L 7, or 14:1. The properties at elevated temperatures have been discussed by Aitchison (87h).

(10) Alloys of Copper-Silicon and Aluminum.—Many foundrymen prefer a copper-silicon-aluminum alloy to either the straight copper alloy or the straight silicon alloy, modified or unmodified, since available copper alloy scrap can be used in part, since the freedom from cracking in the mold approaches that obtained with the silicon alloys, and the proportional limit is higher than with silicon alone. An example of such alloys is given by Dix and Lyon (88l):

Copper	4.17 per cent.
Silicon	4.92 per cent.
Tensile strength	22,000 lbs./in.^{2}
Proportional limit	About 6,000 lbs./in.^{2}.
Elongation in 2 inches	1½ per cent.
Brinell hardness number	59.

Dix and Lyon (88j) got better results as to tensile strength and elongation, but a lower proportional limit (not only on separately cast test bars, but on attached coupons and on specimens cut from a large crank case), with an alloy of 3½ per cent copper, 4 per cent silicon, 1¼ per cent iron than with one of 8 per cent copper, ¾ per cent silicon, ¾ per cent iron. The modified 13 per cent silicon alloy "Alpax" and a heat-treated "Lynite" 4½ per cent copper, ½ per cent iron, ½ per cent silicon, $\frac{1}{10}$ per cent magnesium, $\frac{1}{10}$ per cent manganese alloy gave higher strengths, but the former had a still lower proportional limit than the copper-silicon-aluminum alloy and the latter was not considered to be as desirable for castings liable to shrink or draw.

In another account of an investigation of the Cu-Si-Al alloys with and without manganese, Dix and Lyon (88k) concluded that alloys of Al containing 3 to 5 per cent silicon in combination with Cu within the same limits are suitable for the same general casting purposes as the 8 per cent Cu alloy, the value of silicon alloys lying in their freedom from casting difficulties. The use of 1 per cent manganese raises the strength of the alloys at high temperatures, but impairs the casting properties. The authors concluded that the mechanical properties of the copper-silicon alloys are about the same as for the 8 per cent Cu alloy, the ductility being slightly better and the specific gravity slightly less while the machining properties are inferior to those of the 8 per cent Cu. It is recommended to use the copper in the upper limits and the silicon in the lower limits of the contents specified.

The aircraft alloys of aluminum with 5 per cent Cu, 1 per cent Si, and 4 per cent Cu, 3 per cent Si have been discussed by Daniels (88e). Anderson (88i) considers that the 4 per cent Cu, 4 per cent Si, 92 per cent Al alloy is the most suitable for general casting purposes. Other compositions used are 87:3:10, 90:8:2, 91:6:3, 90:5:5, 95:2.5:2.5 Al-Cu-Si. The development of alloys of this type has been largely due to Pacz (96q), Johnston, Archer, and Jeffries (96c), and to the investigators of the Army Air Corps.

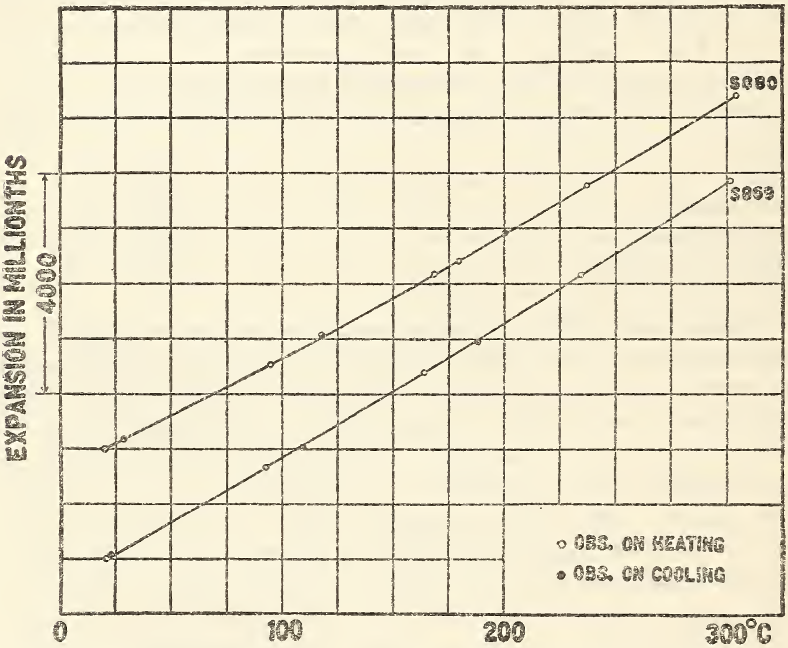

Fig. 94.—*Linear expansion of an aluminum-silicon-copper alloy and an aluminum-silicon-copper-manganese alloy*

This class of alloys is useful for general casting (88i), some of them having better physical properties than the 92:8 Al-Cu alloy, and better casting properties. They contract less than corresponding copper-aluminum alloys and may be cast around hard cores without cracking. An investigation of the coefficient of expansion of sand-cast Cu-Si-Al and Cu-Mn-Si-Al alloys (furnished by the Air Corps, McCook Field, Dayton, Ohio) was made at the Bureau of Standards (88g). The material was heated to 400° C. and allowed to cool in the furnace before measuring. The results are given in Table 57 and curves for two of the runs are shown in Figure 94. Figure 95 shows the effect of composition on the coefficient of expansion. The thermal conductivity of Cu-Si-Al alloys as determined by the Bureau of Standards is given below:

Cu	Si	Al	Mn	Thermal conductivity
2	3	95	------	0.29
3	4	93	------	.32
4	6	90	------	.30
2	3	94	1	.28

Alloys containing 3, 6, and 9 per cent silicon and 0, 2, 4, 6 per cent copper have been studied by Dix and Lyon (881) who find the most

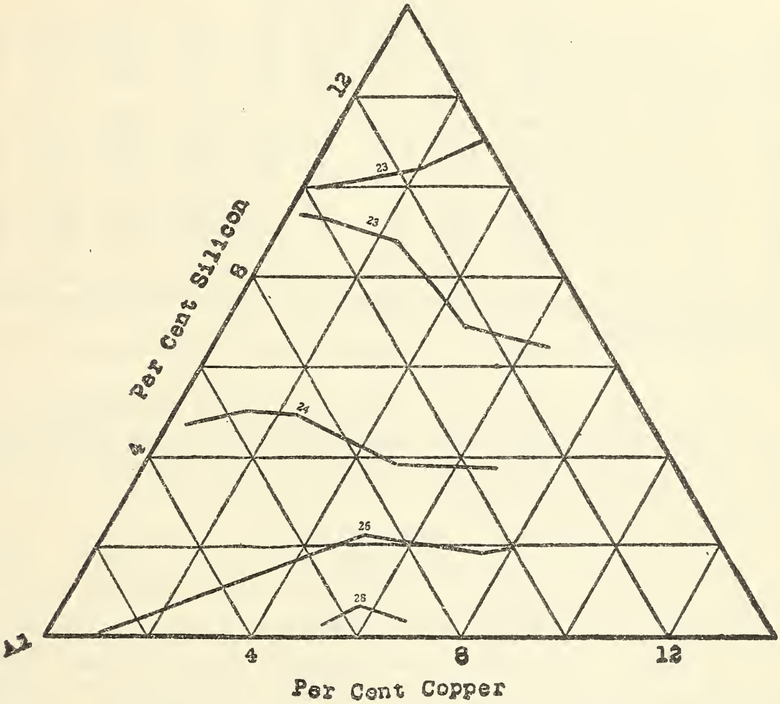

FIG. 95.—*Portion of triangular diagram indicating the effect of composition on the coefficient of expansion of aluminum-rich ternary alloys between 20 and 300° C.*

desirable compositions to lie between 3 and 5 per cent for both copper and silicon. These alloys are as good as the No. 12, and the authors state that they have casting qualities superior to any other alloys of aluminum known to them. For good elongation, without particular machining qualities, the copper content should be low, while for good machining qualities, copper should be in the upper limits and silicon low. Testing the as-cast specimens one month after casting gave practically the same results as after 24 hours.

In the machined specimens the average tensile strength was 860 lbs./in.^{2} lower than for specimens with the skin on. The alloys retain their strength up to 300° F. At 600° F. the strength is the same as that obtained from the 10 to 12 per cent copper alloys.

TABLE 57.—*Average coefficients of expansion of aluminum-silicon-copper and aluminum-silicon-copper-manganese alloys*

Laboratory No.	Chemical composition[1]					Average coefficients of expansion per degree centigrade			
	Al[2]	Si	Cu	Fe	Mn	20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
S869	93.91	3.33	2.2	0.55	0.01	23.4	23.9	24.2	24.4
S867	89.62	7.42	2.43	.53	Nil.	21.7	22.5	23.0	23.4
S870	87.11	9.96	2.33	.60	Nil.	20.7	21.7	22.2	22.7
S872	91.27	3.75	4.41	.57	Nil.	22.4	23.4	23.8	24.1
S873	88.29	6.61	4.53	.57	Nil.	21.4 21.5	22.5 22.3	23.1 22.8	(3) 23.1
S876	84.60	10.28	4.58	.54	Nil.	20.4	21.3	21.8	22.1
S875	88.66	4.08	6.62	.64	Nil.	21.8	22.9	23.4	23.6
S877	83.73	9.45	6.29	.53	Nil.	20.6	21.6	22.0	22.2
S878	93.00	3.12	2.4	.55	.93	22.2	23.4	23.7	23.8
S880	86.39	9.97	2.32	.50	.82	20.4	21.5	22.0	22.4
S879	85.84	10.22	2.49	.56	.89	20.8	21.5	22.0	22.3
S874	85.48	10.18	2.47	.70	1.17	20.4	21.5	22.0	22.3

[1] Chemical analyses made by Aluminum Co. of America on all samples of this series except S869 and S878, which were analyzed by J. A. Scherrer, of this bureau.

[2] Aluminum by difference.

[3] Observation wire broke at about 300° C. The results obtained on a repeated test are given in the next line.

(11) UNIMPORTANT TERNARY ALLOYS.—A few unimportant ternary casting alloys which have been studied more or less thoroughly may be mentioned here before taking up the important class of heat-treatable ternary alloys.

(*a*) *Alloys of aluminum, copper and nickel.*—The alloys of copper and nickel with aluminum find little use in this country. Their general mechanical properties are good. They cast and machine well and take a good polish, but it is difficult to introduce the nickel into the alloys. The alloys used contain up to 14 per cent copper and up to 4 per cent nickel (89b). The 2 per cent nickel 8 per cent copper alloy is used for sand and die castings. The 2 per cent nickel 10 per cent copper, and the 1 per cent nickel 14 per cent copper alloys have been used for permanent-mold cast pistons.

Read and Greaves (70g) have made a study of the properties, microstructure and corrosion of light aluminum alloys with nickel and copper. Tests of working properties showed that the 2 per cent nickel 2 per cent copper alloy was perfectly sound and uncracked after cold-rolling, with necessary annealings, to 0.10 inch; then without further annealing to strip of thickness of 0.02 inch. The alloys containing 3 per cent nickel 2 per cent copper, and 1 per cent nickel 4 per cent copper could be drawn from $\frac{3}{16}$ inch diameter to wire of 0.033 inch diameter without cracking or hollow drawing. The 2 per cent nickel 4 per cent copper and 5 per cent nickel 2 per cent copper alloys could be forged hot from 1½ by 1 by 1½ inches to a thickness of ⅛ inch after heating to 450° C. and remain perfectly sound.

The results of tests of physical properties of alloys with varying percentages of copper and nickel are shown in Table (58).

TABLE 58.—*Tensile properties of aluminum-copper-nickel alloys* (*Read and Greaves 89g, h*)

PHYSICAL PROPERTIES

No.	Chemical composition of chill-cast alloys		As chill cast			
	Copper	Nickel	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Per cent	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*
23C		1.11	14,900	5,800	20.8	36.2
24C		2.22	16,900	6,500	16.7	22.1
25C		3.38	18,200	7,400	13.5	21.1
26C		5.52	21,700	9,000	9.0	11.1
27C	1.01	1.10	18,200	6,200	19.1	29.2
28C	1.00	2.18	18,600	7,400	10.0	15.3
29C	1.03	4.03	23,500	8,100	12.1	14.2
30C	1.02	5.51	24,800	10,700	6.1	8.5
11C	2.04	1.11	21,700	7,200	20.6	24.6
12C	1.92	2.18	22,600	8,100	11.4	15.8
13C	1.97	3.69	24,500	9,000	7.2	9.2
14C	1.99	5.27	28,600	10,300	5.7	7.4
15C	3.94	1.08	24,100	9,000	7.5	11.7
16C	4.05	2.02	23,400	8,300	6.1	7.0
17C	3.84	3.50	21,200	9,900	5.0	6.9
18C	4.04	4.36	25,200	9,900	4.4	5.0

No.	Chemical composition of wrought alloys		Cold-drawn rods [1]			
	Copper	Nickel	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Per cent	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*
23C		1.87	22,700	19,700	12.6	36.9
24C		4.31	27,900	22,900	8.5	24.0
25C	2.00	1.12	32,200	26,200	16.0	47.7
26C	1.97	2.22	30,600	26,000	11.8	33.1
27C	2.13	3.74	33,900	29,700	7.4	12.4
28C	2.10	5.33	37,800	31,700	7.5	15.3
29C	4.07	1.12	37,400	31,400	12.1	28.8
30C	4.13	2.16	36,300	31,700	8.0	19.3
11C	4.07	3.21	34,100	29,900	2.5	3.9
12C	4.08	4.30	36,800	29,600	3.8	6.2

[1] The same as (3) cold-drawn to ⅜ inch in 2 passes.

TABLE 58.—*Tensile properties of aluminum-copper-nickel alloy (Read and Greaves 89g, h)*—Continued

No.	Chemical composition of wrought alloys		Annealed rods [2]			
	Copper	Nickel	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Per cent	*Per cent*	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Per cent*	*Per cent*
23C	----------	1.87	16,300	5,600	34.1	55.8
24C	----------	4.31	20,200	9,900	26.2	42.1
25C	2.00	1.12	23,400	8,300	30.5	56.6
26C	1.97	2.22	22,900	6,300	28.9	44.7
27C	2.13	3.74	23,800	6,300	27.2	37.8
28C	2.10	5.33	26,500	9,900	25.0	36.3
29C	4.07	1.12	29,000	7,400	28.7	44.3
30C	4.13	2.16	27,200	8,100	24.8	30.9
11C	4.07	3.21	25,400	6,300	22.8	28.0
12C	4.08	4.30	25,300	7,200	23.5	29.7

No.	Chemical composition of wrought alloys		Hot-rolled rods [3]			
	Copper	Nickel	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Per cent	*Per cent*	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Per cent*	*Per cent*
23C	----------	1.87	18,200	11,900	28.4	52.5
24C	----------	4.31	22,300	13,500	22.0	36.4
25C	2.00	1.12	25,400	14,300	27.8	52.0
26C	1.97	2.22	26,600	17,000	21.3	38.6
27C	2.13	3.74	28,600	17,900	17.8	29.6
28C	2.10	5.33	31,500	18,160	16.0	23.6
29C	4.07	1.12	32,000	18,400	20.7	36.9
30C	4.13	2.16	30,700	17,900	17.8	28.0
11C	4.07	3.21	28,700	17,300	14.6	18.2
12C	4.08	4.30	29,500	17,000	13.5	18.6

[2] The same as (3) annealed at 450° C.

[3] 2¼ by 18 inches ingot, chill-cast, heated to 400° C., rolled-hot to 1 inch diameter.

The constitution of alloys of aluminum with copper up to 12 per cent and nickel up to 10 per cent has been studied by Bingham and Haughton (89e), who find that the addition of 2 per cent Ni to an 8 per cent Cu-Al alloy causes the disappearance at higher temperatures of $CuAl_2$ present in the binary alloy, but this compound comes out of solution at 270° C. The alloy of 4 per cent Cu, 2 per cent Ni (the basis of Y alloy), undergoes no phase changes from the solidus to 200° C.

The authors also observed that the superiority shown by the nickel-aluminum alloys to ordinary corrosion in water was not maintained when dilute vinegar, oxalic acid, citric acid, and tartaric acid were used.

The authors draw no general conclusions from their work, but it is evident that all the compositions were definitely inferior to duralumin.

Rosenhain (89f) states that the addition of nickel raises the tensile strength 9,500 pounds, and over 6,500 pounds at 250° C. (to 22,500 lbs./in.^{2}). At 350° C. the strength is decreased.

(*b*) *Alloys of aluminum, copper, and magnesium.*—Cu-Mg-Al alloys in the rolled condition have already been described in another publication of this bureau (43jj). Cast alloys containing 7 to 8.5 per cent Cu and 0.1 to 0.3 per cent Mg are used in the foundry as a variation of the 8 per cent copper alloy (43q). Anderson (43q) states that the effect of small additions of magnesium to 8 per cent copper alloy is to increase the strength, reduce elongation, and reduce contraction on freezing.

Small amounts of magnesium are used in some piston alloys (see p. 141) with still higher copper, but the chief alloy in this class is duralumin, with still lower copper. This last is generally used in the heat-treated condition and will be described later, page 212.

An investigation of the ternary alloys of aluminum with magnesium and copper was made by Gayler (43w). The ternary system Mg-Cu-Al is also discussed by Fuss (43s).

The magnesium containing alloys of aluminum and copper are said to corrode more rapidly than the binary alloys free from magnesium (43q). This statement probably does not hold for all the alloys in all physical conditions. The addition of magnesium also reduces the thermal conductivity (43kk).

(*c*) *Alloys of aluminum, molybdenum, and nickel.*—These alloys were studied by Pfautsch (91l) in the high nickel end, the aluminum and molybdenum contents being less than 25 per cent in every case.

(*d*) *Alloys of aluminum, copper, and tellurium.*—These alloys have been studied by Sisco and Whittmore (91w), who used alloys of 5 per cent copper with additions of 0.25, 0.50, 1.75, 1, 2, 3, 4, and 5 per cent tellurium. Only traces of the tellurium were found in the alloys, such tellurium as was left being segregated. Aluminum-telluride probably formed and came to the top as slag. The addition of tellurium to a 5 per cent copper alloy decreases the ductility; in the quenched condition it decreases the ultimate strength. It also produces erratic results in the same melt.

(*e*) *Alloys of aluminum, cadmium, and zinc.*—The alloys of aluminum with cadmium and zinc have been studied by Budgen (91q); the alloys examined containing 0 to 24 per cent zinc, 0 to 10 per cent cadmium. In forging tests at 400° each of the alloys was so fragile that it fell to pieces before 5 per cent reduction of cross section had been made. Many of the alloys broke at all temperatures down to room temperature. In rolling tests at 300° to give 10 per cent reduction most of the alloys fell to pieces at the first pass. Lower temperatures gave almost equally unsatisfactory results. There was found to be no marked or systematic variation of tensile properties of aluminum-rich zinc alloys through the addition of cadmium, though the general tendency is a slight strengthening. The strongest chill-cast alloy was that containing 6 per cent cadmium and 20 per cent zinc, and having a strength of 39,000 lbs./in.^{2}, but only 3 per cent elongation. The addition of up to 10 per cent cadmium does not produce any marked or systematic change in the tensile properties, but causes a slight weakening and no appreciable increase of elongation except for the 6 per cent zinc series. Brinell hardness tests indicate a slight hardening by the addition of cadmium to each series containing a constant proportion of zinc, except for 24 per cent zinc, where softening is evidenced. The general effect of cadmium is to render zinc-aluminum alloys more malleable.

(*f*) *Alloys of aluminum, magnesium, and cadmium.*—These alloys have been described by Valentin and Chaudron (91o), who give a discussion of the constitution of the alloys.

(*g*) *Alloys of aluminum, iron, and zinc.*—These alloys have been discussed by Waehlert (91jj), who states that the addition of iron to zinc-aluminum alloys is not favorable. The tendency to pipe is stronger than in other alloys and other properties are unfavorably influenced.

(*h*) *Alloys of aluminum, copper, and tungsten.*—These alloys have been investigated by Whitmore and Sisco (91p), who found that the tungsten segregated and did not alloy with aluminum or aluminum plus 10 per cent copper in amounts greater than 1.5 to 2 per cent. The addition of tungsten has a great influence on the melting point which is raised about 260° C. above the melting point of a similar alloy without tungsten. Tungsten has little effect on the ultimate strength and elongation. The alloys do not appear to offer possibilities of commercial development.

(*i*) *Alloys of aluminum, tin, and zinc.*—Taylor (17r) has studied the zinc-tin-aluminum system in relation to their physical properties and corrosion resistance, but only one alloy tested by him, one of 79 per cent aluminum, 21 per cent zinc, without tin, could be classed among light alloys.

A study of the ternary diagram of alloys of tin, zinc, and aluminum has been made by Losana and Carozzi (91z), who paid most attention to the heavier alloys.

(*j*) *Alloys of aluminum, zinc, and lead.*—An alloy containing 15 per cent zinc and 1.5 per cent lead is described by Guillet and Cournot (91ee). This alloy was tested for hardness and resistance to shock at 20°, −20°, −80°, and in liquid air. The hardness decreased somewhat to −80° and then showed a hardness of 83 at liquid-air temperature as compared with 55 at 20°. There was practically no change in resistance to shock at the lower temperatures.

(*k*) *Alloy of aluminum, nickel, copper, chromium, and manganese.*—Samples of a cast alloy called "Verilite" of the following approximate composition: Aluminum, 95.5 per cent; nickel, 1.5 per cent; copper, 1.0 per cent; chromium, 1.5 per cent; and manganese, 0.5 per cent were tested at the Bureau of Standards, and showed a tensile strength of but 16,000 lbs./in.^{2} and an elongation of 4 per cent.

The expansion curves for this alloy from room temperature to 300° C. were found to be regular and may be represented by the following second degree equation:

$$L_t = L_0\,[1 + (21.05\,t + 0.01473\,t^2)\,10^{-6}]$$

where L_t is the length at any temperature t between 14 and 302° C., and L_0 the length at 0° C. The length at any temperature, t, as determined from this equation is accurate to ±0.000015 per unit length.

The observations on cooling lie above the expansion curves on heating. At the end of these tests, the specimens were found to be 0.03 per cent longer than before the tests.

Table 59 gives the average coefficients of expansion for several temperature ranges. These values were derived from the expansion curves on heating.

TABLE 59.—*Average coefficients of expansion of a complex alloy of Al, Ni, Cu, Cr, Mn*

Laboratory No.	Average coefficients of expansion per degree centigrade			
	20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.
	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
S425	23.2	24.2	25.0	25.8
S426	23.3	24.2	25.0	25.8

A comparison of the average coefficients of expansion of various light alloys is given in Table 60.

The compositions, so far as they are known, and trade names of a number of alloys are given in Table 61. Many of these are no longer produced, and many of them were never of any commercial importance.

Some miscellaneous alloys for which tensile values are available are listed in Table 62.

TABLE 60.—*Average coefficients of expansion of aluminum and various aluminum alloys*

Series	Aluminum content	Average coefficients of expansion per degree centigrade		
		20 to 100° C.	20 to 200° C.	20 to 300° C.
1. Aluminum:	*Per cent*	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
(*a*) Pure aluminum	99.95	23.8	24.7	25.7
(*b*) Commercial aluminum	99.15	23.9	25.9	26.7
2. Aluminum-copper alloys	87–95	22.2–24.6	23.6–26.8	26.4–29.2
3. Aluminum-silicon alloys	87–95	19.2–22.2	20.2–23.2	22.2–24.8
4. Aluminum-zinc alloys	5–86	24.3–33.3	27.3–37.2	[1] 28.3–40.7
5. Aluminum-manganese and aluminum-manganese-copper alloys	96–98	23.1–23.8	24.2–25.7	25.5–26.9
6. Aluminum-silicon-copper and aluminum-silicon-copper-manganese alloys	84–94	20.4–23.4	21.3–23.9	22.1–24.4
7. Duralumin	94–95	21.9–23.8	22.9–26.0	24.7–26.9
8. "Verilite"	95.5	23.2	24.2	25.0

[1] From 20 to 250° C.

Table 61.—*Compositions and trade names of alloys of aluminum*

[Where an element is known to be present in the alloy, but the quantity is not known, the presence of the elements is indicated by "x" in the proper column. In some cases no indication of the composition of the alloys has been given other than that they are alloys of aluminum, and in this case the name alone is listed]

Name	Al	Cu	Zn	Mn	Mg	Ni	Fe	Si	Sn	Other elements	Reference
A alloy	77	3	20								(91 dd)
Acerial:											
Sheet	Bal.	2.3		1.5	0.1		1.4				(91 dd)
Do	Bal.	3.7		1	.2		1.3				(91 dd)
Do	Bal.	3.8		1	.5		.7				(91 dd)
Cast	Bal.	6.4	.4			0.90	.1	0.4			(91 dd)
Do	91.87	5.7			.12	.98	.94	.39			(91 dd)
Aeral			8							Duralumin type	(91 mm)
Aero:											
Sheet	Bal.	.6		.14	2.1		1.3				(91 dd)
Do	Bal.	.2			2.9		.3	.4			(91 dd)
Cast	Bal.	4.2	27.8				.5	.5			(91 dd)
Aerolite[1]											
Aeron	Bal.	4		x				1			(91 pp)
Albidur							x				
Aldal	Bal.	3.4		.41	.42						(91 c)
Alferium	Bal.	5.68		.69	.65	.002	.52	.5			(91 nn)
Alganite[1]											
Almelec					1.5						(91)
Alpax (as reported)	Bal.		.5		.25			12			(91 x)
Alpax (normal composition)	87							13			
Aludur					x						(91 r)
Alumac		2						3			
Do		4						5			
Alumac (cast)								13			
Aluminite	Bal.	2.7	23.3								(91 dd)
Aluminum silver	95									Ag 5	(91 dd)
Aluni						x					
Alzen	66.6		33.3								
Alzine (Sibley)	80		20								
Argental	Bal.									Ag	
Argentalium	Bal.									Sb	
Argilit	90	6						2		2 Bi	
Atherium											(91 rr)
Autox			x								
Baush A5 casting metal	x	x				x					
Bell metal	83			10						Cd 7	(91 dd)

Bersch bearing	93					7					(91 dd)
Birnal[1]											
Bourbonnes	48.8	.25					.33		50.48		(91 dd)
Chrysiode	6									Ag 92	
Clarus	x	x	x								
Constructal	x		x		x						
Die casting	92	8									(91 dd)
Do	82	18									(91 dd)
Do	86.13	10.17	.24	.03	.32		2.81	.3			(91 dd)
Drittel silver	66.7									Ag 33.3	
Duralumin	Bal.	3.5		.5	.5						(91 dd)
Do	Bal.	5.5		.8	.5						(91 dd)
Do	Bal.	4.2		.49	.76		.67	.34			(91 dd)
Durand's	66.6		33.3								(91 dd)
E alloy	76	2.5	20	.5	.5		.2	.2			(91 dd)
F alloy	Bal.	2.5	20	.5	.5		.2	.75			(91 gg)
Fletcher and Emperor bearing	92.2	7.5							.25		(91 dd)
Fletcher's alloy	95.5	3							1	Sb, 0.5 P, Sn 5	(91 dd)
Fontane	Bal.	3.5		.5						0.5 Ag	(91 oo)
G alloy	Bal.	2.5	18	.35	.35			.8			(91 gg)
Gosmannsche	Bal.	8							5		
Halumin	Bal.	2				1.5	1				(91 b)
Hard Al	77		11.5		4.5						(91 dd)
Huron A-5:											
Casting	Bal.	6.6			.5	1.25			x	Cu 0.25, Mn, Cd 0.5	(91 dd)
Rolled A	Bal.	3.5		.6	.5					Cr 0.1	(91 dd)
Rolled B	Bal.	4.0		.6	.5					Cr 0.1	(91 dd)
Rolled D	Bal.	4.0			.5					Cr 0.6	(91 dd)
Ingots:											
Casting 11	88.85	6.6	2.3	1		1.25					(91 dd)
Casting 12	92	8									(91 dd)
Casting 21	90	10									(91 dd)
Casting 22	83.7	63	5						5		(91 dd)
Casting 31	80.5	3	16	5							(91 dd)
Casting 32	64		36								(91 dd)
Casting 33	81		19								(91 dd)
Casting 34	78		22								(91 dd)
Rolling 3.5	98.3			1.5							(91 dd)
Rolling 5.5	94.5	2	2	1.5							(91 dd)
Rolling 8.5	66.6		33.3								(91 dd)
Ivanium											(91 dd)
Koltchougalumin											(91 qq)
Krupp bearing	87	8							5		(91 dd)
L-5	Bal.	2.5-3.0	12.5-14.5								(91 dd)

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[1] Composition not available.

TABLE 61.—*Compositions and trade names of alloys of aluminum*—Continued

Name	Al	Cu	Zn	Mn	Mg	Ni	Fe	Si	Sn	Other elements	Reference
L-7 (N. P. L.)	Bal.	14		1							(91 x)
L-8	Bal.	12									(91 x)
L-10	Bal.	10							1.25		(91 x)
L-11	Bal.	10	1						1		(91 x)
Lautal	Bal.	x						x			
Levalloy[1]											
Levettal[1]											
Lithalium										Li	
Lynite:											
146	Bal.	7-8.5			0.25		1.25				(91 dd)
122	Bal.	9.25-10.75									(91 dd)
109	Bal.	11.5-13.5									(91 dd)
Crank-case	Bal.	7.8	1.5					1.25			(91 dd)
Alloy (old)	Bal.	5									(91 dd)
Body alloy (recent)	95							5			
Macadamum	x		x								
Mach's	Bal.				2-10						(91 dd)
Magnalium:											
Cast X	Bal.	1.76			1.6	1.16					(91 dd)
Cast Y	Bal.	1.75			1.5				x	Pb	(91 dd)
Cast Z	Bal.	.21			1.58				3.15	Pb 0.7	(91 dd)
Cast	85				15						(91 dd)
Sheet	95				5						(91 dd)
Magnalite	Bal.	2			2	2					(91 dd)
Do	Bal.	2.5	.5		1.3	1.5					(91 dd)
Do	93.09	2.19			1.54	1.45	1.10	.61			(91 dd)
Do	94.27	2.47	.13		1.17	.65	.69	.59			(91 dd)
Do	93.5	2.61			1.37	1.72	.86	.37	.17		(91 dd)
Do	93.9	2.4			1.56	1.19	.47				(91 dd)
Do	93.2	2.44			1.38	1.25	1.35	.37			(91 dd)
Major metal (B. S. analysis)	95.37	1.4	.2	0.12	.35	.9	.65	.32		Pb .14, Ag 0.5, Cr. 05.	(91 dd)
Manhardts	83.33	6.24			.05				10	P. 07	(91 dd)
Maluminum	Bal.	6.4	4.8	.1			1.4	.2		Pb 0.15	(91 dd)
McKinney:											
Cast	96	2		1.5							(91 dd)
Forging, soft	96.5	2		1							
Forging, hard	94.5	3		2							(91 dd)
McAdamite		3.1	12-18		.2						(91 dd)

McAdams, W. A.	68. 5	7. 7	23. 1			. 63					(91 dd)
Do.	60	5	20							Ag 16.5	(91 dd)
Do.	70	3	26							Ag 1	(91 dd)
Do.	70	3	22							Sb 5	(91 dd)
Do.		5								Ag 2	(91 dd)
Do.	80								8	Cd 8, Ag 4	(91 dd)
Do.	82	12								Cd 5, Ag 1	(91 dd)
McLure	Bal.	8. 2		. 2			. 9	. 3	5–6		(91 dd)
Metalline	25	30					10			Co 35	(91 dd)
Meteorite	Bal.		1–2							P 1–4	(91 dd)
Minckinmetal		x				x					
Mock silver	84. 2	5. 5							10. 2	P 0.1	(91 dd)
Montegal											(91 a)
Montago											(91 pp)
Montier's	Bal.	x				x			x		(91 j)
Newman's	92		4. 4		3. 6						(91 dd)
Do.	72		14. 5		13. 5						(91 dd)
N (Naval)	Bal.	6		3							(91 x)
Navaltum	x				x						(91 kk)
Navy	Bal.	1. 5		. 9		. 4	. 4	. 3			(91 dd)
Nuremberg gold	75									Au 25	
Ormiston [1]											
Partinium	Bal.	. 64							. 16	Sb 2.4, W 0.8	(91 dd)
Do.	88. 5	7. 4	1. 7				1. 3	1. 1			(91 dd)
Piston alloys [2]											
Platargan	x									Ag, Pt	(91 s)
Rohmium		5–7			1	1. 5–2. 5					
Romanium	Bal.	. 25				1. 75			. 15	Sb 0.25, W 0.17	(91 dd)
Rosein	30					. 40			. 20	Ag 10	(91 dd)
Rubell	93. 5	4								Cd 2.5	
17S [3]	x										(91 n)
25S [3]	x	x		x				x			(91 n)
51S [3]	x				x			x			(91 n)
SAE 33	Bal.	7. 5	1. 5				1. 2				(91 n)
SAE 35	Bal.							5			(91 n)
Sibley	67		33								(91 dd)
Silium	Bal.							12–14			(91 t)
Silumin	Bal.							11–14			
Skleron (Scleron)		x	x	x		x		x		Li	(91 v)
Solbisky's	Bal.		1			1				Cd 3	(91 ss)
Susini	Bal.	1. 5	. 5	1–3							(91 dd)
Do.	Bal.	2. 5	1, 0	1–5							(91 dd)
Do.	Bal.	4. 5	1. 5	2–8							(91 dd)

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[1] Composition not available.

[2] See Table 39, p. 141.

[3] See heat treatment section.

TABLE 61.—*Compositions and trade names of alloys of aluminum*—Continued

Name	Al	Cu	Zn	Mn	Mg	Ni	Fe	Si	Sn	Other elements	Reference
T metal	8	0.1			3.8		0.5	0.5			(91 dd)
Tiers argent	66									Ag 33	(91 dd)
Titalumin [1]											
Tsungani [1]											
Vanalium											(91 kk)
Verilite	Bal.	2.5		0.3			.7	.4			(91 dd)
Vitalu											(91 h)
Weidrium		x	x			x					(91 ll)
Do					x		x			x	(91 ll)
Willmill A	Bal.						.8	8			(91 x)
Willmill B	Bal.						.8	4.5			(91 x)
Wolframium	98	.36								Sb 1.4, W 0.05	(91 dd)
Do	98	.375							1	Sb 1.44, W 0.04	(91 dd)
W. 0.33	Bal.	14		1							(91 dd)
X.—alloy	Bal.	1.76			1.60	1.16	x			Sb.	
Zimalium	93.5		2.8		3.7						(91 dd)
Do	88.5		4.4		7.1						(91 dd)
Do	74		14.8		11.2						(91 dd)
Zizium	83	1	15						1		(91 dd)
Do	82	3	15								(91 dd)
Ziskon	60		40								(91 dd)
Z	Bal.	.21			1.58		3-1		3.15	0.72 Pb	

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[1] Composition not available.

TABLE 62.—*Compositions and tensile properties of miscellaneous light alloys*

Name of alloy	Manufacturer	Form in which alloy is used	Density	Chemical analysis									Tensile properties				
				Al	Cu	Zn	Mg	Mn	Ni	Fe	Si	Other elements	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area
			*gr/cm*³	*P. cent*	*P. cent*	*P. cent*	*P. cent*	*P. cent*	*P. cent*	*P. cent*	*P. cent*		*Lbs./in.*²	*Lbs./in.*²	*Lbs./in.*²	*P. cent*	*P. cent*
Acieral[1]	Acieral Co. of America.	Sand castings	2.84		6.4	0.4			0.9	0.1	0.4		6,000		22,000	2.0	0.6
Do		Sheet			2.3		0.1	1.5		1.4			37,000		50,000	3.3	5.4
Do		do			3.7		.2	1.0		1.3			51,000		67,000	2.9	7.0
Aero metal[1]	Garford Engng. Co.	Sand castings	3.3		4.2	27.8				.5	.5				24,600	1.0	.3
Do		Sheet (0.1 in.)			.2		2.9			.3	.4				41,000	3.8	11.6
Albidur - aluminum.[2]	Otto Gruson & Co.		2.9												25,000–34,000	1–5	
Aluminite[1]	[W. J. Bruff]	Sand castings	3.3		2.7	23.3				.4	.2				40,000	0	0
Atherium[2]	Prett, Bowley & Co.		2.5												41,000	17	
Bearing metal	Le Ferro Nickel			94–98	1.5–4			¼–1¼				¼–1¼Ag		14,000–20,000	28,000–40,000	16–18	
McAdamite[1]	McAdamite Aluminum Co.	Sand castings	2.8		3.1	12–18	.2						18,000		31,000	0	0
McLure[1]	[L. S. McClure]	do	2.94		8.2			.2		.9	.3	5–6 Sn	15,700		19,600	3.1	2.3
Magnalite[1]	Walker M. Levett Co.	do	2.8		2.5	.5	1.3		1.5				10,000		26,000	2.5	1.6
Magnalium X	(1)	do			1.8		1.6		1.2						19,000–22,000		
Magnalium Y	(4)	do													31,000–47,000		
Magnalium Z	(4)	For rolling															
Maluminum[1]	H. D. Kramm Foundry Co.	Sand castings	2.85		6.4	4.8		.1		1.4	.2	0.15–Pb	13,000		17,100	1.5	2.3
T metal[1]	Light Metals Co	do	2.7		.1		3.8			.5	.5				15,700	3.0	1.1
Tiers argent[2]	Krupp	(5)		66								33 Ag					
Verilite[1]	Verilite Metals Co.	Sand castings	2.8		2.5			.3		.7	.4				16,000	4.0	4.0
Weidrium[2][3]	[Richard Weidner]		2.75–3.1												20,000–28,000	4–12	
Zimalium[2]			3.4														
Ziskon[4]	Carl Zeiss	Castings[6]	2.95	60?		40?									24,000		
Zisium[4]				85?		15?									11,000		

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[1] Tests by Bureau of Standards.
[2] Mentioned by Krause (21).
[3] Contains Ni, Cu, and Zn, or Sn, Fe, and Mg.
[4] Mentioned by Law (31).
[5] Substitute for silver.
[6] For instrument parts.

(d) SPECIFICATIONS FOR CASTING ALLOYS

In Table 63 are given the compositions of several alloys in ingot form as required by specifications of the American Society for Testing Materials, and in Table 64 is given an abstract of specifications for aluminum casting alloys collected from various sources.

TABLE 63.—*Specifications for aluminum base sand cast alloys in ingot form. (A. S. T. M., B58–26T)*

Alloy	Chemical composition							
	Aluminum	Copper	Iron maximum	Silicon	Magnesium	Manganese	Zinc	Remarks
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
A	>96.5	1.0 to 1.5	0.5	<0.5	Trace.	0.7 to 2.0	Trace.	
B	>92.5	>.6	.8	4.5 to 6.0	Trace.	<0.2	<0.20	
C	>90.0	7.0 to 8.5	---------	---------	---------	---------	<0.20	Total of Fe, Si, Mn, Zn, and Sn not to exceed 1.70 per cent.
D	88–92	6.0 to 8.0	---------	---------	---------	---------	<2.50	Total of Si, Mn, and Sn not to exceed 1 per cent.

TABLE 64.—*Abstract of some specifications for aluminum casting alloys*

Specifications	Designation	Alloy	Specified chemical composition	Impurities								Tensile properties				Specific gravity	Remarks
												Minimum specified		Average obtained			
				Iron (maximum)	Silicon (maximum)	Lead (maximum)	Zinc (maximum)	Tin (maximum)	Copper (maximum)	Magnesium (maximum)	Manganese (maximum)	Tensile strength	Elongation in 2 inches	Tensile strength	Elongation in 2 inches		
				P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Lbs./in.*^{2}	*Per cent*	*Lbs./in.*^{2}	*Per cent*		
American Society for Testing Materials Tentative Revision of B26-21.	B26-26T intended to supersede B26-21.	A	Al not under 96.5; Cu 1-1.5 per cent.	0.5	0.5		Tr.			Tr.		18,000	8.0				
		B	Mn 0.7-2.0 per cent; Al not under 92.5 per cent; Si 4.5-6.0 per cent.	1.0			0.20		0.6	Tr.	0.2	16,000	3.5				
		C	Al not under 90.0 per cent; Cu 7.0-8.5 per cent.				.20					18,000					Total of Fe, Si, Mn, Zn, and Sn not to exceed 1 per cent.
		D	Al 88-92 per cent; Cu 7.0-8.0 per cent.	1.5			2.50					19,000					Total Si, Mn, and Sn not to exceed 1 per cent.
American Society for Testing Materials Standard.	B26-21	A	Cu 7.0-8.5 per cent.									18,000	1				Maximum impurities 1.7 per cent, Al. Rem.
		B	Cu 8.5-11.0 per cent.									18,000					Do.
		C	Cu 11.0-14.0 per cent.									19,000					Do.
		D	Cu 2.5-3.0 per cent; Zn 12.5-14.5 per cent.			0.1						25,000					Do.
		E	Cu 2.0-2.5 per cent; Mn 0.75-1.25 per cent.									18,000	8				Maximum total impurities 1 per cent, Al. Rem.

TABLE 64.—*Abstract of some specifications for aluminum casting alloys*—Continued

Specifications	Designation	Alloy	Specified chemical composition	Impurities								Tensile properties				Specific gravity	Remarks
												Minimum specified		Average obtained			
				Iron (maximum)	Silicon (maximum)	Lead (maximum)	Zinc (maximum)	Tin (maximum)	Copper (maximum)	Magnesium (maximum)	Manganese (maximum)	Tensile strength	Elongation in 2 inches	Tensile strength	Elongation in 2 inches		
				P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Lbs./in.²*	*Per cent*	*Lbs./in.²*	*Per cent*		
Navy Department	46-Ala. Nov. 1, 1926.	1	Cu 1-1.5 per cent; Mn 0.7-1.2 per cent.	0.7	0.50		Tr.			Tr.		19,000	10				Al, minimum 96.5 per cent.
		2	Si 4.5-6 per cent	1.0			0.20		0.6	Tr.	0.2	17,000	3				Al, minimum 92.5 per cent.
		[1] [2] 3	Cu 4.0-5.0 per cent	1.2	1.20		.25			0.35	Tr.	28,000	6				Al, minimum 94.5 per cent.
Society of Automotive Engineers.	Aluminum alloys.	30	Cu 7.0-8.5 per cent				.20					18,000 20,000	1-2			2.83	Al, minimum 90 per cent; Zn, Si, Fe Mn, and Sn, maximum 1.70 per cent.
		31	Cu 2.25-3.25 per cent; Zn 12.50-14.50 per cent.									25,000 30,000	>1			3	Al, minimum 81 per cent; Si, Fe, Mn, Sn, maximum 1.70 per cent.
		32	Cu 11.00-13.50 per cent.				.20					19,000 23,000	(Will be practically nothing.) <1			2.95	Al, minimum, 85.50 per cent; Fe, Si, Zn, Mn, Sn, maximum. 1.70 per cent; Si, Mn, Sn, 0.75 per cent.
		33	Cu 6.00-8.00 per cent; Al 88.00-92.00 per cent.	1.50			2.50					19,000 21,000	1-2			2.83	Other impurities, none; Al, minimum 87 per cent.
		34	Cu 9.25-10.75 per cent; Fe 0.90-1.50 per cent; Mg 0.15-0.35 per cent.									24,000 30,000	Is usually. <1			2.96	Other elements <0.75.
		35	Si 4.50-65.0 per cent	1.00			.20		.60		.20	16,000	3.5				Al, minimum, 92.5 per cent.

British Engineering Standards Association.[4]	----------	3-L-11	Cu 6.00-8.00 per cent.	.80	.70	.10	.10	-----	-----	-----	-----	[3] 20,200	3	20,200 29,600 24,600	4-6	2.88	Al remainder.
		2-L-8	Cu 11.00-13.00 per cent Zn 12.50-14.50 per cent; Cu 2.50-3.00 per cent.	.80	.70	.10	.10	-----	-----	-----	-----	[3] 20,200	----------	26,900 31,400 35,800	1-2	2.90	Do.
		2-L-5		.80	.70	.10	-----	-----	-----	-----	-----	[3] 24,600	3		6-10	3.00	Do.
		L-24	Cu 3.50-4.50 per cent; Ni 1.80-2.30 per cent; Mg 1.20-1.70 per cent.	.80	.70	.10	.10	.10	-----	-----	-----	As cast. [3] 24,600 No specifications as heat treated	----------	As cast. 20,600 24,600 Heat treated. 38,100 49,300	As cast 1-2; heat treated, 3-6	2.85	Do.

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[1] Heat treated.
[2] Total of all constituents other than Cu and Al, 2.5 per cent maximum.
[3] Chill cast, not sand cast as in the American specifications.
[4] Abstracted from British Engineering Standards Association, George Mortimer, American Society for Testing Materials, 1925, Pt. II, p. 335.

3. HEAT-TREATED ALUMINUM ALLOYS

While the aluminum-copper-zinc alloys are still used abroad for castings, the aluminum-copper and the aluminum-silicon and aluminum-copper-silicon alloys seem to be displacing them there. Even five years ago, in this country, probably 95 per cent of the casting production was in the "No. 12," 8 per cent copper alloy, this having displaced the nickel-aluminum alloy that was the first important casting alloy in the United States.

The silicon alloys now form a large proportion of the tonnage of castings in this country and are finding increasing use. An ever increasing tonnage is also made of heat-treated castings of the duralumin type.

In the field of wrought aluminum, pure aluminum, and the "hard sheet" or aluminum manganese alloy hold their places for many uses, but an increasing amount of the strong, heat-treated alloys of the duralumin type is being called for.

For electrical conductors, pure aluminum shows no signs of being displaced, although experiments are reported from Europe in the use of heat-treated alloys with a low content of alloying elements, these also being of the duralumin type.

Duralumin and the alloys allied to it, by virtue of their ability to be strengthened by heat treatment, thus form an extremely important section of the light-alloy field. Experience with the wrought alloys of this type is of longer duration and farther advanced than with the cast alloys. Since the general principles governing the heat treatment of all the alloys of this type are the same, duralumin will first be considered, but the discussion must necessarily deal with the alloys as a group more than as individuals, and both wrought and cast materials have to be dealt with from similar points of view.

(a) WROUGHT DURALUMIN, COMPOSITION AND PROPERTIES

The most remarkable light alloy of aluminum is undoubtedly duralumin, the behavior and properties of which were discovered by Wilm (43ii) during his investigation during the years from 1903 to 1911. The remarkable feature about it is that its mechanical properties may be vastly improved by heat treatment; also that part of the heat treatment goes on "spontaneously" at room temperature.

The composition of this alloy varies somewhat. The following range of compositions is common:

	Per cent
Copper	3. 5–4. 5
Magnesium	. 4– . 8
Manganese	. 4–1. 0
Silicon	. 2– . 8
Iron (impurity)	. 3–1. 0
Aluminum	Balance

The alloy can readily be rolled or forged. It is generally used in the wrought condition, since the development of its highest physical properties involves the application of mechanical work to it.

Duralumin ingots are made from hardeners of copper, manganese, and magnesium alloyed with aluminum, which are added to the aluminum at about 800° C. The alloy is then cast in iron molds at a temperature between 690 and 710° C. (43t). Scrap may be remelted at a temperature of 700 to 750° C., using zinc chloride as a flux. The properties of such metal are almost as good as those of the original (43dd).

The electrical resistivity of annealed duralumin is 3.43 μ-cm. In the heat-treated condition, however, in which it is used, the resistivity is much higher, being 4.73 μ-cm. In this condition it has approximately 35 per cent of the volume conductivity of copper. Its thermal conductivity is about 31 cal. sec./cm^3.

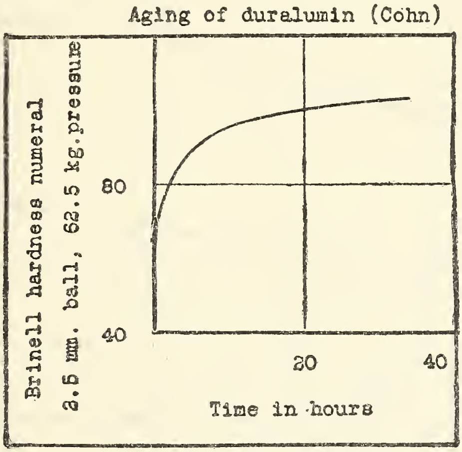

Fig. 96.—*Increase of hardness of duralumin upon aging after quenching.* (*Cohn, 43rr, ss*)

The density of duralumin varies from 2.75 to 2.84 g/cm^3. Its melting range is about 540 to 650° C.

When this alloy is heated for a few minutes at about 520° C. and quenched in water, the hardness is very little increased over that which would be obtained by slowly cooling the same alloy. But upon aging the quenched alloy for several days at ordinary temperature both the hardness and the ductility are increased from 15 to 50 per cent, depending on the composition of the alloy and the quenching temperature (fig. 96). Thus an alloy showed the following changes of properties.

	After rolling, before hardening	After hardening (quenching and aging)
Tensile strength lbs./in.^{2}	37,000	58,000
Elongation per cent	17	23

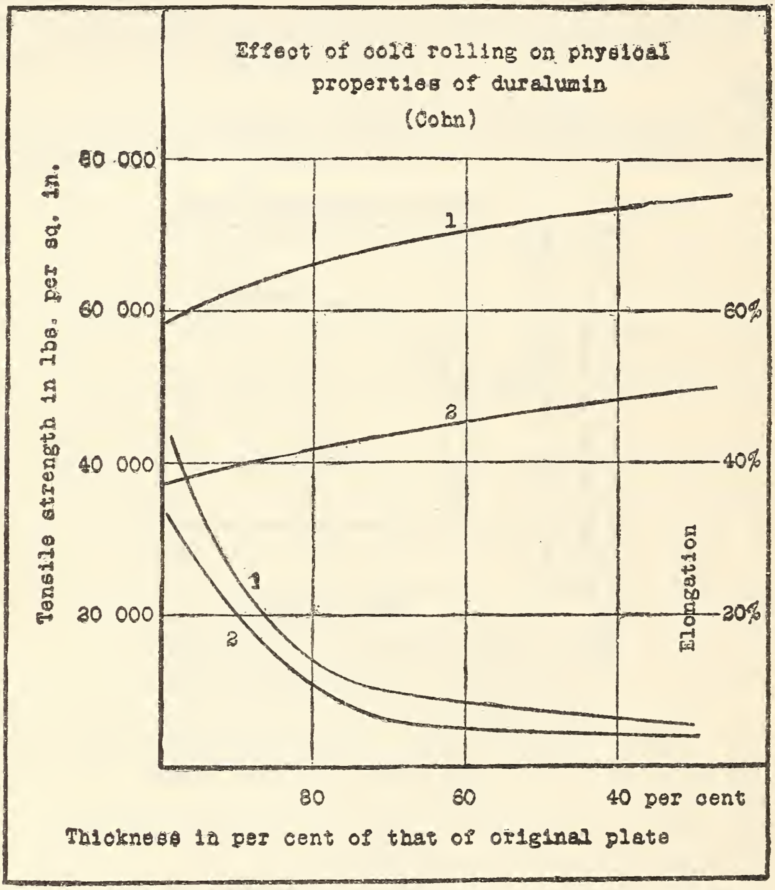

FIG. 97.—*Effect of cold-working on the tensile properties of duralumin.* (*Cohn, 43rr, ss*)

(Samples were rolled cold from a thickness of 7 mm)
Curves 1, tensile strength and elongation of hardened duralumin
Curves 2, tensile strength and elongation of rolled but not hardened duralumin

After hardening this alloy by quenching and aging it may be still further hardened by cold work at the cost, of course, of ductility. (Fig. 97.)

The hardness produced by cold working is, of course, lost upon annealing at rather low temperatures. The curve of Figure 98 shows the effect of annealing at different temperatures followed by air cooling upon the hardness and ductility of a work-hardened duralumin. Duralumin, even in large sections, hardens slightly even when cooled in air, and air cooling of thin sheets produces almost as much hardening as water quenching. It is, of course, the cooling rate, rather than the cooling medium, that is important.

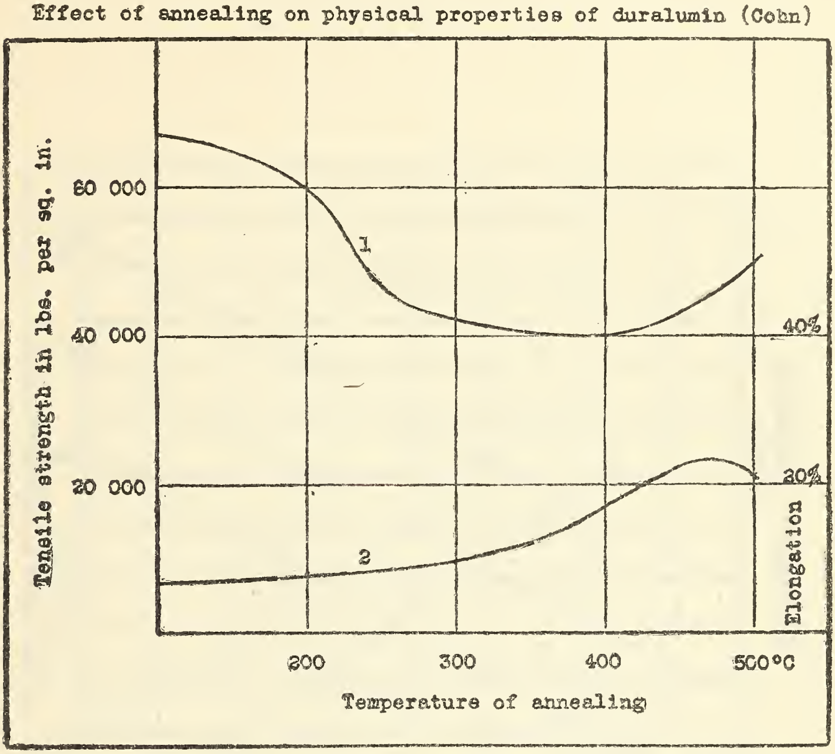

Fig. 98.—*Effect of annealing on the tensile properties of duralumin.* (*Cohn*)

The samples were annealed and cooled in air; curve 1 is that of the tensile strength; 2, of the elongation

Duralumin loses its hardness at higher temperatures. Figure 26 (see p. 80) shows the effect of higher temperatures upon the hardness of this alloy.

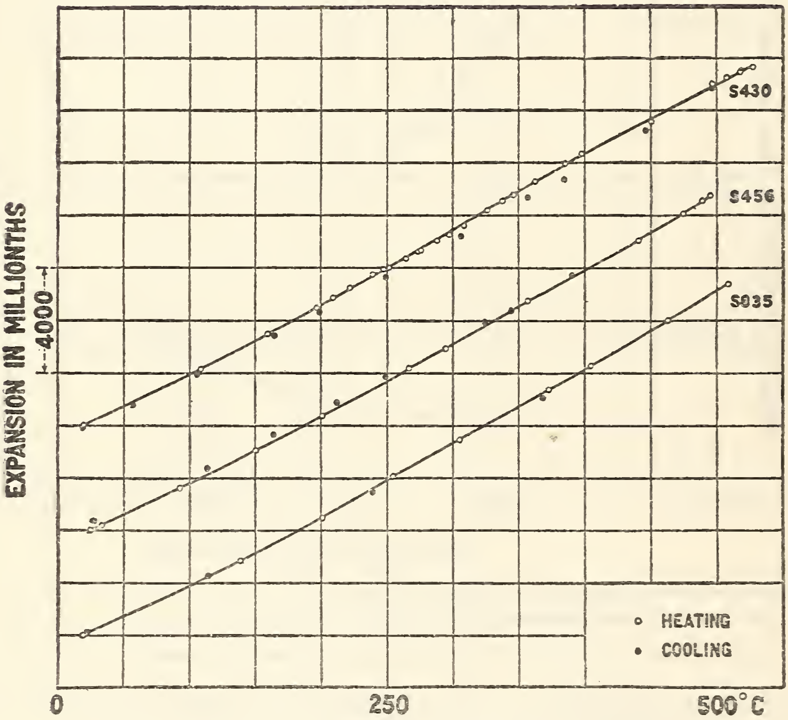

Fig. 99.—*Linear expansion of three samples of duralumin*

S835 sand-cast. S456 hot-rolled. S430 quenched from 520° C. and aged two days at 120° C.

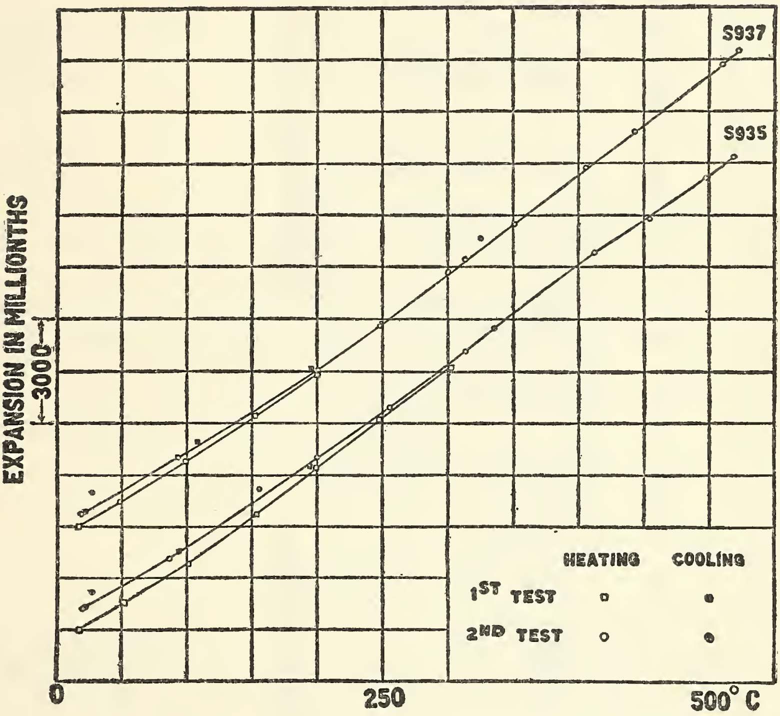

FIG. 100.—*Linear expansion of two samples of duralumin*

S935 hard-rolled. S937 heated to 500° C. and quenched

TABLE 65.—*Chemical compositions, average coefficients of expansion, and length changes of duralumin*

Laboratory No.	Material	Composition						Average coefficients of expansion per degree centigrade						Changes in length due to heat treatment received during test
		Al[1]	Cu	Mg	Mn	Fe	Si	20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.	
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	*Per cent*
S835	Duralumin, sand-cast	94.79	3.68	0.36	0.57	0.35	0.25	23.6	24.6	25.7	26.0	26.7	27.3	+0.01
S836	Cut from same bar as S835							23.2	24.8	25.8	26.0	26.8	27.6	+.03
S456	Duralumin, hot rolled [2]	94.36	3.74	1.08		.52	.30	23.8	24.7	25.3	25.7	26.3	27.2	+.03
S430	Duplicate of S456, cold-rolled to 0.09 inch and heat treated [3]							23.7	25.2	25.8	26.4	27.3	27.3	−.01
S935	Duralumin, hard rolled [4]	94.58	3.66	.52	.51	.37	.16	23.1	26.0	26.5	26.7			+.06
								[5] 22.5	24.6	24.8	25.3	26.2	26.1	+.03
S936	Duplicate of S935							23.1	26.0	26.7	26.9			+.06
								[5] 22.2	23.5	24.1	24.7	25.7	25.4	+.01
S937	Duplicate of S935, heat treated [6]							23.2	24.0	25.3	25.9			+.03
								[5] 21.9	22.9	23.7	24.7	25.7	26.4	+.04
S938	Duplicate of S937							23.2	24.2	25.4	26.2			+.04
								[5] 22.6	24.1	24.9	25.6	26.6	26.9	+.06

[1] Aluminum determined by difference.

[2] Rolled at about 410° C. from 3½ inches to ¼ inch thick.

[3] Quenched in water from 520° C., and aged two days at 120° C

[4] Contains also 0.20 per cent calcium.

[5] Values given on this horizontal line were obtained on a second heating.

[6] Tempered by heating for a short time at about 500° C. and quenching.

The coefficient of expansion of duralumin as determined at the Bureau of Standards (88g) is given in Table 65 and linear expansion curves are given in Figures 99 and 100. It is nonmagnetic, takes a good polish and in the annealed condition can be drawn, spun, formed and stamped. Sheet duralumin shows the following properties:

TABLE 66.—*Tensile properties of sheet duralumin after Knerr (43dd)*

Property	Condition		
	Heat treated	Annealed	Hard-rolled
Ultimate tensile strength ... lbs./in.^{2}	55, 000–62, 000	25, 000–35, 000	67, 000–72, 000
"Yield point" ... do	30, 000–36, 000		55, 000–65, 000
Elongation in 2 inches ... per cent	18–25	10–14	3–8
Brinell hardness	93–100	54–60	130–140
Scleroscope	23–27	9–12	37–42

Anderson (43e) gives the properties of duralumin sheet shown in Table 67.

The properties of duralumin sheet vary somewhat in transverse and longitudinal sections. The strength decreases about 10 per cent for an increase of temperature of 100° C. (43dd). Unger (43kk) finds a slight increase in the ultimate strength and elongation of duralumin at −190° C. over that at room temperature as well as a slight increase in strength and a decrease of elongation on "weathering" for a period of two years, the latter probably due to intercrystalline corrosion which is discussed on page 31.

TABLE 67.—*Effect of heat treatment upon 18 gauge duralumin Anderson (43e)*

Treatment	Proportional limit	Tensile strength	Reduction of area	Elongation in 4 inches
	Lbs/in.^{2}	*Lbs/in.^{2}*	*Per cent*	*Per cent*
As rolled (not treated)	40, 650	51, 740	12. 9	2. 7
Air cooled from 350° C.[1]	7, 210	29, 900	22. 5	11. 3
Furnace cooled 350° C.[1]	5, 080	25, 310	39. 0	15. 0
Air cooled from 400° C.[1]	14, 080	42, 250	24. 1	15. 4
Air cooled from 500° C.[1]	27, 770	60, 480	24. 4	18. 5
Furnace cooled from 500° C	7, 430	32, 290	22. 6	15. 3
Ice-brine quenched at 512° C.[1]	28, 620	61, 030	26. 7	19. 6
Oil quenched at 512° C.[1]	28, 570	61, 670	26. 3	18. 6
Freshly quenched in water at 512° C.[2]	14, 850	42, 280	28. 3	21. 5
Water quenched at 512° C., drawn 1 hour at 100° C	20, 740	55, 250	27. 1	18. 5
Water quenched at 512° C., drawn 10 hours at 100° C	20, 440	55, 590	27. 7	19. 8
Water quenched at 512° C., drawn 1 hour at 200° C	18, 930	49, 900	27. 3	18. 3
Water quenched at 512° C., drawn 1 hour at 300° C	14, 710	38, 430	22. 1	10. 3
Water quenched at 512° C., aged 144 hours in air	28, 470	61, 170	27. 3	17. 6
Water quenched at 512° C., aged 1,440 hours in air	28, 290	61, 650	25. 7	18. 3

[1] After heating for 30 minutes at the temperature indicated and aged six days at ordinary temperature after the treatment. (144 hours in air.)

[2] Not aged.

Phillips (43m, t) gives the coefficient of friction of duralumin to duralumin as 0.33, duralumin to steel, 0.25, duralumin to brass, 0.27. Properties of duralumin under tension, compression, shear, and torsion are given by R. R. Moore (43ll).

Ericksen cupping tests on sheet are given by Anderson (43e). The relation between properties and heat treatment is brought out in the following section on heat treatment, and is also shown in Table 68.

Unless otherwise noted the properties given in Table 68 below are for sheet tested longitudinally. Thicker sections of duralumin will have properties in the fully heat treated condition which vary in strength, according to Knerr (43dd) as follows:

TABLE 68.—*Comparative strength of duralumin in different sections*

	Tensile strength	Elongation
	Lbs./in.²	*Per cent*
Sheet	55, 000–62, 000	18–25
Bar stock ¼–1 inch	55, 000	18
Bar stock 1–1½ inches	50, 000	18
Bar stock over 1½ inches	45, 000	18

According to one producer these tensile strengths for bar stock are minimum, and the elongation on sizes over 1½-inch diameter will not be as high as 18 per cent. Compare Tables 69, 70, and 71 for specification values.

Other alloys will show similar effects of size. This effect is due both to changes in rate of quenching and to the less thorough mechanical working received by the interior of a piece of large cross section.

TABLE 69.—*Specifications for aluminum alloy rods, bars, and shapes. (Duralumin)*

Specification	Designation	Grade	Copper	Magnesium	Manganese	Aluminum (minimum)	Heat treatment	Type	Length, diameter, or thickness (inches)
			Per cent	*Per cent*	*Per cent*				
Federal Specifications Board	Proposed	1	3. 5–4. 5	0. 2–0. 75	0. 4–1. 0	92	Heat treated	Rods and bars	0.125–0.75.
									0.76–1.50.
									1.51–2.50.
									2.51–3.25.
									3.26 and over to be as mutually agreed upon.
								Shapes	All.
							Annealed	Rods, bars, and shapes.	0.125–0.50.
									0.51–1.0.
									1.05–1.5.
									1.51–3.25.
									3.62 and over to 0.125.
									0.126–0.50.
									0.51–.100.
									1.01–2.00.
									2.01–larger.
									20.[2]
									18.[2]
									16.[2]
									14.[2]
									12.[2]
									10.[2]
									8.[2]
									6.[2]
U. S. Army	No. 11033–B, Dec. 6, 1926	1	3. 5–4. 5	. 2– . 7	. 4–1	92			0.50 and less.
									0.50–0.75.
									0.75–1.50.
									1.50–2.00.
									2.00.
									20.[2]
									18.[2]
									16.[2]
									14.[2]
									12.[2]
									10.[2]
									8.[2]
									6.[2]
							Annealed	Rods, bars, shapes	All sizes.
							Quenched	do	0.125–0.750.
								do	0.76–1.5.
								do	1.51–2.50.
								do	2.51–3.25.

TABLE 69.—*Specifications for aluminum alloy rods, bars, and shapes.* (*Duralumin*)—Continued

Specification	Designation	Grade	Tensile properties			Bend test		Tolerance dimensions		Permissible short lengths of nominal or stock lengths	
			Tensile strength (minimum)	Yield point (minimum)	Elongation per cent 2 inches (minimum)	Degrees	Radius of pin equal to thickness (times)	Diameter or thickness of rods, bars, or shapes	Shape, thickness	Shortest acceptable length in feet	Permissible per cent by weight of short lengths
			Lbs./in.^{2}	*Lbs./in.*^{2}							
Federal Specifications Board	Proposed	1	55, 000	30, 000	18						
			50, 000	25, 000	18						
			50, 000	25, 000	14						
			50, 000	25, 000	12						
			50, 000	25, 000	16						
			[1] 35, 000		16						
								±0. 002			
								±0. 003			
								±0. 005			
								±0. 008			
								Shall be mutually agreed upon.			
									±0. 007		
									±0. 010		
									±0. 020		
									±0. 025		
									±0. 035		
										12	80
										10	80
										10	80
										8	80
										8	40
										6	40
										6	40
										4	40

								Forging stock	Other than forging stock			
U. S. Army	No. 11033-B, Dec. 6, 1926	1	-----	-----	-----	-----	-----	±0. 010	±0. 002	-----	-----	-----
								±0. 015	±0. 003	-----	-----	-----
								±0. 020	±0. 005	-----	-----	-----
								±0. 025	±0. 006	-----	-----	-----
								±0. 025	([3])	-----	-----	-----
											12	80
											10	80
											10	80
											8	80
											8	40
											6	40
											6	40
											4	40
			[1] 35, 000	-----	16	-----	-----	-----	-----	-----	-----	-----
			55, 000	25, 000	18	180	8	-----	-----	-----	-----	-----
			50, 000	25, 000	18	180	8	-----	-----	-----	-----	-----
			50, 000	25, 000	14	180	8	-----	-----	-----	-----	-----
			50, 000	25, 000	12	180	8	-----	-----	-----	-----	-----

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[1] Maximum.

[2] Length in feet.

[3] As agreed between contractor and purchaser.

TABLE 70.—*Specifications for aluminum alloy sheets*

Specification	Designation	Grade	Chemical composition				Type	Thickness	Physical properties			
			Cu	Mn	Mg	Al			Tensile strength	Elongation 2-in.	Yield point	Bend[1] diameter "N"
								Inch	*Lbs./in.*[2]	*Per cent*	*Lbs./in.*[2]	
Federal Specifications Board.	Proposed aluminum alloy sheets.	1	3.5–4.5	0.4–1.00	0.2–0.75	92	------------	0.013–0.036	------------	--------	------------	------
								.037– .050	------------	--------	------------	------
								.051– .070	------------	--------	------------	------
								.071– .091	------------	--------	------------	------
								.092 and heavier	------------	--------	------------	------
								.250– .103	------------	--------	------------	------
								.102– .005	------------	--------	------------	------
								All	------------	--------	------------	------
							Heat treated	.013– .020	Min. 55.000	15	Min. 30,000	4
								.021– .128	Min. 55,000	18	30,000	4
								.129– .258	Min. 55,000	15	30,000	6
								.259– .500	Min. 55,000	12	30,000	8
							Annealed	.013– .032	Max. 35,000	8	------------	0
								.033– .064	Max. 35,000	10	------------	1
								.065– .128	Max. 35,000	12	------------	2
								.129– .258	Max. 35,000	12	------------	4
								.259– .500	Max. 35,000	12	------------	6

Specification	Designation	Grade	Tolerances										
			In thickness (inches)			In width (inches)				In length (inches)			
			18, or less, inches wide	18 to 36 inches wide	Over 36 inches wide	¼ to 4 inches wide	4 to 18 inches wide	18 to 36 inches wide	36 to 60 inches wide	18 inches or less	18 to 48 inches	48 to 120 inches	120 to 180 inches
Federal Specifications Board....	Proposed aluminum alloy sheets.	1	±0.0015	0.002	0.0025	--------	--------	--------	--------	--------	--------	--------	--------
			±.002	.0025	.003	--------	--------	--------	--------	--------	--------	--------	--------
			±.0025	.003	.004	--------	--------	--------	--------	--------	--------	--------	--------
			±.003	.003	.004	--------	--------	--------	--------	--------	--------	--------	--------
			5 per cent of T.	5 per cent of T.	5 per cent of T.								
						$+\frac{1}{16}$ $+\frac{1}{16}$	$+\frac{3}{16}$ $+\frac{1}{8}$	$+\frac{1}{4}$ $+\frac{3}{16}$	$+\frac{3}{8}$ $+\frac{1}{4}$	-------- --------	-------- --------	-------- --------	-------- --------
										$\pm\frac{1}{16}$	$\pm\frac{3}{32}$	$\pm\frac{1}{8}$	$\pm\frac{5}{32}$

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[1] Bend test specimens cut from any direction of the sheet shall withstand bending through an angle of 180° around a diameter equal to "N" times the thickness of the sheet without cracking.

TABLE 71.—*Specifications for aluminum alloy plates, sheets, and strips* [1]

Specifications	Size		Tensile strength			Yield point		Elongation			Bend test [2]		Tolerances									
														Width (inches)			Length (feet)					
																	Maximum percentage by weight of short lengths					
			Annealed	Quenched	Quenched and rolled	Quenched	Quenched and rolled	Annealed	Quenched	Quenched and rolled	Annealed	Quenched	Thickness; permissible variations	10 and less	10 to 18	Over 18	10 to 12	8 to 10	6 to 8	4 to 6	2 to 4	Under 2 feet
United States Army, Ordnance Department, No. 57-152, May 25, 1923.	*Inches*		*Lbs./in.*[2]	*Lbs./in.*[2]	*Lbs./in.*[2]	*Lbs./in.*[2]	*Lbs./in.*[2]	*In./in.*	*In./in.*				*Inch*									
	0.0100-0.0201		35,000	55,000	65,000	30,000	55,000	8	12	2	1	2										
	.0226- .1285		35,000	55,000	65,000	28,000	53,000	10	15	2	1	2.5										
	.1443- .2576		35,000	53,000	63,000	26,000	51,000	12	15	3	1	3										
	.2893-over.		35,000	50,000		25,000		12	15		1	4										
	.0100- .0142												±0.0015									
	.0159- .0254												±.0020									
	.0285- .0403												±.0025									
	.0453- .1019												±.0030									
	.1144- .1819												±.0060									
	.2043-over.												±.0100									
	.1019 and less.													±0.060	±0.060	±0.090						
	Over .1019													±.060	±.090	±.125						
	Nominal or stock length	Per cent by weight required																				
	Feet																					
	12	50															50	40	30	20	10	0
	10	60																40	30	20	10	0
	8	70																	30	20	10	0
	6	80																		20	10	0

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[1] Aluminum alloy must have a maximum specific gravity of 2.85. Annealed sheets, plates, and strips shall not show a scleroscope hardness exceeding 12.

[2] Bend test specimens cut from any direction of the sheet shall withstand bending through an angle of 180° around a diameter equal to "N" times the thickness of the sheet without cracking.

Transverse properties, as noted above, are lower than those in the longitudinal direction. A forged, heat-treated duralumin airplane propeller tested at the Bureau of Standards gave 57,500 lbs./in.^{2} tensile strength on longitudinal specimens and 49,500 on transverse specimens. These differences are more marked in heavy, forged sections than in sheet.

The "yield point" of duralumin and alloys of that type is not as definite a property of the alloy as is the case with mild steel. The stress-strain diagram for these aluminum alloys does not show a definite kink in the curve, but instead a slowly curving knee (43dd, e). Drop-of-beam methods of testing will not serve. Divider tests, as usually made, tend to give results decidedly higher than the truth. There is, with sufficiently sensitive and accurate equipment and test methods, a proportional limit which is considerably lower than the figure usually given for yield point. The "yield point" in tests of Table 72 with Bureau of Standards given as source, is the stress at which an extension, under load, of 0.012 inch in 2 inches or 0.006 inch per inch, is shown by the extensometer. In those tests with American Society for Steel Treating Recommended Practice as source, it is the same for alloys with "yield points" between 40,000 and 50,000 lbs./in.^{2}, while for alloys with "yield points" below 40,000 and above 50,000 lbs./in.^{2} the extension under load is 0.005 and 0.007 inch per inch, respectively. Templin (32f) suggests using different percentages of extension under load to define the "yield point" of various nonferrous alloys, according to the modulus of elasticity of the alloy in question. In Templin's scheme, the extension at the "yield point," in per cent is given by the equation $f=\frac{0.15E}{10^7}$, where f is the yield point factor (100 times the unit deformation in inches per inch) and E is Young's modulus. For aluminum, and its alloys with $E=10^7$ lbs./in.^{2} the unit deformation is 0.0015 of an inch per inch. Data from other sources seldom give in detail the method of testing for "yield point." In such alloys, it would seem more logical to follow the German practice (Scheur, 43d) and use the terminology "0.0001 inch per inch," "0.002 inch per inch" or "0.006 inch per inch limit," to define the test conditions, rather than to call it a "yield point," but data available in the literature are too indefinite to allow adopting such a practice in this circular. It would be still better were more data available on proportional limit, such as are given by Strauss (39g) in Table 72b.

TABLE 72.—*Properties of duralumin and similar alloys* [1]

HARDENING AGENT, $Mg_2Si+CuAl_2$

Source	Designation	Composition							Annealed	Quenched in water from—	Aged at—	Yield point	Tensile strength	Elongation	Brinell hardness 500 kg 10 mm
		Zn	Cu	Mg	Si	Mn	Fe	Cr							
										° *C.*	° *C.*	*Lbs./in.*²	*Lbs./in.*²	*Per cent*	
A. S. S. T	17SO		4.0	0.5	0.35	0.6	0.5		Yes			7,000–10,000	25,000–35,000	14–22	45– 55
	17ST									510 (950° F.)	20 (68° F.)	30,000–40,000	55,000–63,000	18–25	90–105
	A17SO		2.5	.3	.35	.01	.5		Yes				20,000–25,000	20–28	30– 40
	A17ST									510 (950° F.)	20 (68° F.)	15,000–20,000	35,000–45,000	20–28	55– 75
	B17SO		3.5	.3	.35	.01	.5		Yes				20,000–25,000	20–28	30– 40
	B17ST									510 (950° F.)	20 (68° F.)	20,000–25,000	42,000–50,000	20–28	65– 85
	Special 17SO		4.0	.5	1.25	.6	.5		Yes			7,000–10,000	25,000–35,000	12–20	42– 55
	Special 17SW									495 (925° F.)	20 (68° F.)	30,000–40,000	55,000–65,000	18–25	90–105
	Special 17ST									495 (925° F.)	157 (315° F.) 18 hrs.	50,000–55,000	63,000–70,000	8–14	95–125
Archer and Jeffries	Superduralumin high silicon.		4.3	.50	.78	.49				510	20		59,500	25	
			4.3	.50	.78	.49				510	120 (70 hrs.)		67,000	20½	
			4.3	.50	.78	.49				510	150 (20 hrs.)		75,500	13	
A. S. S. T	Duralumin AD		3.0	.30		.60		0.10	Yes				22,000–28,000	10–22	54– 60
	Duralumin AT		3.0	.30		.60		.10		510 (950° F.)	20 (68° F.)	25,000–30,000	50,000–55,000	18–25	89– 96
	Duralumin BD		4.0	.50		.60		.10	Yes				25,000–35,000	10–22	54– 60
	Duralumin BT		4.0	.50		.60		.10		510 (950° F.)	20 (68° F.)	30,000–40,000	55,000–65,000	18–25	93–105
	Duralumin BH (BT hard rolled after aging.)		4.0	.50		.60		.10		510 (950° F.)	20 (68° F.)	55,000–65,000	67,000–72,000	3– 8	130–140
Colvin, F. H	11S		4.0	.30–1.00		.60–1.00	(2)			Yes.	Yes.	30,000–40,000	55,000–63,000	18–25	90–110
Bureau of Standards [3]	17S		4.1	.61	.32	.51	.34		Yes			[4] 12,000	32,500	20	
	17ST		4.1	.61	.32	.51	.34			510	20	[4] 41,000	61,000	23	
	17ST worked		4.1	.61	.32	.51	.34			510	[5] 20	[4] 63,500	72,500	8	
	17ST		3.8	.62	.40	.54	.59			510	20	[6] 30,000–40,000	[6] 55,000–62,000	[6] 18–24	
	17ST		4.2	.47	.20	.47	.20			510	20	[4] 42,500	59,500	19	
	17S type without Mn.		3.7	.45	.22	.02	.36			510	20	[4] 36,000	53,500	21½	
	17S type low Cu		3.1	.63	.21	.50	.55			510	20	[4] 36,500	52,000	17	
	17S type low Cu and low Mn.		2.5	.40	.24	.02	.28			510	20	[4] 30,000	42,500	19	
	17S type low Fe and Si.		4.2	.52	.10	.47	.08			510	20	[4] 45,000	61,500	18½	
	17S type high Fe		3.8	.63	.24	.50	1.15			510	20	[4] 40,000	53,000	16	
	Duralumin B_2		3.9	.60	.31	.58	[7] .51		Yes			[4] 13,500	27,500	18	
	do		3.9	.60	.31	.58	[7] .51		Yes	[8] 510	20	[4] 36,500	62,000	21	
	Duralumin worked.		3.9	.60	.31	.58	[7] .51		Yes	[8] 510	[4] 20	[4] 59,000	71,500	7	
	Duralumin		4.3	.44	.21	.52	[9] .35			[8] 510	20	[6] 32,000–41,000	[6] 57,000–65,000	[6] 14–23	

Anderson			4.0	.45	.24	.59	[9] .80			(10)	(10)	[11] 40,500	51,500	[12] 2½	
			4.0	.45	.24	.59	[9] .80		Yes			[11] 7,500	32,500	15½	
			4.0	.45	.24	.59	[9] .80			[8] 512	20	[11] 28,500	61,500	18½	
			4.0	.45	.24	.59	[9] .80			512	20	[11] 28,500	61,000	17½	
			4.0	.45	.24	.59	[9] .80			512	100 (1 hr.)	[11] 20,500	55,500	18½	
			4.0	.45	.24	.59	[9] .80			512	200 (1 hr.)	[11] 19,000	50,000	18½	
Bureau of Standards	"Y"		4.1	1.56	.20	tr.	[14] .25			[15] 520	20	35,000	60,000	16	
Eleventh Rept.[13]	"Y"		Similar to above							530	20	[16] 29,500	60,000	17	
Kroll	Beryllium duralumin.		4.5	.50	.40		[17] .43			500	20		53,000	19	
	Germanium duralumin.		4.5	1.10	.40		[18] .40			525	130 (2 hrs.)		54,500	18	
N. P. L.	E [19]	20	2.5	.25	.50-1.0	.50				as rolled			69,000-72,000	15-18	
	E [19]	20	2.5	.25	.50-1.0	.50				400	20		79,000-85,500	13-16	
	E [20]	20	2.5	.25	.50-1.0	.50				400	20		91,000	9	
	E [20]	20	2.5	.25	.50-1.0	.50				400	20		85,500	15	
	F [19]	20	2.5	.25	.75	.50				as rolled			72,500	18	
	F [21]	20	2.5	.25	.75	.50				400	20		80,500	16	
		20	2.5	.25	.75	.50				400	20		79,500	19	
	G [21]	[22] 18	2.5	.35	.80	.35				400	20		77,500	19	

HARDENING AGENT, $CuAl_2$

		Cu	Si	Mn	Fe		°C.	°C.	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	
A. S. S. T	25SO	3.9-5.0	0.5-1.1	0.5-1.1		Yes			7,000-12,000	23,000-25,000	12-20	45-55
	25SW	3.9-5.0	0.5-1.1	0.5-1.1			520 (970° F.)	20 (68° F.)	15,000-30,000	45,000-53,000	15-22	68-85
	25ST	3.9-5.0	0.5-1.1	0.5-1.1			520 (970° F.)	145 (290° F.) 12 hrs.	30,000-40,000	55,000-63,000	16-25	90-105
Fuss	Lautal	4	2.				Yes.	Yes.		54,000-60,000	18-32	
Kroll	Beryllium Lautal	4.5	.40		[23] .42		520	130 (48 hrs.)		52,500	27½	
	Germanium Lautal.	4.5	.40		[24] .40		525	150 (48 hrs.)		53,500	23	
Scheuer	Aeron					Yes				31,500-35,500	18-25	
	do						Yes.	20		42,500-50,000	18-25	
	do						Yes.	(25)		51,000-60,000	18-25	
Bureau of Standards	25SO	4.2	.90	.68	[26] .45	Yes			[4] 12,000	28,000	24½	
	25SW	4.2	.90	.68	[26] .45		525	20	[4] 30,500	49,000	19	
	25ST	4.2	.90	.68	[26] .45		525	(27)	[4] 37,500	59,500	25	
J. I. M	Alferium						Yes.	Yes.	31,000-40,000	51,000-60,000	14-22	
P. & LeC		6.0		1.17			550	150 (50 hrs.)	47,000	65,000	17	[28] 129
		6.0		1.17			550	110 (200 hrs.)	37,000	62,000	25	[28] 117

See footnotes at end of table.

TABLE 72.—*Properties of duralumin and similar alloys*—Continued

HARDENING AGENT, Mg_2Si

Source	Designation	Composition				Annealed	Quenched in water from—	Aged at—	Yield point	Tensile strength	Elongation	Brinell hardness 500 kg 10 mm
		Zn	Mg	Si	Fe							
							°C.	°C.	*Lbs./in.*[2]	*Lbs./in.*[2]	*Per cent*	
A. S. S. T.	51SO		0.45-.80	0.60-1.20		Yes			4,000- 6,000	14,000-19,000	22-32	25-32
	51SW		.45-.80	.60-1.20			520 (970° F.)	20 (68° F.)	15,000-20,000	30,000-40,000	20-30	55-70
	51ST		.45-.80	.60-1.20			520 (970° F.)	155 (315° F.) 18 hrs.	30,000-40,000	45,000-50,000	10-18	90-100
Bureau of Standards	51SO		.61	1.00	[29] 0.38	Yes			[4] 6,500	15,500	31	
	51SW		.61	1.00	[29] .38		520	20	[4] 22,000	36,500	27	
	51ST		.61	1.00	[29] .38		520	(30)	[4] 43,500	49,000	13½	
Heyn and Wetzel	Aludur		.59	.88	.71		520	20 (6 da.)		33,500	21½	
	do		.59	.88	.71		520	100 (18 hrs.)		35,500	23½	
	Aludur, cold-rolled 10 per cent.		.59	.88	.71		520	18 hrs. and cold rolled.		53,500	15	
Sanders and Meissner		5	.50	.30			520	20 (5 da.)		38,500	18	
		10	.50	.30			520	20 (5 da.)		44,500	19	
		4	1.00	.30			520	20 (5 da.)		39,500	15½	
		8	1.50	.20			520	20 (5 da.)		29,000	15	
		5	1.25	.75			520	20 (5 da.)		52,000	19	
Kroll	Beryllium Aludur		1.0	1.3	[31] .45		550	170 (2 da.)		52,500	16	
	Germanium Aludur.		1.2	1.2	[32] .40		550	170 (2 da.)		44,800	15	

HARDENING AGENT Li_3Si OR UNKNOWN

Source	Designation	Composition	Annealed	Quenched in water from— / Aged at—	Yield point	Tensile strength	Elongation	Brinell hardness 500 kg 10 mm
Scheuer	Scleron	Not given, contains Li	Yes	(Details not given)	(33)	42,500	15-20	
Do	do	do	Yes	do		57,000-71,000	10-15	
Sander	Constructal No. 2	Not given, contains 3 per cent hardening elements.		do				
				Normal treatment [34]		55,500-58,500	21-23	
				Varied treatment		51,000-54,000	26-28	
				do		74,000	11	
	Constructal No. 8	Not given, contains Zn		Thin sheet [34]		67,000-74,000	15-20	

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[1] All material in sheet form, tested longitudinally unless noted.

[2] Also 0.30-0.60 per cent Ca.

[3] Bureau of Standards tests on sheet 0.06 inch thick unless noted.

[4] Stress for inch/inch extension under load.
[5] As cold-rolled from 0.088 to 0.062 inch after aging.
[6] In various thicknesses of sheet.
[7] Plus less than 0.02 Cr.
[8] In oil.
[9] Plus 0.10 per cent Cr.
[10] As rolled, not quenched.
[11] Proportional limit.
[12] In 4 inches.
[13] Sources Eleventh Report to the Alloys Research Committee. Table 42 of that report.
A. S. S. T.—Recommended Practice for heat treatment of wrought aluminum alloys of high strength—1927.
N. P. L.—Rosenhain, Archbutt and Hanson, Eleventh Report to the Alloys Research Committee, Institute of Mechanical Engineers, 1921.
P. and LeC.—Portevin and LeChatelier, Amer. Soc. Steel Treat., V, 1924, p. 457.
J. I. M.—Journal Institute of Metals, **35**, 1926, p. 536.
Scheuer—Zeit. fur Metallkunde, **19**, 1927, p. 16.
Fuss—Zeit. fur Metallkunde, **16**, 1924, p. 343, and **19**, 1927, p. 19.
Kroll—Metall. und Erz, 23, 1926, pp. 226, 590.
Heyn and Wetzel—Mitt. Kais. Wilh. Inst. fur Metallforschung, 1922, p. 10.
Sanders and Meissner—Zeit. fur Metallkunde, **16**, 1924, p. 12.
Sander—Sander, W., Constructal, Zeit. fur Metallkunde, **19**, 1927, p. 21.
Colvin F. H.—Am. Mach. **58**, 1923, p. 321.
Anderson, R. J.—A. S. T. M., **26** (2) 1926, p. 349.
[14] Plus 1.90 per cent Ni.
[15] In boiling water.
[16] Proof stress 25,000 lbs./in.^{2}
[17] Plus 1.8 per cent Be.
[18] Plus 1.3 per cent Ge.
[19] ⅞-inch rod forged and rolled.
[20] ⅞-inch rod extruded and rolled.
[21] Sheet 0.04–0.05 inch thick.
[22] Given as 1.80 in Eleventh Report to Alloys Research Committee. Corrected to 18.0, Proc. Inst. Mech. Eng., 1921, p. 711.
[23] Also 1.05 per cent Be.
[24] Also 1.3 per cent Ge.
[25] Elevated temperature; proportional limit, 17,000.
[26] Also 0.10 per cent Mg.
[27] As received—aging time and temperature not known—presumably 140° C., 8 to 15 hours.
[28] 1,000 kg. 10 mm.
[29] Also .01 per cent Mn and .05 per cent Cu.
[30] As received—aging time and temperature not known—presumably 155° C., 18 hours.
[31] Also 0.95 per cent Be.
[32] Also 1.6 per cent Ge.
[33] Proportional limit 25,500–28,500.
[34] Quenched and aged.

TABLE 72b.—*Mechanical tests of duralumin and other aluminum alloys in forgings* [1] *(Strauss, 39g)*

Composition, per cent						Heat treatment				Proportional limit [2]	Tensile strength	Elongation in 2 inches	Reduction of area	Izod impact [3]	Brinell hardness [4]
Si	Cu	Mn	Mg	Ni	Zn	Quenched in water or cooled in air [5]	From—	Aged at—	Hours aged						
							° C.	° C.		Lbs./in.²	Lbs./in.²	Per cent	Per cent	Ft.-lbs.	No.
(6)						Air	315			1,500	10,800	49.50	89	17	20
(7)						do	315			3,600	14,600	34	79	23.50	28
1.0			0.6			do	315			5,600	17,000	36	69	25.50	31
						Water	510	20		8,650	31,000	33	58	26	58
						do	510	150	2	19,000	35,500	24.50	46	20.50	74
.8			1.1			Air	315			3,600	17,000	27.50	64	23	27
						Water	510	20		10,700	33,500	30.50	53	24.50	59
						do	510	150	49	24,000	41,000	12	36	7	86
						do	535	150	25	29,500	45,500	18.50	33	7	93
			1.5			Air	315			9,150	25,000	25.50	63	29	42
						Water	510	20		7,200	26,500	32	58	31	42
						do	535	150	25	20,000	36,000	22.50	52	30	68
	0.7		1.5	0.7		Air	315			13,500	29,000	21.50	47	22.50	53
						Water	510	20		15,000	42,500	28	45	26	67
						do	535	150	25	26,500	51,000	22.50	43	22.50	88
		1.5				Air	315			11,700	24,500	21	50	19.50	50
	1.2	.8				do	315			10,200	24,500	23.50	57	28.50	44
	1.3	1.3		2.0		do	315			14,800	34,500	13.50	35	14.50	65
2.0	3.0	.6				do	315			11,700	27,500	18.50	45	17.50	50
						Water	530	150	50	12,700	39,000	18	42	18.50	67
	3.5					do	510	150	50	16,800	40,000	16.50	41	21	69
						do	560	150	50	11,200	36,500	20	47	20.50	74
1.0	4.0	.6				do	530	150	2	10,700	43,500	22	37	24.50	73
						do	530	150	50	25,000	52,000	16	27	17.50	98
(8)	3.5					do.[9]	510	150	50	16,800	40,000	16.50	41	21	69
						do	560	150	50	11,200	36,500	20	47	20.50	74
	4.0	.6	.3			Air	370			20,000	35,000	13.50	27	16	65
						Water	510	150	50	30,500	54,000	11.50	30	16	100
.8	4.5		.2			do	510	150	2	19,000	47,500	27	42	22.50	78
						do	510	150	50	36,500	53,500	14	33	10	109

.7	5.0	--------	--------	--------	--------	-----do-----	530	150	49	26,000	53,500	11	24	12	100
--------	5.0	1.0	--------	--------	--------	----do-----	530	150	49	26,000	54,000	11.50	26	9.50	100
						----do-----	560	150	49	33,500	59,500	8.50	18	8.50	107
--------	4.0	--------	1.5	2.0	--------	----do-----	510	20	--------	27,000	56,500	15.50	20	9	94
						----do-----	510	150	50	36,500	62,000	10	17.50	5.50	127
--------	3.0	.6	.5	--------	2.0	-----do-----	500	20	--------	26,000	58,500	23.50	36	19.50	98
(10)	--------	--------	1.0	--------	7.0	Air-----	370	--------	--------	27,000	57,500	15	20	10	97
						Water-----	510	150	50	26,000	45,500	12.50	26	6	100
--------	--------	--------	--------	--------	30.0	--------	--------	--------	--------	21,000	55,000	14	20	7.50	105

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[1] Unless noted, specimens were chill cast in about 3½-inch diameter, forged to ⅞-inch square, tested in 0.505-inch diameter bar.

[2] Ewing extensometer used on 2-inch test length, direct readings to 0.00002 inch.

[3] Mesnager drilled notch, 2 mm diameter, specimen 10 by 10 mm, 10 by 8 mm at notch.

[4] 500 kg load, 30 seconds.

[5] Held at annealing or quenching temperature two hours unless noted.

[6] Electrolytically refined pure aluminum.

[7] Commercially pure aluminum.

[8] Forged from 10-inch ingot to 1-inch round.

[9] Held at quenching temperatures six hours.

[10] Contains also 2.3 per cent iron.

Data on the metallography of duralumin, on the corrosion resistance, the resistance to repeated stress, and to impact, and the high temperature properties of duralumin will be found in other sections of this circular.

Sadtler and Gregg (43c) find that duralumin cold-rolled after aging shows a greater elongation under constant load above the proportional limit than is the case when cold-rolling is done immediately after quenching and before aging.

Long-time dead-weight tests have been made on B. & S. 22 gauge heat-treated duralumin sheet in the laboratories of the Aluminum Co. of America. This material tested in the normal way showed the following mechanical properties:

Tensile strength	lbs./in.^{2}	61, 500
Yield point	do	40, 000
Proportional limit	do	35, 000
Elongation in 2 inches	per cent	16. 5

The specimens are being tested under stresses as follows, and have shown deformations as indicated after a period of 14 months:

TABLE 73.—*Deformation of duralumin under 14 months' loading*

Specimen No.	Stress	Ultimate strength	Unit deformation	
			Deformation after 14 months under dead load	Usual tensile test
	Lbs./in.^{2}	*Per cent*	*Inch per inch*	*Inch per inch*
1	55, 000	89. 6	0. 090	0. 0770
2	50, 000	81. 5	. 040	. 0365
3	40, 000	65. 2	. 005	. 0045
4	35, 000	57. 0	. 003	. 0035
5	30, 000	48. 9	Negligible.	. 0030
6	25, 000	40. 7	Negligible.	. 0025
7	20, 000	32. 6	Negligible.	. 0020

Although additional deformation measurements have not yet been taken, none of the specimens had been broken after a duration of load of 18 months.

(b) HEAT TREATMENT OF ALUMINUM ALLOYS OF THE DURALUMIN TYPE

(1) THEORY.—The theory underlying the heat treatment of aluminum alloys whose properties may be improved by heat treatment was in its early stages when the first edition of this circular was prepared. Merica and coworkers at the Bureau of Standards were then studying the reasons for the age-hardening of duralumin, which had not been explained, although the fact that quenched duralumin did age-harden had been discovered by Wilm (43ii) in the period 1903–1911.

According to Guertler[7] the discovery was accidental.

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[7] Guertler, W. The Light Metal Alloys. Lecture before Washington, D. C., Chapter of Am. Soc. for Steel Treating, Oct. 15, 1926.

Although considerable commercial use had been made of duralumin, the suitable range of compositions and the heat treatment to give the improvement in properties were fairly well defined, the metallurgical explanation for the choice of composition and of heat treatment was not known.

Merica and coworkers (43mm) determined the range of solubility of the compound $CuAl_2$ in aluminum, using aluminum of 99.71 per cent purity, and explained the heat treatment of duralumin in relation to the equilibrium diagram. Dix and Richardson (43h) later, using aluminum of 99.92 per cent, and in some cases of over 99.97 per cent purity, made a more complete study of the solubility relations. Their diagram (fig. 101) is of the same form as that given by Merica.

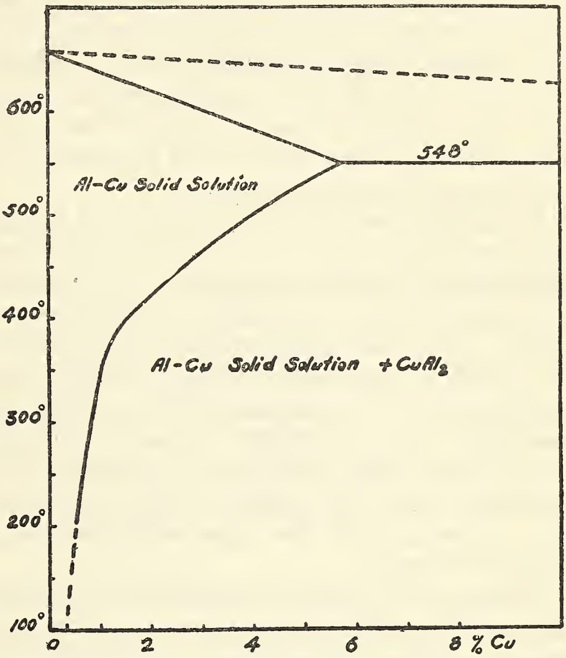

FIG. 101.—*Aluminum-copper system at aluminum-rich end. (Dix and Richardson, 61a)*

Merica's theory of age hardening of duralumin is, in brief, that when an alloy of, say, 3.5 per cent Cu, is heated to 500° C. for a sufficient length of time all the $CuAl_2$ compound is taken into solid solution in aluminum. On quenching, the alloy is rapidly cooled to room temperature without immediate precipitation of $CuAl_2$ from the solid solution as would be the case were the cooling to take place slowly. The quenched alloy is still soft, not hard like a quenched steel, although somewhat harder than in the annealed condition; but the tendency of the $CuAl_2$ to come out of solution is sufficient so that, with the lapse of time at room temperature (the natural aging process), particles of $CuAl_2$, too fine to be seen with the microscope, are precipitated and with further lapse of time agglomerate to larger, but still invisible particles. $CuAl_2$ is itself hard, and the dissemination of particles of it through the soft aluminum matrix is believed to harden and strengthen the alloy. The dispersion of fine particles is thought to "key" the material against slip and thus harden it. The slip-interference theory of Jeffries and Archer (44) involves the conception, which Merica had advanced, that hardness, that is, resistance to deformation, increases as the fine particles agglomerate and grow to a critical size. Further growth, beyond the critical size, produces a softening, the matrix being freed from some of the restraint previously put upon it by the myriads of fine particles. Still further growth induced at sufficiently high temperatures brings about full softening; that is, annealing.

It is questionable whether the interference with slip is due to a sort of mechanical keying, as suggested by Jeffries and Archer, to the effect of atomic forces acting between the tiny particles and their surroundings (44k), the particles being of colloidal size (91e), "rumpling" of the slip-planes or upsetting of the space lattice, (39a) lattice distortion without necessary precipitation of particles (43a) or the formation of pseudomolecules and hardening by bending of electrons at lattice discontinuities (44a).

That particles of $CuAl_2$ are precipitated during the aging process is made more certain by experiments of Dix and Richardson (43h), who demonstrated the appearance of a fine precipitate of $CuAl_2$ in a 4 per cent Cu alloy, quenched from 540° C. and reheated two weeks at 200° C. The chief objection (43k) to the precipitation theory is that the electrical resistivity increases during aging. In most alloys precipitation of a compound from a solid solution decreases the resistivity. But, as Merica (43l) points out, quenched duralumin is in an unstable state and that various factors may come in in such a condition to alter the relations found in alloys that are in equilibrium. Corson (2a) has also attempted an explanation of the apparent anomaly.

Whether or not such an explanation of hardening is correct or complete in all details, the phenomena met in heat-treatment of duralumin and other aluminum alloys susceptible of heat treatment, are consistent with the idea that the mechanism of heat treatment consists in obtaining a solid solution by heating to a temperature within the solid solution field of the equilibrium diagram, above the slanting line denoting the boundary between the solid solution or single-phase field and a field in which a precipitation of a compound within the solid solution matrix (two-phase field) is the stable form. By quenching the solid solution with sufficient rapidity the alloy is obtained in an unstable state, the precipitation of the compound being retarded. An approach to equilibrium through precipitation and agglomeration of the particles of the compound takes place, the rate of approach and the degree of completeness depending on both temperature and time. As the agglomeration of the particles proceeds the strength and hardness of the alloy increase up to a certain critical size and dispersion of the particles. When agglomeration proceeds beyond this point, the strength and hardness decrease up to the fully annealed state as a limit.

This explanation holds equally well not only for most of the heat-treatable aluminum alloys, but also for other alloys, such as lead-antimony (44a) and iron-tungsten (43o), and the generalization can be made that alloys whose equilibrium diagrams show solubility relations of the same nature as is exhibited by the high-aluminum end of the Al-Cu diagram are at least potentially capable of heat treatment. Fuller explanation of the theory involved is given by many writers, including Merica (44m), Knerr (43dd), Archer (44n), Jeffries (43ff), Jeffries and Archer (3b), and in many of the publications of the National Physical Laboratory of England on aluminum alloys. For other theories, see Meissner (43k), Fraenkel and Scheuer (43r), and Konno (44j).

As a consequence of the theory, it follows that the composition chosen must be one in which the necessary solubility relations hold, and that heating before quenching should be to a temperature and for a time that will effect the solution of the hardening compound without bringing about a partial melting by overstepping the liquidus line of the diagram. It will be seen from Figure 78 that with a low copper content, say 2 per cent, there will be wide latitude in quenching temperature as the range between the liquidus and the $CuAl_2$ solubility line is large, but that only a small amount of $CuAl_2$ will be precipitated as equilibrium is set up. With copper at 5 per cent the temperature range between that necessary to get a complete solid solution and that of the liquidus is very narrow. The presence of other elements affecting the solubility of the hardening compound also has to be taken into consideration.

If the composition, the temperature, or the time of heating, is such that not all the hardening compound goes into solution, the excess may act as nuclei for precipitation of more of the compound during quenching or on aging and too little compound may be left in solid solution to bring about the full improvement of properties due to the controlled precipitation and agglomeration of the compound.

After the solid solution has been obtained by heating within the proper range, the rate of chilling; that is, the size of the specimen and the nature and temperature of the quenching medium, also affect the amount of unprecipitated compound left to be controlled.

After quenching, the control of precipitation is affected by regulating the temperature and time at temperature. The plasticity of the matrix and the mobility of the precipitate increase with temperature. At liquid-air temperatures, the aging is greatly slowed down. At ordinary room temperatures, it goes on automatically in duralumin which contains Cu, Mg, and Si, and progresses with lapse of time practically as far as it can usefully be brought at higher temperatures. In an alloy of the duralumin type free from copper, there is some aging at room temperature, but to develop full hardening higher temperatures must be used, while in the Cu-Al alloy without Mg, practically no aging takes place at room temperature, and higher temperatures have to be used.

It is a most fortunate fact that in all these three types of alloy the agglomeration of the precipitate does not go on automatically at room temperatures with lapse of time to a degree which brings about softening; that is, once the alloys are hardened by aging or artificial aging, they do not complete the cycle that they would complete at higher temperatures. They do not self-anneal and are industrially stable as to hardness.

There are two hardening agents in duralumin, the compound $CuAl_2$ and the compound Mg_2Si. The equilibrium diagram for magnesium and aluminum (67a) shows a curved solubility line between the alpha and beta solid solutions, but the alloys high in aluminum do not show the possibility of precipitating a compound from solid solution. The amount of magnesium used in the alloys of the duralumin type is within the alpha solid solution range and their ability to harden is not ascribable to the magnesium by itself, though Mg_2Si and secondary effects of magnesium are concerned.

But the system Al-Mg_2Si has an equilibrium diagram (43ee) exactly similar in nature to that shown in Figure 48 for $CuAl_2$ in aluminum. About 1.6 per cent Mg_2Si (1 per cent Mg, 0.6 per cent Si) is in solution at about 580°, whereas less than 0.30 per cent is soluble at room temperatures. The retention of solid solution by quenching and the subsequent precipitation of hardening particles of Mg_2Si takes place just as in the case of $CuAl_2$, save that to harden the alloy with $CuAl_2$ materially (in wrought form) aging must be at elevated temperatures, while that with Mg_2Si hardens somewhat at room temperature.

It happens that ordinary commercial aluminum contains sufficient Si as accidental impurity, so that no additional Si need be alloyed with the material to produce a composition capable of hardening. If Wilm had been working with aluminum free from silicon he would not have made his accidental discovery, and the development of heat-treatable aluminum alloy might have been long delayed.

Merica (44l) ascribed the hardening of duralumin mainly to $CuAl_2$, but since the alloys free from magnesium do not harden on room temperature aging the National Physical Laboratory (2f) ascribed it to Mg_2Si. Later experience has shown that both are precipitation hardeners, and both these types of alloys are in commercial use, as well as duralumin itself, in which both hardening agents are concerned.

The more complex case, that of duralumin itself, involves the effect of Cu on the solubility of Mg_2Si and of Mg on the solubility of $CuAl_2$, as well as the changes in rate of precipitation and agglomeration of both compounds on aging, brought about by the presence of the additional elements.

The solubility relations for the duralumin type of alloy with both Cu and Mg have been studied by Miss Gayler (43w). To the information brought out in her work, Archer (44n) adds the observation that the presence of Mg, without Si, confers the property of age hardening at room temperatures upon the Al-$CuAl_2$ alloys made from very pure refined aluminum.

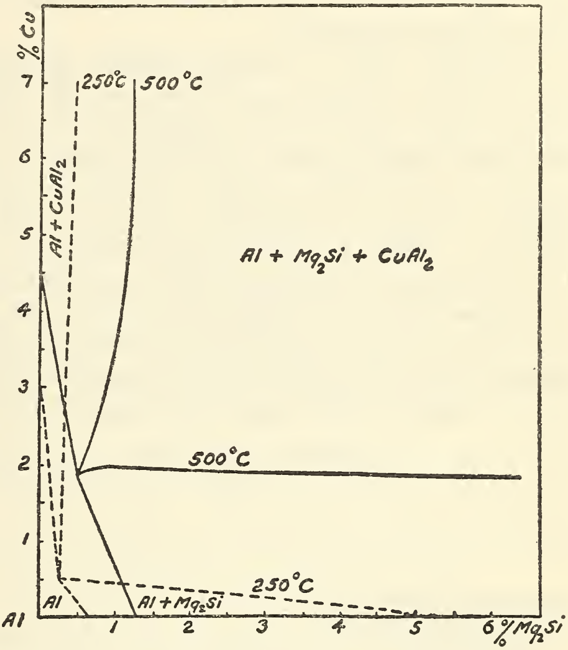

Fig. 102.—*Solubility of Mg_2Si and $CuAl_2$ in alloys annealed at 500° C. and quenched in water from 500° C. (solid lines) and 250° C. (dotted lines). (Gaylor, 43v)*

Miss Gayler's data on solubility of Mg_2Si and $CuAl_2$ at 500 and 250° C. for the ternary system Al-$CuAl_2$-Mg_2Si are shown in Figure 102.

(2) Effect of Alloying Elements and Added Elements.—(*a*) *Manganese.*—Most duralumin and Al-$CuAl_2$ alloys contain 0.5 to 1 per cent manganese. Dix and Keith (68a) have studied the equilibrium on the high Al end of the diagram between Al and the compound $MnAl_3$. Again, the form of diagram is similar to that of the Al-$CuAl_2$ system. At 650° C. about 0.65 per cent Mn is soluble; at 550° C., less than 0.23 per cent; and at 200° C., less than 0.14 per cent; so that hardening by quenching and precipitation is again possible, and $MnAl_3$ may enter into the hardening of duralumin. There is also an undercooling effect producing a dispersion of very finely divided particles upon chill casting which can be agglomerated on annealing.

Corson (681) states that one effect of Mn is in inhibiting grain growth on heating prior to quenching, as well as in decreasing the crystal size in the original casting.

The exact rôle of Mn in duralumin has not been fully explained. The addition of small amounts of Mn to alloys of Al with Cu, with Zn, or both has been generally found at least harmless and probably beneficial on mechanical properties of the cast alloys, and the Al-Mn alloy itself is a good wrought alloy. Archer and Jeffries (91i) state that Mn increases strength and imparts a somewhat fibrous structure. If the quenching temperatures of 550 to 565° C. reported by Portevin and Le Chatelier (91u) for an alloy with 6 per cent Cu and over 1 per cent Mn are correct it would appear that Mn may raise the temperature of the solidus and thus permit more latitude in quenching temperature.

(*b*) *Silicon "25S," "Lautal" (without magnesium).*—The addition to duralumin of an excess of Si above that required to form Mg_2Si with the Mg used also has an effect, which, again, has not been fully described though Archer and Jeffries ascribe at least a part of its action to combination with iron present as impurity to form an iron silicide or ternary Fe-Al-Silicide, which puts the iron in a less harmful form. Archer and Jeffries find that with an alloy of 4.3 per cent Cu, 0.8 per cent Si, 0.5 per cent Mg, and 0.5 per cent Mn, Fe content not stated (that is, decidedly higher in Si than duralumin made from ordinary commercial Al without intentional addition of Si) forged, water quenched from 500 to 515° C., gave the following results, which may be compared with usual values for ordinary wrought duralumin.

TABLE 74.—*Properties of "superduralumin"*

	Tensile strength	Elongation
	Lbs./in.²	*Per cent*
Ordinary duralumin fully aged	57,000	20
Special high Si duralumin:		
3 days at room temperature	59,000	25
70 hours at 120° C	67,000	20
20 hours at 150° C	75,000	13

The high Si duralumin has been termed "superduralumin" (43b). A high-silicon content is used in a modification of the copper-aluminum alloys, called "Lautal" (88f, h), which contains around 4 per cent Cu and 2 per cent Si and no Mg. This acts much like the plain Al-Cu alloy. (Kroll (91tt), however, gives 4½ per cent Cu, ½ per cent Si as the composition of Lautal.) The effect of heat treatment and the chemical properties of this alloy have been studied by Meissner (88h), who found that there was comparatively little improvement of this alloy on aging at room temperature. Aging for 16 and 24 hour periods at different temperatures showed that the maximum hardness is obtained at 150°, the maximum elastic limit at 165°, the maximum strength at 160°, maximum elongation at 100° for the 16-hour period, while for the 24-hour period the maximum elastic limit was obtained at 165°, maximum strength at 140°, maximum elongation at 125°. Meissner declares that every aging temperature has a definite aging period related to it in which the critical degree of dispersion of $CuAl_2$ is obtained in Mg-free aluminum alloys, and that overstepping the critical dispersivity permits a coagulation to larger particles accompanied by a decrease of strength and a renewed increase of capacity for change of shape, and finally of elongation. With further temperature increase, coagulation is sufficiently great to be seen under the microscope.

The chemical resistance of Lautal was expected to decrease with increase of aging temperature, and Meissner found that with 16-hour aging the corrosion in sea water increases gradually to 100° C., rapidly from 100 to 150° C., and again gradually from 150 to 200° C. With 24-hour aging the corrosion increases abruptly from 60 to 150° and from 175 to 200° C. Although overstepping the critical dispersion causes a sharp decrease in strength the corrosion curve shows only a slight increase. The critical dispersion is so sharply defined that overstepping it slightly has a very unfavorable influence on the properties. Aging Mg-free alloys at elevated temperatures has the disadvantage that when high tensile properties are obtained the resistance to sea-water corrosion is already diminished, though immediately after quenching the alloys show small corrosion.

Lautal can be cold-rolled, bent, forged, drawn, but not folded (88f). It can be welded, and Fuss and Bohner (88f) state that it can also be used as an aluminum solder. The specific gravity of normal Lautal is 2.74, electrical conductivity 40 per cent of that of pure copper and over 70 per cent of that of pure aluminum (88f).

Portevin and Le Chatelier (91u) have discussed the influence of quenching temperature and aging temperatures. They point out, in discussing Brinell hardness numbers, that specimens aged at different temperatures to the same Brinell hardness are not identical in other properties. They noted a peculiar slippage during the higher stress range of a tensile test of material not fully aged and think that it is due to the unstable condition of the material, since it disappears when aging is complete. On the other hand, it reappears if the material is given a softening anneal, which is not in accord with this idea. Moreover, Knerr (43dd) reports similar false yield points in both freshly quenched and aged duralumin.

The effect of increasing the quenching temperature of a 3.5 per cent copper alloy appears to be to cause no change in hardness for alloys quenched from 350, 424, and 550° C. and aged, but the hardness of the alloy quenched but not aged increases from 35 at 350° C. to 42.7 at 550° C. (61l). The effect on a 2 per cent copper alloy appears to be a decrease of hardness for both the quenched and quenched and aged alloy at 425° C. with increase at 550° C.

In their investigation of high-strength aluminum alloys, Archer and Jeffries (61b) state that there is no hardening of the aluminum copper type of alloy on room temperature aging after quenching, but that an increase of hardness is obtained on reheating at 100 to 175° C. Archer and Jeffries in discussing the solution heat treatment, or treatment required for solution and diffusion of soluble constituents, state that there is probably a critical rate of cooling from solution treatment that will just retain the solid-solution structure, and that this rate probably varies with the composition of the alloy, temperature of solution treatment, and time at heat. The solid solution resulting from the solution treatment is unstable at ordinary temperatures, there being a tendency for precipitation which is opposed by the rigidity of structure. From 100 to 200° C. there is a gradual increase of strength and hardness up to a maximum followed by gradual decrease. The maximum of hardness is attained after the maximum of tensile strength. In commercial aluminum-copper alloys, the copper may be in solid solution or atomic dispersion, as fine highly dispersed particles of $CuAl_2$ produced by precipitation from solid solution at temperatures below 200° C. or as relatively large particles of $CuAl_2$ that have never been in solid solution. The second form is most effective as a hardening agent. Hardness is expected to increase with copper, but less rapidly after the limit of maximum solubility is exceeded. (See also (61e).) The following figures are given by Archer and Jeffries for the properties of a commercial copper-aluminum alloy (25S), which contains about 4.2 per cent Cu, 0.9 per cent Si, and 0.7 per cent Mn.

TABLE 75.—*Properties of an Al-Cu-Si alloy "25S"*

	Tensile strength	Yield point[1]	Elongation	Brinell hardness
	Lbs./in.²	*Lbs./in.²*		
Extruded	30, 000–40, 000	15, 000–20, 000	10–18	50–65
Annealed 350° C., slowly cooled	25, 000–35, 000		15–20	45–55
Quenched 515 to 540° C	45, 000–53, 000	18, 000–25, 000	15–20	70–85
Heat-treated; tempered for 4 to 15 hours at 100 to 160° C	53, 000–63, 000	30, 000–40, 000	18–25	90–110

[1] Stress for 0.005 inch per inch extension under load.

(*c*) *Iron.*—Study of the high Al end of the Al-Fe system has not been reported in sufficient detail to establish thoroughly the equilibrium relations between Al and $FeAl_3$. Since Dix (64c) found the iron constituent visible in specimens quenched from 640 to 645° C. and in those annealed at and slow cooled from that temperature, when the aluminum contained only 0.06 per cent Fe, it does not appear that iron in itself enters into the hardening of duralumin on aging. Iron produces hard eutectic particles which might act as nuclei for precipitation and disturb the conditions that would hold in its absence. Iron in too large amounts does interfere with the precipitation-hardening process in the Al-$CuAl_2$ alloys. Archer and Jeffries cite the case of a 3.8 per cent Cu alloy containing 1.2 per cent Fe which fails to harden at all on aging 18 hours at 150° C. (which, with the usual content of iron, would age to about 55,000 lbs./in.^{2} tensile). A similar alloy with 1.2 per cent Si hardened to 42,500 lbs./in.^{2} tensile strength, thus showing that silicon was able to counteract part of the harm done by iron. On the other hand, a similar alloy, containing 0.50 per cent Mn, 0.24 per cent Si, and 0.63 per cent Mg, aged at room temperature, hardened to 53,000 lbs./in.^{2} tensile strength, its elongation being 16 per cent, somewhat under that for corresponding tensile strength of material lower in iron, so that relatively large amounts of iron do not appear as harmful in duralumin as in the Al–$CuAl_2$ alloy.

(*d*) *Calcium.*—Some duralumin-type alloys in the past have contained calcium up to, say, 0.10 per cent, and the properties of the alloy were reputed to be approximately those of the alloy without calcium. According to Grogan (57a, c) the compound $CaSi_2$ is formed in the presence of both Ca and Si, but has very low solubility in Al, and does not cause age hardening. It might, therefore, be expected to withdraw useful silicon that would otherwise form Mg_2Si. According to Frary (96m) the addition of 0.3 to 0.6 per cent Ca to an alloy of 4 per cent Cu, 0.6 to 1.0 per cent Mn, 0.3 to 1.0 per cent Mg, is used to remedy hot shortness and increase the ability to withstand cold work. Kroll (91tt) and Meissner (43j) have discussed the effect of calcium and other alkaline earth and alkali metals and do not agree as to the effect of Ca.

(*e*) *Chromium.*—Chromium up to about 0.10 per cent is used in commercial duralumin by one American producer on the basis of improvement in machining properties without having other detrimental effects. There seems to be no appreciable difference in properties of the alloy with and without it. According to Knerr (43dd) the presence of chromium improves the burnishing qualities.

(*f*) *Nickel "Y" alloy.*—A variant of duralumin is the "Y" alloy containing, besides the usual amount of copper, 2 per cent nickel and 1½ per cent magnesium (or about double the usual amount) which the National Physical Laboratory of England has advocated both for castings and for wrought material, but which, outside of a small use in pistons, seems to have little commercial use in England and almost no use in America. Rosenhain (39a) states that none of the heat-treatable alloys, including the lithium-bearing Skleron; the silicon-stiffened Lautal, or the nickel-bearing "Y" alloy attain figures for tensile strength or ductility markedly superior to duralumin. He states that "Y" alloy can not be described as a variety of duralumin because the presence of nickel prevents that of $CuAl_2$ (by taking it into the ternary Cu-Ni-Al compound), so that hardening by $CuAl_2$ plays no part. However, since there is such a similarity in the heat treatment of the various alloys hardened by Mg_2Si and by $CuAl_2$ it is more convenient for the purposes of this circular to group all such alloys under the class of duralumin.

Nickel has very little effect on the solubility of Mg_2Si in aluminum (2f), but it increases the solubility of $CuAl_2$ (89e). An alloy of 4 per cent Cu, 2 per cent Ni, without Mg does not age harden at room temperature to any marked degree.

Besides the precipitated Mg_2Si, there is present in "Y" alloy a little $NiAl_3$ (possibly some $CuAl_2$, but probably not), and a considerable amount of a ternary compound containing both $CuAl_2$ and $NiAl_3$. The equilibrium relations of the ternary compound, usually designated as "T," are quite complex and with some proportions of Ni and Cu, "T" may first take up some of the excess $NiAl_3$ and then decompose, giving up $NiAl_3$ again, as the temperature falls, but an alloy of the Cu and Ni content specified for "Y" but without Mg does not have phase changes in the solid state, at least down to 200° C. The mechanism of hardening of "Y" is doubtless much the same as in ordinary duralumin. Archbutt and Grogan (44b) have recently stated that essentially the same properties are developed in wrought "Y" alloy on aging for 30 minutes at 100° C. as are obtained on long aging at room temperatures. Results on castings were variable, but they recommend two hours at 100° C. for chill castings.

The high temperature properties of "Y" alloy are probably due to the presence of the ternary compound, and the nickel serves a useful purpose when strength is to be retained at high temperatures as in automotive pistons. For other uses as a competitor of duralumin at ordinary temperatures, the nickel-bearing duralumin seems to offer no marked advantages, and its ductility is somewhat below that of duralumin.

Another similar heat-treatable alloy, also used for pistons to some extent is called "Magnalite" and contains 2 per cent Cu, 1.5 per cent Ni, 1 per cent Mg, and 0.6 per cent Si.

(*g*) *Zinc, "Constructal."*—Zinc-duralumins are known in which Mg_2Si and $CuAl_2$ are presumably the chief means of hardening. Nevertheless, age hardening is possible in the Al-Zn alloys without Mg. While the more recent equilibrium diagrams (85 u, v, m, n, k, a) for this system vary widely in some details, all agree in that an alloy of 75 per cent Al at 400° C. is a solid solution, gamma, and that on cooling this breaks down first to gamma and beta and then to gamma and alpha. The solubility line between gamma and the other fields is a curved one of the general shape found in equilibrium diagrams of heat-treatable alloys. Instead of a compound, as is met in the

$Al-CuAl_2$ and $Al-Mg_2Si$ diagrams, a solid solution is here involved. After quenching from the homogeneous gamma field, the breakdown into gamma and beta, and, in turn, into gamma and alpha is extraordinarily rapid.

The first result is hardening, within a few seconds after quenching; due to fine particles of alpha in critical dispersion. Coalescence then takes place, and the alloy then softens with time. This phenomenon is considered quite analogous to the hardening and tempering of steel, but, contrary to the case of steel, the tempering occurs at room temperature.

The majority of the recent workers find that below 18 per cent zinc the gamma solid solution alone exists at any temperature below the liquidus, so that heat-treatment of straight Al-Zn alloys below 18 per cent zinc would be without results. Tanabe (85k) shows that within that range the properties are the same after annealing at 300° C. and after quenching from 500° C. and aging seven days. Tiedmann (85d), however, found some changes taking place on aging in alloys ordinarily supposed to lie in the homogeneous gamma field. Four per cent zinc showed no change while 11 per cent zinc did. Nishimura (85i) states that he has observed age hardening in alloys above 5 per cent zinc. The concensus of opinion, however, seems to be that in the age hardening of the complex aluminum alloys containing zinc up to about 20 per cent, the hardening is due chiefly to the other elements.

Eger (43oo) has discussed the thermal equilibrium of the Al-Zn-Mg alloys. Sanders and Meissner (91bb) have described some Al-Zn-Mg-Si alloys, one of which with 5 per cent zinc, 1½ per cent magnesium, ¾ per cent silicon, after quenching and aging approximates to the physical properties of duralumin. See Tables 72a and 72b. Hanson and Gayler (86b) have shown that the solubility of $CuAl_2$ in aluminum is decreased by the addition of zinc.

Although the generic name "Constructal," as is so often the case with these trade names, applies to any alloy made by a certain foreign firm, it is probable that this term applies primarily to alloys containing zinc in amounts below those which would allow of heat treatment on the basis of the usual equilibrium diagram, plus magnesium in the approximate amounts necessary to form $MgZn_2$. The high strength "Constructal" probably contains about 9 per cent of this compound. It is understood that an excess of either zinc or magnesium results in inferior workability and poor properties.

This alloy is susceptible of heat treatment, and is reputed to have mechanical properties similar to, or perhaps better than duralumin, a tensile strength of 75,000 lbs./in.^{2} being claimed. The resistance to corrosion of any aluminum alloy containing zinc would ordinarily be expected to be inferior, though if the zinc were all combined as

$MgZn_2$ this might not necessarily be true. Corson (2a) who discusses such alloys makes the definite statement that the alloys are too sensitive to corrosion to be of much use. In the absence of data giving exact composition, heat treatment and resulting mechanical properties, and of tests made on aluminum free from silicon, neither the claims for commercial usefulness of alloys of the "Constructal" type nor the mechanism of their hardening by heat treatment can be intelligently discussed. A recent patent to Guertler and Sander (96n) describes such alloys.

Rosenhain, Archbutt, and Hanson (85p) showed that in an alloy of 15 per cent Zn plus Mg_2Si, but without copper, aging took place at room temperature, but the maximum hardening occurred on aging at 150° C. The effect of zinc on the solubility of Mg_2Si at various temperatures has not been clearly established. The zinc duralumins are quenched from about 400° C., instead of about 510° C., as is the case with copper duralumins; corresponding to differences in the equilibrium diagrams.

Unless the added elements change the solubility relations of $CuAl_2$ or Mg_2Si so that heat treatment can not be carried out, modified duralumins could be produced by the addition of many different elements and with a wide range of compositions. For example, Kroll (91tt) showed that duralumin in which Cu was replaced by Ag has its usual aging properties.

Rosenhain, Archbutt, and Hanson (91gg) have described several heat-treatable Al-Cu-Zn-Mg-Mn-Si alloys. Much difficulty was met in working the alloys with zinc, but by proper combination of forging and rolling, or extrusion and rolling, they were prepared in wrought form. They are strong in the as-rolled condition, and the strength can be somewhat increased by heat treatment. The difficulties of working the high-zinc alloys, their high specific gravity and their poor resistance to corrosion have kept them from any large practical use. (See Table 72.)

(*h*) *Lithium, "Scleron."*—The lithium-aluminum alloys, according to Assman (66d) show a decrease in solubility of Li with decrease in temperature and he at first suggested that such alloys were to some extent capable of heat treatment. He later found (66e) that the response to heat treatment was ascribable to the solution and precipitation of a lithium silicide Li_3Si instead of to Li alone; that is, an alloy of the duralumin type can be produced in which Li is substituted for Mg. Thus, a 4 per cent Cu duralumin and a 12 per cent Zn duralumin each of which contained Li_3Si instead of Mg_2Si were found by Assman to show very similar characteristics as to quenching temperature, hardening on aging, and softening on annealing, as are found in the Cu and Zn duralumins containing Mg_2Si.

These lithium duralumins have had some commercial exploitation abroad under the name of "Scleron." Some of these alloys are described by Reuleaux (66b), who does not give the exact composition, but states that copper, zinc, nickel, manganese, and silicon, as well as lithium, play a part in these alloys.

The properties reported by Reuleaux (see Table 72) do not indicate that any notable improvement is brought about by the substitution of Li for Mg.

(*i*) *Beryllium.*—Kroll (53a) and Corson (2a) suggest that beryllium may form a silicide which would act like Mg_2Si or Li_3Si. On room temperature aging of alloys containing 4.5 per cent Cu, 0.6 to 0.7 per cent Be, 1 per cent Si for eight days after quenching, the Brinell hardness rose from an average of 60 to one of 84. The properties he gives for "Beryllium Lautal" (see Table 72) do not indicate any notable improvement over those of other alloys of the duralumin group. For other types of aluminum beryllium alloys see pages 316, 317.

(*j*) *Germanium.*—Kroll also thinks that germanium may also act to replace silicon, a magnesium germanide being formed which is dissolved and precipitated. The experimental work on this point is not very convincing because the aluminum used contained enough silicon so that the effect of a magnesium germanide without side effects from Mg_2Si was not established.

Since he states that the germanide is violently attacked by water, it is probable that such alloys would have little practical value even if sufficient germanium were available for their preparation in commercial quantities.

(*k*) *Magnesium* ("*51S*") (*without Cu*).—Just as it is possible, by omitting the magnesium from the duralumin composition to secure an alloy, such as "25S," hardened by $CuAl_2$ only, which approaches duralumin in mechanical properties after heat treatment but which needs higher temperature aging, so is it possible by omitting the copper to secure an alloy hardened by Mg_2Si only, which again has nearly as good mechanical properties as duralumin after heat treatment, and which again needs higher temperature aging. This latter type of alloy, known in this country as "51S," contains 0.45 to 0.80 per cent magnesium and 0.60 to 1.20 per cent silicon, without copper. Its properties are given in Table 72 and comment on its behavior in heat treatment has been made above under "theory," and will be dealt with further below.

(3) EFFECT OF TEMPERATURE.—Inasmuch as the effect of heat treatment of alloys of the duralumin type depends on the quenching temperature and the time at that temperature, the rate of quenching (size of specimen and nature and temperature of the quenching medium) and on the time and temperature at which the precipitation

hardening or aging takes place, all these factors have to be considered for each composition of alloy.

Practically all the heat treatable aluminum alloys are harder after quenching than in the fully annealed condition, but are still relatively soft. Duralumins containing both Mg_2Si and $CuAl_2$ show appreciable aging in one hour at room temperature, and aging is practically complete in two days. Since cold working of the aged material raises its tensile strength but decreases its ductility and increases its corrodibility, it is customary, in order to avoid embrittling the material, to perform any forming or straightening operations that may have to be done after quenching within one hour after quenching and as much sooner as is practical. Rivets, for example, are usually not driven after more than an hour has elapsed since quenching, but are reheated and requenched. Aging is accelerated at temperatures above room temperature.

Alloys such as "51S," which contain Mg_2Si alone as the hardening agent, age to a considerable extent at room temperature, but to secure full hardening elevated temperatures must be employed. On account of slower aging, the time available for forming operations is increased over that available with duralumin. The maximum strength attainable with this type of alloy is lower than with duralumin. This type becomes very soft and workable on annealing and is suitable for heavy-forming operations on annealed material before quenching.

Alloys such as "25S," free from Mg_2Si, but hardened by $CuAl_2$ only, do not age to an appreciable extent at room temperature. Aging must be carried out at elevated temperatures to accomplish hardening. Conversely, as much time as may be desired is available for forming the material before aging. This convenience makes the alloy suitable for heavy-forming operations after quenching, and for some purposes offsets the necessity of an added heating as compared with duralumin, which ages automatically without heating. Such alloys, however, withstand severe forming operations better after annealing than they do in the quenched state.

(*a*) *Accelerated aging.*—When accelerated aging is resorted to in duralumin itself, the temperature of boiling water is seldom exceeded. A temperature of 100° C. for one hour gives nearly complete aging, but longer time does no harm, since 10 days at that temperature does not soften the alloy. Duralumin sheet quenched from 950° F. (520° C.) aged at room temperature and at 100° C. for periods up to 10 days gives the following (A. S. S. T. Recommended Practice):

Table 76.—*Effect of accelerated aging on duralumin*

ROOM TEMPERATURE

Time	Yield point [1]	Tensile strength	Elongation
	Lbs./in.²	*Lbs./in.²*	*Per cent*
1 hour	21,000	45,000	19
1 day	32,500	54,500	19
2 days	33,000	56,000	19
6 days	34,500	56,500	19½
10 days	34,500	57,000	19½
100° C.			
1 hour	30,000	53,500	22
1 day	32,500	55,500	21
2 days	33,000	56,500	22
10 days	33,500	56,000	21½

[1] Stress for 0.005-inch per inch extension under load.

Aging one hour at 150° C. does not appreciably soften duralumin (43e), but at higher temperatures the strength drops rapidly at one hour of heating. Very brief heating at higher temperatures could be used but the difficulty of stopping before softening sets in makes higher temperatures inadvisable. Prolonged treatment at 120° C. brings about some softening.

With alloys like 51S, containing Mg_2Si but no $CuAl_2$, the aging temperature and time varies from 4 to 18 hours at 100 to 160° C. (91i). Optimum properties for most uses are obtained at 150° C. for 18 hours (A. S. S. T. Recommended Practice), a treatment that would soften duralumin itself, considerably.

With the 25S type of alloy, containing $CuAl_2$ as the only agent for precipitation hardening, 8 to 15 hours at 140° C. give optimum properties (A. S. S. T. Recommended Practice).

It should be remembered that at temperatures below room temperature (winter weather) the aging of duralumin will go on more slowly than at normal temperature. Summer temperatures may be sufficient to hasten materially the rate of hardening. Similarly, in the other alloys, as the temperature of the accelerated aging process is raised, the time required is decreased.

Typical curves of changes in properties of duralumin during normal aging, and at different temperatures, are shown, after Anderson in Figures 103 and 104.

Similar data for Al-Cu alloys free from Mg are shown in Figures 105 and 106 after Portevin and Le Chatelier (61f). The copper and manganese content of the alloy used by Portevin and Le Chatelier was higher than is normal for commercial alloys in this country, but the form of the curves is typical for alloys of its class.

(*b*) *Annealing.*—Annealing of all the three types, that with Mg_2Si alone, with $CuAl_2$ alone or with both, is accomplished at 300 to 350°

C., and is preferably followed by slow cooling, especially if the higher temperature has been used, since rapid cooling will retain whatever $CuAl_2$ or Mg_2Si has been brought into solution by heating above the solubility line. Material that has been fully aged is heated to 425° C. and very slowly cooled to below 260° C. for complete annealing. Annealing is generally done in air. Figure 107 after Grard (2e) shows the effect of various annealing temperatures upon cold-worked material.

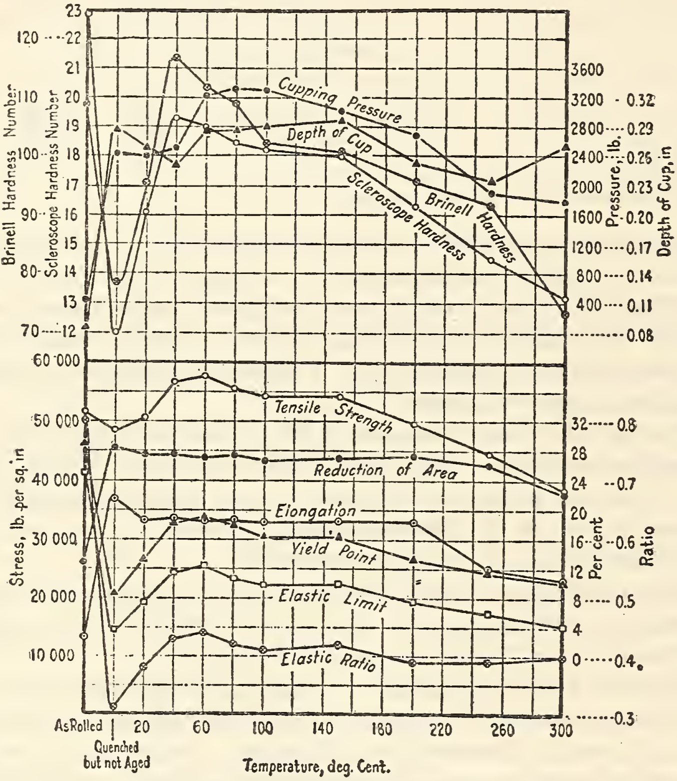

FIG. 103.—*Some mechanical properties of No. 18 gauge duralumin sheet as affected by water quenching from 512° C., followed by aging for 1 hour in the range 20 to 300° C. (Anderson, 43e)*

(4) PRECAUTIONS IN HEAT TREATMENT.—The three types differ less in the temperatures required for solution treatment before quenching than they do in the required temperatures for precipitation hardening. Duralumin should be heated to 505 to 515° C. (940 to 960° F.) while for the other two types the temperature range is 515 to 525° C. (960 to 980° F.).

(*a*) *Quenching temperature,* "burning."—Very careful pyrometric control of temperature is required as is very complete uniformity of temperature. If the temperature rises above the solidus line of the equilibrium diagram, partial fusion of the eutectic will take place and the metal will be "burnt" and ruined so that it can not be salvaged by reheat-treatment, but must be remelted.

If the "burning" temperature has not been reached, retreatment can be carried out as many times as may be desired. The required quenching temperature is lower in the case of duralumin-type alloys containing considerable amounts of zinc than is the case with the more commonly used alloys free from zinc.

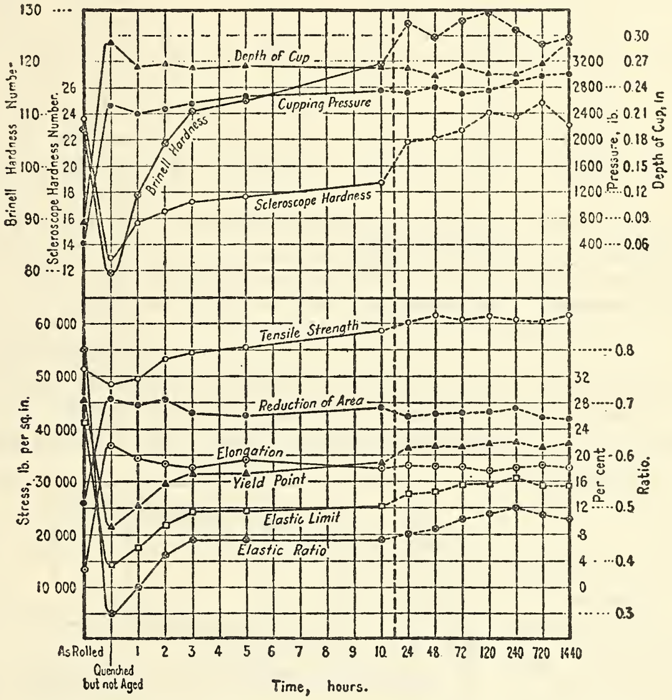

FIG. 104.—*Some mechanical properties of No. 18 gauge duralumin sheet as affected by water quenching from 512° C., followed by aging to 1 to 1,440 hours at the ordinary temperature.* (*Anderson, 43e*)

(*b*) *Quenching medium.*—The time at temperature had best be sufficient to take practically all the precipitate into solid solution. The greater the previous mechanical working, the more quickly full solution is attained. In general, one-fourth to one-half hour is sufficient for sections below one-half inch thick. Very thick pieces may require hours. Heating is done in a nitrate bath or in air. For safety precautions to be taken in the use of nitrate baths see A. S. S. T. Recommended Practice. A stirred nitrate bath is often used on account of its temperature uniformity.

The quenching medium may be air in the case of very thin sheets or very small pieces, but water is generally used. The physical properties are little altered whether the water is hot or cold. Where accelerated aging at 100° C. is to be done, the pieces are usually quenched in boiling water and left in it for aging. Boiling water dissolves adhering nitrate salts better than cold water. Cold-water quenching has been found to give to duralumin better resistance to the intercrystalline type of corrosion than hot water or oil quenching.

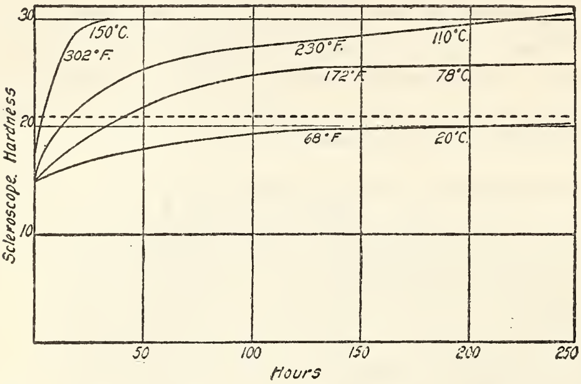

Fig. 105.—*Influence of aging temperature on the rate of hardening an aluminum copper-manganese alloy without magnesium (4.3 per cent copper and 0.8 per cent manganese). Specimens quenched in water at 565° C. (Portevin and LeChatelier, 61f)*

Oil quenching often stains the articles to some extent, and may be objectionable from the point of view of appearance. From the point of view of physical properties, hot water and oil act about the same as quenching media for these alloys.

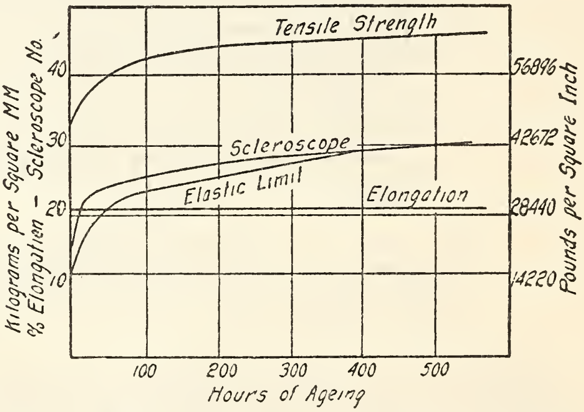

Fig. 106.—*Effect of aging a quenched aluminum copper-manganese alloy without magnesium, quenched in air from 575° C., aged at 110° C. (Portevin and Le Chatelier, 61f)*

The principles and practice of heat treatment of duralumin and other heat-treatable light wrought aluminum alloys are given by Cohn (43gg), Merica and coworkers (44m), Grard (2e), Portevin and LeChatelier (91u), Portevin and Chevenard (91aa), Hanson and, Gayler (43ee), Gayler (43aa, v) Guillet and coworkers (91ee, hh, e) Knerr (43dd), Anderson (43e, f, q) Meissner (44p), Assman (44f), Archer and Jeffries (91i), Jeffries (44h, 43ff), Archer (44n), Schweizer (91m), Heyn and Wetzel (43cc), and various others.

The effect of changes in composition or of the amounts of impurities have been discussed above to some extent. If the aluminum matrix is hardened by the addition of Cu, Mg, or Si above the amounts necessary to form as much $CuAl_2$ and Mg_2Si as will be taken into solution on heating before quenching, the excess of these elements, and such amounts of other hardening elements such as Zn, Mn, Fe, etc., as may be present will, in general add somewhat to the strength of the alloy, but such additions are likely to result in lowering the ductility, as well as (except in the case of Si) increasing the specific gravity.

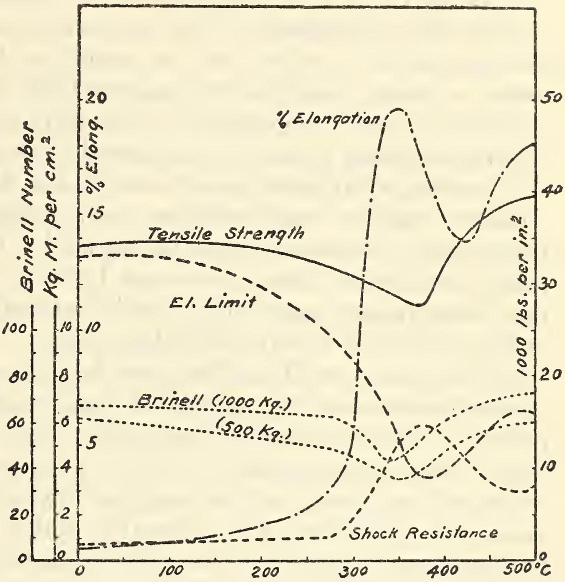

Fig. 107.—*Variation in mechanical properties of duralumin with annealing temperature.* (*Grard, 2e*)

Metal subject to 50 per cent cold work, annealed and cooled very slow

If the added element can combine with Si, with Mg, or with Cu so that the amount of $CuAl_2$ or Mg_2Si available for solution and precipitations is cut down, there will be a specific effect of such addition. Iron forms some complex combinations with Si and Al (see p. 240, in regard to "X" constituent). Nickel forms a ternary compound "T" with Cu and Al.

Further effects are shown in cases where the solubility of Mg_2Si or $CuAl_2$ is altered by the presence of other elements. As Table 72 shows, decrease in copper content below about 4 per cent tends to decrease the strength of the heat-treated alloys hardened in whole or in part by $CuAl_2$, with, in general, a slight increase in ductility. In general, commercial aluminum carries enough Si to form sufficient Mg_2Si for the development of full hardening of duralumin. Table 72 contains several duralumins with 0.20 to 0.25 per cent Si which are little if any weaker than those with higher Si. As the refined grade of aluminum comes into greater commercial use (over half a million pounds have been produced so far) scrap aluminum of that class will require admixture of silicon or of other scrap high in Si if it is to be used for making up duralumin.

Schweizer (91m) gives a number of curves showing the effect of progressive changes in magnesium, silicon, and copper content of duralumin.

(*c*) *Welding after heat treatment.*—It is often desirable to join built-up duralumin parts by welding. Since welding heats the metal far beyond the softening temperature for some distance away from the fused part of the joint, the effect of heat treatment will be destroyed in the regions so heated. Heat treatment after welding confines the region of inferior properties more nearly to the fused part.

The fused part is in the condition of a casting (and generally one of imperfect soundness). The cast structure does not respond to heat treatment anywhere near as readily as does thoroughly worked metal, so that a weld in the heat-treatable alloys can not be made to have as good properties as unwelded metal. For this reason riveting is largely resorted to in aircraft structures.

Of course, if sufficient metal is added in a weld, the strength of the structure may be made sufficient, even though the unit strength of the metal in the cross section of the weld is low. Welding of duralumin and similar alloys is covered by many articles mentioned in the bibliography, page 361. Special attention is directed to the articles by Knerr (41m) and Nelson (41q).

(5) STABILITY OF HEAT-TREATED ALLOYS.—The stability of heat-treated alloys over long periods of time is a question that naturally presents itself in the case of duralumin "51S" and other alloys which age at room temperatures. In alloys completely protected from corrosion of any type, so that only internal change, but not surface attack, is considered, any alteration which takes place at normal temperatures is believed to be well within the variation of properties found in testing sister specimens.

Some loss of ductility has been noted in specimens after long periods of time, but such a loss of ductility has been noted in specimens stored for several years at the Bureau of Standards, even though not exposed to the weather, and has been definitely connected by metallographic examination, with slight intercrystalline embrittlement. Thus, a decrease in ductility can not be ascribed to internal changes only unless there is no possibility of corrosion. No tests have been reported to show appreciable deterioration when corrosion was entirely prevented.

Whether any internal change would take place on long storage in tropical climates is not definitely known.

(c) HEAT-TREATABLE CASTING ALLOYS

Heat treatment, involving establishment of a solid solution by heating, preservation of the solid solution by quenching, and aging at room temperature or elevated temperature to bring about controlled precipitation of $CuAl_2$, Mg_2Si, etc., is obviously applicable to cast alloys of suitable compositions as well as to wrought alloys.

It is much more difficult to bring about complete solution of the network of $CuAl_2$ and Mg_2Si, which separate out on cooling, in a sand casting, than it is in a thoroughly worked wrought alloy in which these particles have been broken up and distributed more uniformly. The coarse structure of a casting is inherently weaker than that of a wrought alloy of the same composition. Therefore, it is not possible to secure the same properties by heat treatment of castings as of forgings or rolled stock.

The difference between castings and forgings is wider in the aluminum alloys than in steel, because the grain refinement brought about in steel by normalizing by passing through the transformation from austenite to ferrite and pearlite, can not be accomplished in the aluminum alloys to the degree obtained in steel, since there is no change in aluminum comparable to that of gamma to alpha iron.

An important step in making a cast alloy of any suitable composition which will respond effectively to heat treatment is to make it as fine-grained as is practical. This is accomplished by rapid solidification; that is, by using a low pouring temperature, and, if practical (as it seldom is, save in permanent mold castings for pistons, etc.), to cast in a chill mold instead of a sand mold. For example, Daniels, Lyon, and Johnson (43pp) cast an alloy of 4.35 per cent Cu, 0.22 per cent Mg, 0.52 per cent Si, 0.95 per cent Fe in different molds. Upon heat treatment, 495° C. (925° F.) 96 hours, quenched in cold water, aged 8 hours at 150° C. (300° F.), they gave the properties shown in Table 77.

TABLE 77.—*Tensile properties of cast duralumin specimens made in different types of molds*

	Tensile strength	Elongation in 2 inches
	lbs./in.^{2}	*Per cent*
Dry Albany molding sand	30,000	2½
Green Albany molding sand	34,800	4
Dry carborundum fire sand	33,000	3½
Green carborundum fire sand	33,500	4
Cast-iron mold, mold temperature 450° C. (850° F.)	35,500	4
Cast-iron mold, mold temperature 230° C. (450° F.)	38,000	6½

Strasser (96d) points out the improved properties obtained on heat treatment of chill-cast duralumin and similar alloys.

(1) CAST ALLUMINUM-COPPER ALLOYS.—In castings of alloys in which a eutectic (as of Al and $CuAl_2$) is formed, the eutectic, in most alloys, first appears at a composition lower in the alloying element (in copper, in the Al-Cu alloys) than the equilibrium diagram would indicate. To set up equilibrium conditions and take this eutectic into

solution requires very long annealing. As the content of alloying element increases, the tendency of the eutectic, which because of its lower melting point, forms around the grains of the matrix, to form a thick network about the grains, increases, and it becomes increasingly difficult to get the network into solution. Remnants of a network composed of a brittle material like $CuAl_2$ tend to produce low ductility in the casting.

The composition of a cast alloy for heat treatment should thus be low enough in alloying elements to avoid the retention of the network.

The familiar "No. 12" alloy of 8 per cent copper is not usually considered suitable for heat treatment because its composition is so high in copper that, even under equilibrium condition, excess $CuAl_2$ is still present and the network can not be destroyed. Corson (2a), however, claims that heating and quenching No. 12 improves impact and bend tests and reduces corrodibility.

Due to "over-shooting" of equilibrium during freezing and the establishment of a thick network in alloys of higher copper content, it results that 4 per cent copper is about as high as can be used with most satisfactory results in a casting to be heat treated. Wilm (96j) stated in 1907 that the tensile strength of the cast 4 per cent Cu alloy could be raised by heat treatment to about 32,000 lbs./in.^{2} tensile strength with an elongation of 7 per cent, thus obtaining at that early date results similar to those now commercially obtained with this alloy. Wilm's patent covered the temperature used to-day for the solution-heating before quenching, although his idea of the upper limit of the permissible range of temperature was in error.

Early experiments at the Bureau of Standards (35p) on heat treatment of aluminum alloys in which quenching was avoided and solution heat treatment was followed only by air cooling, and aging was at room temperature, brought about only slight improvement in properties, even of Cu, Mg, Si, Al alloys. Later work by Jeffries and Gibson (35o) in which oil or water quenching was used established the necessity of quenching, and the necessity for aging the Al-Cu alloys, without Mg, at elevated temperature was also brought out. The time of heating before quenching was too short in those tests, and the full value of heat treatment was not yet brought out. Alloys high in iron were favored as a result of this work because the full benefits of heat treatment were not obtained, and the strength given by iron to the alloys as cast was such that the sum of the residual strength from that source and that added by a heat treatment that would now be considered incomplete made them seem preferable.

Later work by Archer and Jeffries (35j, a) has shown that a much longer soaking time before quenching gives best results and that the iron should be kept low, preferably even below 0.25 per cent (which is difficult of attainment with commercial aluminum, though feasible with the extra-pure refined grade), while increase in silicon was an improvement. The usefulness of silicon is thought to be in combining with iron (as was noted in wrought alloys, see p. 240). Hence, in the heat-treated Al-Cu alloys silicon is often intentionally added even though it does not enter into the precipitation-hardening compound as it does when Mg is also present.

Archer and Jeffries (35a) point out that remarkable properties are obtained in alloys practically entirely free from iron and silicon. Using refined aluminum of 99.93 per cent purity, alloys with 4½ per cent copper gave the following results:

TABLE 78.—*Properties of a cast Al-Cu alloy made from aluminum of exceptional purity*

	Yield point (0.5 per cent extension under load)	Tensile strength	Elongation in 2 inches	Brinell
	Lbs./in.^{2}	*Lbs./in.*^{2}	*Per cent*	
As cast (tested 2 days after casting)	9,000	[1] 20,000	7.50	46
540° C. 1 hour, water 2 days, 20° C	22,500	32,000	5.50	76
540° C. 8 hours, water 2 days, 20° C	22.500	40.000	14.50	75
540° C. 40 hours, water 2 days, 20° C	24,000	42,000	19.00	83
540° C. 40 hours, water tested at once, no aging	17,500	36,000	20.50	62

[1] Unless otherwise noted, all tensile-test data given in this section are for unmachined, cast-to-size, sand-cast test bars.

One test bar, artificially aged, gave 54,000 lbs./in.^{2} tensile and 15 per cent elongation. These results are far superior to those obtained with metal of ordinary commercial purity and indicate a possible large-scale commercial use for electrolytically refined metal where maximum strength and toughness are required in castings.

These results clearly show that room temperature aging can take place in cast alloys hardened by precipitation of $CuAl_2$ even though it does not take place appreciably in the commercial wrought "25S" alloy. The purer the aluminum used in making up the aluminum copper alloys, the more marked is their room temperature aging. With a given composition and purity, castings show a greater tendency to age harden at room temperatures than does the wrought alloy. It has been suggested as a possible explanation that both the presence of impurities and mechanical working somewhat increase the rigidity of the alloy, thus opposing precipitation of $CuAl_2$, which is accompanied by an increase in volume.

(2) CAST ALUMINUM-COPPER-SILICON ALLOYS.—Daniels and Warner (88b) have described tests on a sand-cast alloy of this class of 4.3 to 4.9 per cent Cu, 0.8 per cent Si, 0.6 per cent Fe, 0.03 per cent Mn, heated to 510° C. (950° F.) 24 hours, quenched in

boiling water and aged at 100 to 150° C. (212 to 300° F.) for two hours. The specimens were cast to size or close to size. The following average values were obtained:

	As cast	Heat treated
Tensile strength (2 inches by ½ inch) lbs./in.^{2}	21, 500	31, 000
Tensile proportional limit (8 inches by ¾ inch) do	5, 000	9, 000
Elongation in 2 inches per cent	2. 2	5
Compression strength lbs./in.^{2}	35, 000	44, 000
Compression proportional limit do	6, 500	11, 500
Torsion, ultimate strength lbs./in.^{2}	19, 500	23, 000–29, 500
Torsion, proportional limit do	3, 600	3, 000– 7, 000
Torsion, modulus of rigidity	4, 700	4, 700
Charpy impact, round notch ft.-lbs	1. 4	3
Brinell 500-kg. 10-mm ball	58	77
Rockwell ⅛-inch ball	71	85

Heat treatment improved all the properties of the sand-cast alloys except the modulus. The machined specimens were inferior in strength and generally in ductility to the unmachined, whether cast or heat treated. The tensile properties of bars of small cross section were superior to those of large cross section. The impact resistance was at least doubled by heat treatment, the impact value being greater for the alloy having lower Cu content. The Brinell hardness was raised by heat treatment.

Other data for this type of alloy (No. 195 of the Aluminum Co. of America) give 37,000 lbs./in.^{2} tensile, 12 per cent elongation (96p) 28,000 to 38,000 and 6 to 12 per cent (88d) with 31,000 and 8 per cent as the averages, 29,500 and 5½ per cent (88c), 28,000 to 35,000 and 5½ to 11 per cent (44j), 29,000 and 4½ per cent minimum (88e).

Archer and Jeffries (88a) state that to obtain highest ductility the alloy should not be aged at elevated temperatures. They give the following average values:

TABLE 79.—*Properties of cast, heat-treated Al-Cu alloy No. 195*

	Tensile strength	Elongation in 2 inches	Brinell hardness 1,000 kg, 10 mm
	Lbs./in.^{2}	*Per cent*	
Quenched and aged at room temperature	31, 000	8	65
Quenched and aged in boiling water	33, 500	4½	75
Quenched and aged at higher temperature	41, 000	1½	100

The "yield point" (extension under load of 0.5 per cent) shortly after quenching is 14,000 to 18,000 lbs./in.^{2}, but on aging at room temperature it increases to 20,000 to 25,000, the elongation also decreasing slightly. Aging at higher temperatures gives still higher "yield points."

Dix and Lyon (88j) compared specimens cut from a Liberty motor (8 cylinder) crank case made from No. 195 analyzing 4.57

per cent Cu, 0.55 per cent Fe, 0.45 per cent Si, 0.11 per cent Mn, 0.10 per cent Mg, heat treatment not given, with attached, cast-to-size test bars, all being cast in sand. The specimens cut from the crank case itself averaged 24,500 lbs./in.^{2} tensile strength and 8,000 proportional limit, with 2½ per cent elongation, while the attached test bars gave 32,000 lbs./in.^{2} tensile and 5¼ per cent elongation. Similar castings of "modified" 13 per cent Si alloy, 8 per cent Cu alloy and an alloy of 3½ per cent Cu, 4 per cent Si, 1¼ per cent Fe, were cut up and gave, respectively, 20,000, 3,500, 3¾ per cent; 15,000, 8,000, less than one-half per cent; 18,000, 5,500, 1½ per cent for tensile strength, proportional limit and elongation. Thus, the heat-treated alloy was superior for the purpose in hand, especially as to proportional limit. Dix and Lyon point out that complicated castings that would be liable to warp, and work in heat-treatment may require changes of design so as to make heat treatment practical.

Daniels (88e) points out that the solution heat treatment of the Al-Cu-Si alloys may have to be extended up to 96 hours at 510° C. (950° F.). Archer and Jeffries (88a) state that 48 hours at slightly below 500° C. is not as satisfactory as 5 hours at 520°. In chill castings, with finer grain to start with, 2 hours at 520° are equivalent to 22 hours at 500° C.

(3) Cast Aluminum-Magnesium-Silicon Alloys.—Just as in the wrought alloys precipitation hardening can be produced by either CuAl$_2$ or Mg$_2$Si, either hardening compound can be used in cast alloys, though in commercial practice the alloy hardened by the Mg$_2$Si compound is as yet little used.

Daniels (43qq) has reported on tests of alloys hardened by Mg$_2$Si. Some of his results are given in Table 80.

Table 80.—*Physical properties of aluminum-magnesium-silicon alloys. According to Daniels (43qq)*

Composition		As sand cast			Heat treated					
					96 hours at 552° C. (1,025° F). cold water 8 hours at 150° C. (300° F.)			Annealed 96 hours at 552° C. (1,025° F.) furnace cooled		
Mg	Si [1]	Tensile strength	Elongation in 2 inches	Brinell No.	Tensile strength	Elongation in 2 inches	Brinell No.	Tensile strength	Elongation in 2 inches	Brinell No.
		Lbs./in.^{2}	*Per cent*		*Lbs./in.^{2}*	*Per cent*		*Lbs./in.^{2}*	*Per cent*	
0.46	0.34	17,000	15	30	18,000	14	31	11,700	26½	20
.90	.47	18,000	5	40	30,000	9	60	11,300	20	20
.98	.66	16,500	5½	36	30,000	8	61	11,900	17½	22
1.16	1.02	18,000	3	48	34,000	6	65	11,600	14	22
1.70	1.00	18,500	2	48	25,000	6½	56	---------	---------	-------

[1] Fe content 0.55 to 0.60 per cent.

The optimum properties for this heat treatment were obtained on alloys of 0.9 to 1.2 per cent Mg, 0.5 to 1.0 per cent Si. With smaller or larger amounts of Mg, the response to heat treatment was diminished. The best composition tried, with about 1.2 per cent Mg and 1 per cent Si has an excess of Si over that required to form Mg_2Si. Other alloys, with 4 per cent Mg, 2 per cent Si, 5 per cent Mg, 3 per cent Si and 9 per cent Mg, 5 per cent Si were tested, but gave poorer results.

The work was not carried far enough to establish the best time and temperature for the solution treatment before quenching, and the temperature used seems high; the effect of variation in iron content was not studied, nor were variations in the time and temperature of accelerated aging.

However, the work established that properties of the same general order as those for the heat-treated 4 per cent Cu alloy may be obtained with the Mg-Si alloy.

(4) Cast Duralumin (Al-Cu-Mg-Si Alloys).—Obviously, the combination of $CuAl_2$ and Mg_2Si will produce hardening on heat treatment in cast duralumin, just as in the wrought alloy.

The 4 per cent Cu alloy (No.195) may be altered by increasing the copper a trifle and adding up to 0.20 per cent Mg and is then designated by the Aluminum Co. of America as No. 196 (88a). The crank case examined by Dix and Lyon (88j) and designated by them as No. 195 showed 0.10 per cent Mg and hence, is more properly to be classed as duralumin. Archer and Jeffries (88a) state that the amount of Mg (½ to 1 per cent) used in wrought duralumin of that copper content is too high for best results in castings. With 4.0 per cent Cu, 0.20 per cent Mg, 0.25 per cent Fe heat-treated sand castings have been obtained with up to 50,000 lbs./in.^{2} tensile strength and 8½ per cent elongation. Hanson and Gayler (91k) state that in duralumin the iron content may be ignored as it does not affect the solubility of Mg_2Si. In view of American data on the effect of iron in the heat-treatable casting alloys, it does not seem safe to ignore the possible effect of iron in cast duralumin, although its effect in cast alloys containing Mg_2Si has not yet been completely determined. The effects of manganese, and of excess silicon are also incompletely known.

Jeffries and Gibson (35o) studied a series of alloys with considerable variation in composition. Those of 3 to 3½ per cent Cu, 1¼ to 1½ Fe, ½ to 1½ per cent Mg, heat treated at 500° C. for one hour, quenched in oil, and reheated to 150° C. for one hour gave 33,000 to 38,000 lbs./in.^{2} tensile strength, and 1½ to 3 per cent elongation. From later developments of this work there was evolved an alloy of 2½ to 3 per cent Cu, 1¼ to 1½ per cent Fe, ¼ to ¾ per cent Mg, which according to Daniels (88e) and to Johnson (88c) has been found in use at McCook Field by the Army Air Corps, to average 28,000 to 31,000 lbs./in.^{2} tensile, 3 per cent elongation, 67 to 70 Brinell, after heating to 525° C. (975° F.) two hours, quenching into boiling water and aging two hours at 150° C. (300° F.).

Daniels, Lyon, and Johnson (43pp) have studied variations in the copper content of this alloy and find that its increase to 4 per cent reduces the elongation proportionally more than it increases the tensile strength.

Alloys of 0.40 per cent Mg, 0.25 per cent Si, 1.15 per cent Fe with 2, 3, and 4 per cent Cu were heated at 495° C. (925° F.) five hours, quenched in boiling water and held in it two hours. Specimens tested 15 and 554 days after heat treatment gave the following:

Table 81.—*Properties of cast, heat-treated duralumin*

Cu (per cent)	15 days		554 days	
	Tensile strength	Elongation	Tensile strength	Elongation
	Lbs./in.^{2}	*Per cent*	*Lbs./in.^{2}*	*Per cent*
2	27,800	5.7	30,200	4.0
3	27,400	2.8	28,800	2.1
4	29,600	2.5	32,000	1.7

Daniels, Lyon, and Johnson conclude that two hours in boiling water does not complete the aging process, but that heating for eight hours at 150° C. (300° F.) produces full hardening and a stable condition.

(5) Piston Alloys.—An alloy of the Al-Cu-Mg-Si-Fe group, higher in copper and in duralumin, and used for pistons, is described by Daniels (43p, 88e, 89a). This contains 9½ to 10 per cent Cu, ¼ per cent Mg, ¼ to ½ per cent Si, 1¼ per cent Fe. Sand-cast test bars gave:

Table 82.—*Properties of heat-treated piston alloy*

	Tensile strength	Elongation in 2 inches
	Lbs./in.^{2}	*Per cent*
As cast, within 1 week after casting	25,500	1.0
As cast, 6 months after casting	27,300	.5
Heated to 495° C. (925° F.) 5 hours, quenched and aged 16 hours, in boiling water	36,000	.7

Daniels (88e) states that four hours at 510° C. (950° F.) followed by a boiling water quench and reheating to 200° C. (400° F.) for two hours, gives 37,000 tensile, 0.5 per cent elongation, 120 Brinell; that is, equivalent results to the longer treatment. Temperatures above 510° C. gave poor or erratic results.

(6) "Y" Alloy.—Y alloy or "L-24" (4 Cu, 2 Ni, 1½ Mg, 0.7 Si), an alloy developed by the National Physical Laboratory, has in

the sand cast and heat treated condition the following properties; according to Jeffries (35–c).

Maximum stress	lbs./in.^{2}	35, 000
Elongation in 2 inches	per cent	1. 5
Brinell hardness	about	90

Better properties can be developed on chill cast, or on wrought material, see page 197.

Jeffries classes this as a versatile alloy, giving good results in sand castings, chill castings, and in wrought form, but states that for no single use does it excel other cheaper alloys.

Hurren (38b) states that in commercial practice he was never able to obtain anything like the high figures published by the Light Alloys Research Committee.

Strauss (39g) says that of the strong aluminum alloys it is the most difficult to cast and to work satisfactorily, and that it is not particularly resistant to corroding media.

The heat treatment of this sand-cast "Y" or British "L–24" alloy in the range 3¾ to 4½ Cu, 1¾ to 2¼ Ni, 1¼ to 1½ Mg, ½ Si (maximum), ¾ Fe (maximum) used for piston alloys and recommended by Mortimer (36a) for general high-duty service in the heat-treated condition has been described by Lyon and Daniels (89a, d). The "Y" ages after casting, without quenching to a similar extent that the alloy just described above does. Daniels (89a) finds the 510° C. (950° F.) four hours boiling water quench, 200° C. (400° F.) one-hour treatment gives 36,000 tensile, 0.5 per cent elongation, 95 Brinell on sand-cast test bars. With extended heating at 510° C. values as high as 50,000 tensile, 0.5 per cent elongation, 110 Brinell are sometimes obtained. Cylinder heads with pins that might warp in quenching are air cooled instead of quenched, the other conditions of heat treatment being as above given. This lowers the strength to 33,000 lbs./in.^{2} but does not lower the hardness.

Daniels (89a) finds that the "Y" alloy runs about 2,000 lbs./in.^{2} lower in tensile strength than the Al-Cu-Mg-Si-Fe alloy, but is less erratic in hardness. The "Y" alloy seems to respond somewhat more reliably to heat treatment. The "Y" alloy anneals less readily, as shown by tests of the strength at room temperature after reheating to various temperatures. The fact that the "Y" alloy is strong when tested at elevated temperatures has been discussed under pistons (p. 77). Jeffries (35c) considers the properties of "Y" for use as pistons at high temperatures to be no better than those of a 12 per cent Cu, three-fourths to 1 per cent Mn alloy, which is, of course, cheaper than "Y."

Rosenhain, Archbutt, and Wells (91cc) have discussed the various precautions necessary in making chill castings of "Y" alloy. The usual results for chill castings properly made and handled heated five hours at 520 to 530° C. quenched in boiling water and aged eight days were 40,000 to 46,500 lbs./in.^{2} tensile, 4 to 7 per cent elongation. In salt bath heating 525° C. was the maximum temperature that could be used without blistering the bars, while with air heating, 530° C. was safe.

Without proper precautions, the strength may be as low as 30,000 pounds after heat treatment, even in a chill casting.

The British Engineering Standards Association draws its specifications on the basis of tests of chill-cast test bars (36a) so that most British data for "L–24" or "Y" are on a different basis from American data. According to Mortimer, the properties of heat-treated chill cast specimens of "Y" give 38,000 to 49,000 lbs./in.^{2} tensile strength with 3 to 6 per cent elongation; such figures may be compared with the figures previously given for heat-treated sand castings. Another name for "Y" alloy is Magnalite (89d). Swan (91x) gives the composition of magnalite as similar to "Y" alloy save that the copper is only 2 per cent and the nickel only 1½ per cent.

(7) ALLOYS CONTAINING ZINC.—An alloy containing copper and zinc, with high iron, designated as No. 145 by the Aluminum Co. of America, and containing about 11 per cent Zn, 2½ per cent Cu, 1½ per cent Fe, shows a slight age hardening on standing at room temperatures without quenching. Sand castings show 25,500 to 34,000 lbs./in.^{2} tensile strength and 3 to 6 per cent elongation. Rosenhain, Archbutt, and Hanson (91gg) find that alloys of 15 per cent Zn, 3 per cent Cu increased in strength in nine months as much as from 29,500 lbs./in.^{2} to 39,000 lbs./in.^{2}, although the behavior was erratic.

Alloys of this class to which Mg is added, naturally have age-hardening properties. A chill-cast alloy of 8.2 per cent Zn, 0.80 per cent Cu, 0.44 per cent Mg, 0.38 per cent Si, 0.65 per cent Fe, submitted to the Bureau of Standards for test, was stated to be age hardened, but no information was given as to the heat treatment used nor the period of aging. It showed 40,000 lbs./in.^{2} tensile strength with 4½ per cent elongation, Brinell 80. The specific gravity was 2.875.

On account of the higher specific gravity of the alloys containing zinc and their liability to crack, commercial attention has been centered on other alloys for castings to be heat treated.

The uniformity found in wrought heat-treated alloys can not be expected in castings, the heat treatment takes a longer time, and many complicated castings can not be heat treated without danger of warping and cracking.

For service where a better combination of strength and ductility is needed in a casting than can be obtained with alloys not amenable to heat treatment, heat-treated castings of suitable alloys offer advantages which often outweigh the extra cost of production.

4. DYNAMIC PROPERTIES OF LIGHT ALLOYS

The light aluminum alloys having the most useful dynamic properties; that is, resistance to impact in single or repeated blow notched bar tests, and resistance to repeated stress, are, in general, heat-treated alloys.

Since data on results of dynamic tests are less complete than those on other mechanical tests, it is more convenient to discuss together such tests for all the alloys, and for wrought and cast materials, rather than under the individual alloys. For the same reason magnesium alloys, which, in general, show up well in such tests, are considered here rather than in the section dealing with magnesium.

(a) SINGLE-BLOW NOTCHED BAR IMPACT TESTS

Because of the diversity of shape of specimens and notches, single-blow-impact tests are not capable of accurate general intercomparison, and it is necessary to confine comparisons of various alloys to series of tests made under the same test conditions.

The tests most used are the Charpy, in which the specimen is supported at both ends, and is struck back of a notch at the middle of the specimen, and the Izod, in which the specimen is gripped at one end and struck on the notched side upon the free end above the notch. In either test the notch may be cut at various depths and angles or may be made by drilling so that the base of the notch is circular. See Dix (45f).

Petrenko (45d) has made impact tests upon heat-treated duralumin. The notches used were standard (60°, ¼ mm radius at base); sharp (60° sharp angle at base); round (2 mm diameter at edge similar to that used by Strauss); deep (same, but base at center of specimen, similar to that used by Dix). The test results follow:

Table 83.—*Izod tests on duralumin*

Material	Composition					Yield point[1]	Tensile strength	Elongation	Reduction of area	Brinell 500 kg
	Cu	Mg	Mn	Si	Fe					
							Lbs./in.²			
A	4.0	0.60	0.58	0.54	0.58	42,000	61,000	16	17½	113
B	3.7	.46	.48	.28	1.00	36,500	58,500	15	28	106
C	3.7	.36	.49	.32	.90	35,000	57,000	24	32½	100

Material	Izod foot-pounds notch							
	Standard		Sharp		Round		Deep	
	x	y	x	y	x	y	x	y
A	10.60	7.64	----	----	----	----	----	----
B	13.30	9.52	13.08	8.6	16.33	13.02	8.05	7.38
C	16.38	12.93	15.30	10.97	20.45	17.47	10.30	9.45

[1] Stress for extension of 0.003 inch per inch, under load.

x=notch in the plane of rolling.
y=notch at right angles to the plane of rolling.

Knerr (43dd) quotes impact tests from Unger and Schmidt showing that the impact resistance of heat-treated duralumin remains the same from 20° C. down to −190° C. (liquid-air temperature).

Greaves and Jones (45c) have studied the impact strength of heat-treated duralumin at various temperatures and find that there is a minimum at 250°, the impact strength then being about half that which it is at room temperature, but that the impact strength rises with further increase in temperature till at 400° it is double its room-temperature value, then falling rapidly with further rise of temperature.

The maximum coincides with the usual hot-rolling temperature for the alloy.

They also studied aluminum of 99.78 per cent purity and found variable impact results at −80° C. At −50° C. the impact figure (Charpy V notch 2 mm deep ¼ mm radius at base) was 5 kgm falling to 3 kgm at 200° C., remaining constant up to about 400° C. and then falling to 1.5 kgm at 600° C.

Lea (45g) has given impact tests with the British Standard Izod specimens.

TABLE 84.—*Izod tests on sand and chill-cast alloys*

Composition						How cast	Tensile strength	Izod notched bar
Cu	Zn	Ni	Fe	Mn	Sn			
							Lbs./in.^{2}	*Ft.-lbs.*
2. 50	1. 0	------	------	------	------	Sand (from crank case)	------	3. 2 –4. 25
12	------	------	------	------	------	Chill	21, 500–27, 000	0. 55–1. 1
12	------	------	------	------	------	Sand	19, 500	. 55– . 75
11. 3	------	------	------	------	------	Chill	19, 500	. 45– . 70
11. 3	------	------	------	1. 4	------	do	18, 000	. 40– . 50
10	------	------	------	1	2	do	16, 500	1. 25
9	------	------	------	------	2	do	15, 500	1. 5
8	------	------	------	1	------	do	17, 000–25, 000	1. 2 –1. 5
9	1. 50	------	------	------	2	do	24, 500	1. 55–2. 1
9	1. 50	------	------	------	2	Sand	16, 000	1. 1 –2. 0
12	------	1	------	------	5. 50	do	15, 500	. 6 – . 8
12	------	1	------	------	5. 50	Chill	------	. 88– . 95
7	1	------	------	------	1	do	------	1. 9 –2. 4
7	1	------	------	------	1	Sand	------	1. 85–2. 13
------	------	------	5	------	------	Chill	16, 500	1. 8
2. 50	12. 50	------	------	------	------	do	28, 000	2. 4 –4. 65
2. 50	12. 50	------	------	------	------	Sand	23, 500	2. 85–3. 3

Batson (45e) gives Charpy impact tests (notch 1 mm deep, root radius ⅔ mm angle 90°) at room temperature (about 20° C.) and at approximately 250° C. on sand cast and chill cast alloys and on some wrought alloys.

TABLE 85.—*Charpy tests on sand and chill cast alloys at 20 and 250° C.*

Composition				How cast	Tensile strength at 20° C.	Charpy, kgm	
Cu	Zn	Sn	Mn			20°	250°
					*Lbs./in.*²		
7	1	1		Sand		0.032–0.082	0.011–0.015
7	1	1		Chill		.072	.014
10		1		Sand		.024	.008
12		2	1	Chill		.011	.011
9	1.50	2		do		.021– .051	
2.50	12.50			Sand		.043	
2.50	12.50			Chill		.134	
7	1	1		Sand		.032	.013
7	1	1		Chill		.072	.014
12				Sand	19,500–21,000	.011– .013	.013– .016
12				Chill	23,500–26,500	.019– .022	.029– .033
2.50	12.50			do	28,500	.130	.100
14			1	Sand		.007	.009
14			1	Chill		.008	.011
14		1	1	do	17,500	.011	.007
14	1	1	1	do	18,000	.010	.006
8			1	do	18,000–24,000	.034	.036
8			1	From chilled piston casting		.010– .013	.013– .016
9	1.50	2		Sand	19,500	.021	
9	1.50	2		Chill	24,500	.051	.009
10.50		1.25		Sand	17,500	.018	
10.50		1.25		Chill	26,500	.020	
12		2	1	do	20,000	.011	.006– .011
9	1.50	2		From chilled piston casting		.016– .022	.007– .008
2.50	12.50			Sand	20,000–26,500	.11 – .15	.09 – .15
2.50	12.50			Chill	19,000–26,500	.19 – .20	.19 – .28
12.50				Sand	17,500	.012– .015	.012– .016
12.50				Chill	19,000	.032– .040	.024– .026
6				Sand	16,500	.056	.056
6				Chill	19,500	.140	.097
8				Sand	15,500	.030	.032
8				Chill	19,500	.010	.061
14			1	Sand	17,000	.008	.008
14			1	Chill	22,000	.017	.016

Composition						How cast	Tensile strength	Charpy, kgm		
Cu	Zn	Mn	Ni	Mg	Si			20°	250°	
							*Lbs./in.*²			
4			1.75	1.50		Sand	24,500	0.009	0.010	
4			1.75	1.50		Chill	29,500	.013	.015	
8			2	1.50		Sand	24,500	.017	.017	
8			2	1.50		Chill	26,500	.046	.035	
									150°	240°
3		1		.50	1	Rolled		.076	0.067	
5		.50		.75	.75	do		.043	.037	0.020
6		.50		.50	1	do		.032	.030	.016
3	20					do		.53	.66	
2.50	20	.50		.50	1	do		.31	.44	
4			2	1.50	.25	do		.26	.24	.15
4		.50	2	1.50	.25	do		.24	.19	.13
4		.50	2	.50	.75	do		.26	.27	.21
2			1.50	1	.50	do		.39	.35	.17

Dix (45f) has used a Charpy bar with a 2 mm drilled hole as the base of the notch, the base being at the center of the specimen; that is, 5 mm deep. Results are also given for unnotched bars, as are slow-bending tests. Dix gives the following for sand-cast alloys containing up to 12 per cent copper:

TABLE 86.—*Charpy tests on sand-cast alloys of various copper contents*

Composition			Tensile strength	Elongation	Brinell 500 kg	Charpy test
Cu	Fe	Si				
			Lbs./in.²	*Per cent*		*Ft.-lbs.*
0.09	0.28	0.34	13,500	20	24	8.9
.07	.39	.35	12,250	18	23	10.5
2.16	.39	.30	19,000	11	40	5.4
3.99	.45	.34	21,000	5.50	55	1.8
8.09	.46	.25	23,000	2.75	72	1.0
12.04	.45	.27	22,500	.75	85	.8

R. R. Moore (46k) has given Charpy (round notch) and Izod figures on some wrought aluminum and magnesium alloys on which endurance properties have been cited (p. 279).

TABLE 87.—*Impact tests on aluminum and magnesium alloys*

Material	How worked	Tensile strength	Charpy	Izod
		Lbs./in.²	*Ft.-lbs.*	*Ft.-lbs.*
Aluminum	Rolled	22,500	18.7	24
Magnesium	Extruded	32,500	2.9	4
Magnesium alloy 8.7 per cent Cu	Forged	41,000	1.8	4
Do	Longitudinal transverse	30,000	1.35	2.3
Do	As cast	28,000	1.5	2.5
Magnesium alloy 4 per cent Al	Extruded	35,000	3.6	----------
Magnesium alloy 4 per cent Al, ¼ per cent Mn.	do	39,000	3.3	----------
Magnesium alloy 6½ per cent Al	do	41,500	3.0	----------
Mg alloy 6½ per cent Al, ¼ per cent Mn.	do	44,500	2.9	----------
Mg alloy 10 per cent Cu	do	39,000	1.7	----------
Duralumin	Rolled and heat treated	51,000	13.9	----------
Do	Rolled and twice heat treated	51,000	19.4	----------
Do	Rolled and annealed	25,000	17.3	----------
Electron (Mg with 4.4 Zn, 0.4 Cu)	Rolled	36,500	2.9	----------

Gwyer and Phillips (45a) give the following for modified silicon alloys:

Table 88.—*Izod tests on modified silicon alloys, effect of variation in Si and Fe*

AVERAGES COMPARED WITH STANDARD ALLOYS

Composition				How cast	Tensile strength	Elongation	Izod
Si	Cu	Zn	Fe				
					Lbs./in.^{2}	*Per cent*	*Ft.-lbs.*
	8	--------	--------	Chill	20,000–25,500	3–4	1.2–1.6
	2.50	12.50	--------	do	24,500–33,500	3–9	2.5–3.0
11	--------	--------	--------	do	29,000–31,500	10–15	6–8

EFFECT OF VARIATION IN SILICON

8.18	--------	--------	--------	Chill	28,000	14.50	8.4
8.92	--------	--------	--------	do	29,500	18	10.0
9.89	--------	--------	--------	do	29,500	15.50	7.4
11.08	--------	--------	--------	do	30,500	12.50	7.6
12.15	--------	--------	--------	do	31,000	15.50	6.5
13.12	--------	--------	--------	do	29,000	9	4.5
13.69	--------	--------	--------	do	23,500	3	2.9
14.98	--------	--------	--------	do	23,500	2	2.3
8.18	--------	--------	--------	Sand	22,500	11	7.8
8.92	--------	--------	--------	do	23,500	10	7.2
9.89	--------	--------	--------	do	26,500	14.50	7.0
11.08	--------	--------	--------	do	25,500	14	6.1
12.15	--------	--------	--------	do	26,000	13	4.8
13.12	--------	--------	--------	do	23,500	3.50	3.6
13.69	--------	--------	--------	do	24,500	3.50	3.7
14.98	--------	--------	--------	do	21,500	3	3.1

EFFECT OF IRON

Composition		Tensile strength (sand cast)	Elongation (sand cast)	Izod	
Si	Fe			Sand cast	Chill cast
		Lbs./in.^{2}	*Per cent*	*Ft.-lbs.*	*Ft.-lbs.*
10.68	0.34	31,000	11	5.6	8.4
10.82	.55	24,000	8.50	3.7	6.0
11.16	.71	24,000	4.50	3.4	5.9
11.06	.91	19,000	3	1.9	1.8
11.12	1.09	17,000	3	1.3	1.1
10.73	1.42	10,500	1.50	1.1	.8

Strauss (45b) has used the Izod test with a 2 mm diameter drilled hole as notch, but with the base of the notch only 2 mm from the surface of the specimen instead of at the center. His tests were on sand castings and are given in Table 89.

TABLE 89.—*Comparison of impact and tensile properties of various aluminum casting alloys*

Essential nominal composition								Propor-tional limit	Tensile strength	Elonga-tion in 2 inches	Reduc-tion of area	Impact (Izod)	Foot-note
Si	Fe	Cu	Mn	Mg	Ni	Zn	Al						
Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*Per cent*	*Ft.-lbs.*	
------	------	------	------	------	------	------	99.8	1,000	8,850	34.0	66.9	13.3	------
------	------	------	------	------	------	------	99.4	2,000	13,000	29.1	53.0	17.3	------
------	------	------	------	1.5	------	------	97.7	5,600	20,850	4.9	7.7	6.6	------
------	------	0.7	------	1.5	0.7	------	96.4	9,500	21,200	.2	.3	2.1	------
------	------	------	------	5.0	------	------	94.2	9,300	25,850	4.7	7.1	5.0	------
------	------	------	------	10.0	------	------	89.2	17,300	23,150	.2	.0	1.5	------
5.0	------	------	------	------	------	------	94.4	------	17,270	3.4	------	2.0	------
5.0	------	------	------	------	------	------	94.4	------	15,970	4.1	------	1.9	------
5.0	------	------	------	------	------	------	94.4	2,600	18,200	5.0	6.5	2.4	------
5.0	------	------	------	------	------	------	94.4	2,400	17,100	4.4	5.5	2.5	------
5.0	------	------	------	------	------	------	94.4	------	17,310	4.0	------	1.0	------
5.0	------	------	------	------	------	------	94.4	------	16,800	5.2	------	4.9	(1)
12.0	------	------	0.5	------	------	------	86.9	------	22,900	5.2	------	4.0	(2)
12.0	1.0	------	------	------	------	------	86.9	------	20,250	5.7	------	2.4	(1)
13.3	------	------	------	------	------	------	86.1	------	24,630	12.3	------	3.9	(1)
13.3	------	------	------	------	------	------	86.1	3,600	24,800	17.5	19.6	3.7	(1)
13.3	------	------	.5	------	------	------	85.6	5,100	25,200	18.2	17.5	5.8	(2)
------	------	1.2	.8	------	------	------	97.3	------	20,300	10.9	------	7.9	------
------	------	1.2	.8	------	------	------	97.3	------	21,830	10.3	------	6.3	------
------	------	1.2	.8	------	------	------	97.3	2,700	21,250	12.1	10.0	9.1	------
------	------	1.3	1.3	------	2.0	------	94.7	4,700	25,700	6.4	10.1	4.1	------
2.0	------	3.0	.6	------	------	------	93.9	5,700	23,700	1.7	1.8	1.8	------
2.0	------	3.0	.6	------	------	------	93.9	11,000	33,100	2.3	3.2	2.0	(3)
------	------	3.5	------	------	------	------	95.8	10,000	27,200	3.3	7.6	6.9	(3)
------	------	3.5	------	------	------	------	95.8	20,400	33,350	1.2	3.9	4.3	(3)
------	------	4.0	------	------	------	------	95.3	5,100	22,000	2.2	4.4	3.6	------
1.0	------	4.0	.6	------	------	------	93.9	11,600	31,900	4.3	11.6	4.8	(3)
.8	------	4.5	------	.2	------	------	94.0	20,900	30,250	3.4	10.1	2.9	(3)
3.0	------	4.0	------	------	------	------	92.5	------	19,930	.9	------	1.5	------
3.0	------	4.0	------	------	------	------	92.5	------	21,270	.8	------	1.0	------
1.0	------	4.2	------	.2	------	------	94.1	------	31,730	2.0	------	4.5	(3)
1.0	------	4.2	------	.2	------	------	94.1	------	33,800	3.5	------	5.4	(3)
------	------	8.0	------	------	------	------	91.3	------	19,480	.6	------	1.5	------
------	------	8.0	------	------	------	------	91.3	------	19,200	1.0	------	1.6	------
------	------	10.0	------	------	------	------	89.3	11,200	30,700	.9	1.2	1.5	------
------	1.2	11.0	------	.2	------	------	87.4	------	30,630	.4	------	1.0	------
------	1.2	11.0	------	.2	------	------	87.4	------	33,600	.4	------	1.0	------
------	------	4.0	------	1.5	2.0	------	91.8	21,800	31,850	.3	1.1	1.0	(3)
------	------	4.0	------	1.5	2.0	------	91.8	21,900	25,750	.0	.0	1.1	(3)
------	------	------	------	------	3.5	------	95.7	3,600	18,600	8.0	10.6	3.3	(4)
3.5	------	------	------	------	2.5	------	93.4	2,100	19,600	3.9	5.2	2.0	------
------	------	------	1.5	------	------	------	97.7	2,000	18,050	16.7	25.0	8.4	------
------	------	3.0	.6	.5	------	2.0	93.2	15,000	19,450	.2	.0	1.1	------
------	2.3	------	------	1.0	------	7.0	89.4	24,100	32,600	.5	.4	1.0	------
------	1.0	3.0	------	.4	------	8.0	87.4	26,000	28,750	.2	.0	2.0	------
------	------	------	------	------	------	30.0	69.2	17,900	42,300	1.1	3.3	2.5	------

[1] Modified by sodium process.
[2] Modified by Pacz process.
[3] Quenched and tempered.
[4] Cast 1¼ inches thick in chill.

Strauss comments on his data as follows:

> For strengths above 20,000 lbs./in.^{2} combined with high resistance to impact use may be made of the 1.5 per cent magnesium; the 13 per cent silicon or the 1.2 per cent copper—0.8 per cent manganese alloys. Of these, the first possesses the highest proportional limit, the second the highest tensile strength, and the third the highest impact value.
>
> In the alloys of higher proportional limit only the 5 per cent magnesium and the heat-treated alloys of 3 to 5 per cent copper (with or without small amounts of other elements) possess good resistance to impact loading. Of these, the last-mentioned group may be produced to yield the better combination of mechanical properties. Based upon this fact alone, the heat-treated, copper-bearing alloys undoubtedly will play a prominent rôle in the rapidly expanding field for aluminum-base metals.

Both strength and ductility play a part in the resistance to notched-bar impact, but, as Strauss shows, there is no simple relation which will allow calculation of the impact resistance from the values of a tensile test. In castings the common copper-zinc aluminum alloys exceed the 8 per cent copper alloy in impact resistance because of their greater strength, the ductility being of the same order of magnitude, while the silicon alloys, of similar tensile strength, exceed the 8 per cent copper alloy in impact resistance because of their greater ductility. If the silicon or the iron is increased to the point where the ductility is low the impact resistance is also low.

The heat-treated light alloys that combine strength and ductility have a very useful impact resistance.

(b) REPEATED IMPACT TESTS

Repeated impact tests on notched bars are difficult to interpret. For a weight of hammer and height of fall that will break the bar in a small number of blows, say 100,000, they give results which rate the alloys rather similarly to a single-blow notched-bar test. Under conditions in which the bar is broken after a larger number of blows, the results are more of the nature of those from an endurance test, but differ from it in that the endurance test is made on bars very carefully shaped to avoid local concentration of stress, while the notched bar repeated impact test has very high stress concentration at the notch, and the actual stresses can not be accurately estimated.

Most available data are for Stanton tests, or those made with similar apparatus, a cylindrical notched bar being supported at both ends and struck over the notch by a hammer, the bar being turned 180° between blows.

Gibson (46n), using a sharp 60° notch and a 5.46-pound hammer, studied some aluminum alloys. His curves indicate the following relations.

TABLE 90.—*Effect of height and fall of hammer in repeated impact test*

Number blows to fracture	Height of fall of hammer (inches)		
	8 per cent Cu alloy	3 per cent Cu-8 per cent Zn alloy	Forged and heat-treated duralumin
10	1	2	----------
100	.5	1	3
1,000	.3	.5	1
10,000	.25	.3	.6
100,000	.20	(1)	.4

[1] Not determined.

The greater resistance of the Cu-Zn-Al alloy, compared to the 8 per cent Cu alloy, at very large loads is not so apparent at lighter ones, and the curves may finally cross, since true endurance tests indicate that the latter probably has a slightly greater endurance limit.

R. R. Moore (46h, k) has made Stanton tests. His curves indicate the following:

TABLE 91.—*Stanton tests on duralumin and magnesium base alloy*

Number blows to fracture	Foot-pounds energy of impact					
		Extruded alloys of magnesium				
	Heat-treated forged duralumin	6½ per cent Al	6½ per cent Al, ¼ per cent Mn	4 per cent Al	4 per cent Al, ¼ per cent Mn	10 per cent Cu
500	1.0	0.5	0.6	0.4	0.5	0.32
1,000	.8	.38	.5	.3	.38	.27
5,000	.4	.22	.22	.18	.22	.18
10,000	.3	.18	.18	----------	.18	----------
50,000	.18	----------	----------	----------	----------	----------

Stanton tests of various sand-cast aluminum alloys, using the 60° sharp notch, were made by the Aluminum Castings Co., and gave the following results:

TABLE 92.—*Stanton tests on sand-cast aluminum alloys*

Composition		Number of blows to failure at 0.30 inch drop	
Cu	Zn	4.7-pound hammer	2.3-pound hammer
	-------	-------	[1] 2, 200
2	-------	-------	4, 500
4	-------	200	5, 000
6	-------	-------	8, 000
8	-------	300	7, 000
10	-------	30	5, 000
12	-------	-------	4, 000
	4	500	2, 500
	8	1, 300	4, 500
	12	4, 000	20, 000
	16	5, 000	50, 000
	20	6, 000	65, 000
	24	10, 000	80, 000
	28	15, 000	100, 000
	32	16, 000	130, 000
	36	20, 000	160, 000
6	5	400	15, 000
5	10	8, 000	90, 000
3	[2] 15	14, 000	100, 000
4½	15	15, 000	120, 000
2½	19	20, 000	175, 000
2	25	24, 000	190, 000
1¾	30	25, 000	200, 000
2	22	23, 000	-------
3	3	900	-------
3	6	1, 000	-------
3	12	5, 000	-------
4	8	1, 500	-------
2	10	4, 000	-------
2	9	180	-------
7	3	250	-------
8	5	150	-------

[1] Commercial Al.
[2] Also ½ per cent Mn.

Welter (46d) has used a test similar to the Stanton, but with a reduced section instead of a sharp notch, and has compared various cast alloys as follows:

TABLE 93.—*Repeated impact tests of various cast-aluminum alloys*

Alloy			Number of blows to failure with hammer of stated weight—					
Cu	Zn	Si	4.2 kg	1.5 kg	0.75 kg	0.50 kg	0.30 kg	0.25 kg
8	------	-------	-------	-------	-------	-------	-------	More than 4,000,000.
2	10	-------	14	350	8, 228	-------	696, 000	4,000,000.
	------	12. 8	84	935	2, 340	9, 250	-------	750,000.
1. 0	------	12. 8	-------	-------	-------	6, 000	-------	2,000,000.
. 8	------	12. 8	43	625	1, 905	16, 000	-------	More than 4,000,000.
. 5	------	12. 8	-------	-------	-------	11, 000	-------	1,600,000.

Hurren (38b) made repeated impact tests with an Eden Foster machine (using a test bar similar to that employed in the Stanton test, a 2-pound hammer and a 1-inch fall) upon chill-cast specimens of aluminum alloys with, respectively, 3½ per cent copper, 12 per cent zinc, and 3 per cent copper, 10 per cent zinc. The former varied from 10,500 to 22,500 and the latter from 1,200 to 30,500 blows before fracture. The lower values were given by metal poured too hot or overheated in melting and the higher ones by metal not overheated and poured cold. Tests on "Y" alloy, with 3.8 per cent copper, 2.4 per cent nickel, 1.5 per cent magnesium, 0.4 per cent iron, gave—as cast, 1,000 to 4,000 blows, and, as heat treated, 13,000 to 42,000 blows. The higher pouring temperature gave the worst results on the alloy as cast but the best results on the alloy as heat-treated.

(c) ENDURANCE TESTS

Data on the endurance properties of aluminum alloys—that is, their resistance to repeated stress—are meager, and much of that given in the literature is none too reliable.

Endurance testing is tedious enough on steels where the hardest steels may require testing to 2 million and the softest ones to 10 million alternations of stress before the endurance limit can be taken as sufficiently established, but nonferrous alloys generally require testing to at least 100 million cycles before sufficiently definite results are obtained, unless the exact type of alloy in question has previously been thoroughly tested by long-time runs and the fact thoroughly established that an endurance limit may be shown at a smaller number of cycles. Indeed, in duralumin, R. R. Moore has had bars break after 200 million cycles of stress, so that if the accepted definition of an endurance limit as "that stress which the material will endure without failure no matter how many times the stress be repeated," be taken, it is not yet certain that there is a real endurance limit for duralumin, though McAdam (46b) is satisfied that one exists at least for practical purposes.

The relationship between the logarithm of the stress and the logarithm of the number of cycles to failure in a series of endurance tests is best represented for most materials by a straight line from the proportional limit of the material down to the endurance limit, but if a real endurance limit exists the graph should become horizontal, parallel to the log-cycle axis, at the stress corresponding to the endurance limit, and specimens tested at any stress below the endurance limit should remain unbroken, no matter how long the test may be continued.

R. R. Moore (46p) shows a graph for annealed and one for quenched and aged duralumin, both of which fail to become asymptotic, though tests were carried to 400 million cycles. Templin (46i) has carried a test of quenched and aged duralumin out to more than 2 billion cycles at a stress range of 8,000 lbs./in.^{2} without failure.

Even this long test does not prove absolutely that there is an endurance limit for duralumin, because the point obtained by Templin's test lies below R. R. Moore's log stress-log cycle curve for duralumin, and does not establish a break in the curve.

Hence, it is necessary, in reviewing endurance-limit data for aluminum alloys, to state the number of cycles to which tests were carried in order to show upon what basis the endurance limits given by different investigators were determined. This does not mean that a test carried only to 100 million or even 10 million cycles is valueless, but only that "endurance-limit" figures so determined should be taken only for what they really show.

Tests on aluminum alloys made by the so-called rapid methods, such as the rise-of-temperature test, or the change-in-rate-of-deflection method, may be dismissed as valueless so far, on the evidence of Templin (46i), Moore (46h, k), and Gough (2j).

Tests made by running a few million cycles at a low initial stress which does not break the bar, then raising the stress and running a few more million cycles, and so on till the bar breaks, can not be accepted as satisfactory, because of the likelihood that the phenomenon of "strengthening by understressing" will be met. Such a phenomenon is thoroughly established for steel, and occurs to a less marked extent in some nonferrous metals. If the phenomenon does occur, a test made in that fashion will give results that are too high and values that are unsafe for the use of the designer. Quite a number of tests on aluminum alloys made at the National Physical Laboratory during the war rush and before correct methods of endurance testing were understood were made in such fashion, and care has to be taken in reading the literature of such tests to examine the test methods as well as the tabulated data so as to be able to accept or reject the tabulated figures. The method of loading from low stresses up is now repudiated by the National Physical Laboratory, since Gough, of that laboratory, now characterizes (2j) such a method as "quite futile," and states that a fatigue range so obtained is nearly always too high.

Rosenhain (46m) has lately recognized that strengthening by understressing definitely occurs in "Y" alloy. McAdam (46c, e, g), has clearly shown it for annealed duralumin, and R. R. Moore (46h, k, l), has shown it in magnesium, in a magesium aluminum alloy, and has found indication of it for pure aluminum. Hence, strengthening is to be expected to a greater or less degree in all the light alloys. Retesting a strengthened bar at a higher stress may give valuable corroborative evidence that it would have lasted far longer at the lower stress and affords a useful means of saving time (46r) (see foot-note to Table 94 also), but they tell nothing whatever about the behavior of a nonstrengthened bar at the higher stress.

Most endurance data for light alloys have been obtained in rotating beam or rotating cantilever tests on material rolled or forged to approximately 1-inch diameter. These rotating tests give completely reversed stress, the maximum unit tensile and compressive stresses in the surface of the specimen being equal. The endurance limit reported for such tests is the maximum stress regardless of sign; that is, it is half the stress range.

Very few figures are available on tests of aluminum alloys made by axial loading methods, either under completely reversed stress or under varying axial stresses; for example, from no load to a definite tensile load. Whether rotating tests can be taken as giving identical results with those that would be obtained on axial loading tests is still a moot point, no axial tests having been made on aluminum, and data on other materials being as yet insufficient to settle the question (46s, h, k, l, 2j). Axial loading tests are under way in the laboratories of the Aluminum Co. of America and useful data may be expected on this point.

It is not yet settled whether there may or not be a size factor in endurance testing; that is, whether, for example, a 1-inch diameter bar and a 0.1-inch or 0.01-inch thick sheet otherwise comparable will show the same endurance limit. In reversed bending tests at the Bureau of Standards no consistent relation was found between thickness of sheet, ranging from 0.024 to 0.120 inch and endurance properties, and it is probable that any apparent size factor is, instead, ascribable to differences in the exterior and interior of a thick section rather than to a true size factor.

Similarly, the effect of speed is not yet thoroughly understood. It is generally assumed that up to 2,000 cycles per minute variations in speed have no effect, if the test methods are such that dependable stress values are obtained, but it is not certain that this holds at much higher speeds.

Finally, it should be noted that test values unless otherwise noted refer to apparently sound material.

Tests at the Bureau of Standards indicate that sheet duralumin which has been somewhat corroded on exposure and shows perceptible intercrystalline embrittlement may have its endurance properties lowered by, say, 25 per cent.

Tests by McAdam (46t) indicate that, under a continuous stream of fresh or salt water, rotating endurance test specimens of duralumin may show a "corrosion-fatigue limit"; that is, roughly, perhaps, one-half that shown by similar tests in air, and that on commercial aluminum and aluminum-manganese alloy the reduction of the endurance limit due to simultaneous repeated stress and corrosion may be as great or greater than in duralumin. (See footnotes to Tables 94 and 95.)

Irrespective of the condition of working or heat treatment, McAdam finds the following "corrosion-fatigue" limits:

	Fresh water	Salt water
	Lbs./in.^{2}	*Lbs./in.*^{2}
Commercial aluminum	±4, 000–5, 000	±2, 500–3, 500
Aluminum manganese (1¼ per cent Mn)	±5, 000–6, 000	±3, 500–4, 500
Duralumin	±7, 000–9, 000	±6, 000–8, 000

R. R. Moore (46p) has shown that corrosion by salt water prior to carrying out the endurance test may give, on thin sheet duralumin, an endurance limit some 35 per cent lower than is obtained on the material prior to corrosion, even though the tensile strength is but slightly diminished.

McAdam's tests (46t) on other materials have indicated that simultaneous corrosion and repeated stress give a lower endurance limit than does a comparable amount of corrosion of the specimen prior to testing. Wrought, heat-treated alloys of the duralumin type have naturally received more attention in regard to endurance properties than have the wrought alloys of lower static strength or the cast alloys.

Data on heat-treated duralumin and duralumin type alloys and on two tests of annealed duralumin are given in Table 94.

Question marks have been placed after the data in the column headed "Safe at" in the case of tests that were obviously carried to too few cycles to give acceptable results.

In the Bureau of Standards tests on sheet duralumin attempts were made to correlate the endurance behavior of the 14 lots (7 each of two different compositions) with various other properties without success. From the other data available, it is unlikely that the difference in composition is directly responsible for the difference found in endurance properties.

R. R. Moore (46l) found perceptible differences in the endurance properties of the same material as received in the heat-treated condition and after retreatment, supposedly the same as had been previously used.

McAdam (46b, e) got perceptible differences between two lots of similar composition of unstated heat treatment (tested as received from the manufacturer). One lot was lower in tensile strength than the other, but Gibson (46n) used material of even lower tensile strength and got higher endurance properties than did McAdam on his weaker material.

It is evident that the endurance properties of heat-treated duralumin can not be taken as fixed and definite; they appear to vary

TABLE 94.—*Endurance tests of duralumin type alloys*

HEAT-TREATED DURALUMIN

	Composition					Quench	Aging	Static tests				Endurance properties		Source
	Cu	Si	Mg	Mn	Fe			Brinell	Tensile strength	Elongation per cent in 2 inches	Reduction of area	Safe at—	Tests carried to millions of cycles	
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*				*Lbs./in.*[2]		*Per cent*	*Lbs./in.*[2]		
A	4.50	0.20	0.51	0.95	0.47	Not stated			61,500–65,000	13–14½	28½–33	±22,000(?)	15	46p.
B	3.80	.42	.45	.54	.46	do			69,000–71,000	13½–17½	29½–37½			
C	4.18	.19	.66			do		118	67,000	16	21	±21,500(?)	12	46q.
D	3.61	.48	.70	.60		930° F. 1 hour cold H_2O	300° F. 1 hour	100	47,500	27	37½	±15,000	100	46n.
E	3.25	.28	.70	tr.	.28	930-950° F. 7 to 30 min. boiling H_2O.	Aged at room temperature.	100	51,000	16	50½	±14,000	400	46l.
F	3.25	.28	.70	tr.	.28	925° F. 30 min. boiling H_2O.	do	100	51,000	29	47½	±12,000	400	46l.
G	4.35	.25	.71	.64	.77	Not stated			53,400	24	35	±12,000	[1] 200	46e.
H	4.28	.34	.42	.62	.59	do			61,600	26	31	±16,000	200	46b.
I	3.80	.40	.62	.54	.59	do		107–117	55,000–62,000	13–24	25–34	±19,000	200	46s.
J	4.30	.21	.44	.52	[2].35	do		108–120	57,000–65,000	14–23	17–26	±15,000	200	46s.
K						do			57,000	23		Over ±8,000	2,029	46i.
	3.72	1.02	.28	.50	.42	do			69,000	18	23	Less than ±16,000 [3]	[4] 100	46t.

OTHER HEAT-TREATED ALLOYS

	Cu	Si	Mg	Mn	Fe	Quench	Aging	Brinell	Tensile strength	Elongation per cent in 2 inches	Reduction of area	Safe at—	Tests carried to millions of cycles	Source
L	4.55	0.82	None.	0.82	0.56	Not stated			59,500	24	37½	±15,000	120	46b.
M	0.15	.56	0.55	tr.	.54	do			45,000	17½	22½	Less than ±12,000	[4] 50	46b.
N	4.00	(?)	1.50	(?)	(?)	520–530°; C., boiling water.[5]	Aged at room temperature.		±45,000	±6		±15,500(?)	12	46m.

ANNEALED DURALUMIN

	Cu	Si	Mg	Mn	Fe	Quench	Aging	Brinell	Tensile strength	Elongation per cent in 2 inches	Reduction of area	Safe at—	Tests carried to millions of cycles	Source
	3.25	0.28	0.70	tr.	0.28	700° F. 20 minutes furnace cooled.		50	25,250	25	61	±10,800	200	46l.
	4.12	.47	.64	0.52	.51	Annealed			29,500	19½	47	±11,000	27	46e.
	4.18	.37	.42	.60	.54	do			33,500	17½	43	±13,500 [6]	400	46t.

[1] 80 million at low stress, balance of 200 million at higher stresses; initial stress used as criterion.

[2] Also 0.10 per cent Cr.

[3] In tests made in a stream of fresh water; allowing corrosion to take place during the endurance test a specimen stressed at ±10,000 lbs./in.² broke in 20 million cycles. In tests made in a stream of salt water; allowing corrosion to take place during the endurance test a specimen stressed at ±8,000 lbs./in.² broke in 30 million cycles.

[4] No unbroken bars.

[5] "Y" alloy; chill casting poured at 750° C. not wrought; also contains 2.00 per cent nickel; composition represents that aimed at, not by analyses.

[6] In tests made in a stream of fresh water; allowing corrosion to take place during the endurance test a specimen stressed at ±8,000 lbs./in.² broke in 20 million cycles. In tests made in a stream of salt water; allowing corrosion to take place during the endurance test a specimen stressed at ±7,000 lbs./in.² broke in 50 million cycles.

from lot to lot according to some unknown variable. The temperature to which the alloy is heated before quenching and the time the material is held at that temperature govern the homogeneity of the solid solution before quenching, and are also important in determining whether or not the material is damaged by incipient melting of the eutectic. The rate of cooling in quenching; that is, whether the material is quenched in cold water, hot water, or oil, regulates the degree of retention of the solid solution during quenching.

The separation from the unstable solid solution of the compounds that cause hardening is in turn regulated by the temperature at which aging takes place. All these variables together are concerned in the heat treatment of duralumin, and there is a considerable likelihood that changes in the details of heat treatment may have a greater effect in altering the endurance properties than they do in altering the static tensile properties. When the endurance properties have been studied in relation to the heat treatment of duralumin it may be possible regularly to secure the resistance to repeated stress shown by one lot of sheet material tested at the Bureau of Standards, which, although tested without machining or polishing the surface of the rolled sheet, showed, in no thickness, and irrespective of whether the specimen was taken longitudinally or transversely, no test results on sound, uncorroded metal that would indicate a poorer resistance to repeated stress than the ability to withstand 200 million cycles at ±19,000 lbs./in.^{2} or more.

From preliminary results, it is expected that lower values may be found in tests in the high-speed fatigue machine operating at about 12,000 cycles per minute now being developed at the Bureau of Standards, but reasonable extrapolation of the tangent line on all graphs available for heat-treated duralumin meeting the United States Navy Specifications (55,000 lbs./in.^{2} tensile strength, etc.) and tested at speeds below 2,000 cycles per minute indicate in every case that the sound, uncorroded and unnotched material would withstand 10 billion cycles at ±10,000 lbs./in.^{2}.

Templin's test of a specimen that ran 2 billion cycles at ±8,000 lbs./in.^{2} without breaking adds credibility to the extrapolation.

At an engine speed of 2,000 r. p. m. an airplane in continuous flight for 10 years would pass through about 10 billion stress cycles.

Knerr (43dd) cites German authorities to the effect that duralumin cold-worked after heat treatment to 6 per cent elongation will safely withstand stress variations from 0 to 20,000 lbs./in.^{2} in tension. This stress range is the same as the ±10,000 lbs./in.^{2} taken above as safe to 10 billion cycles.

R. R. Moore has given data on tests of certain wrought alloys continued to a sufficient number of cycles to establish rather definitely that there is an endurance limit for the materials tested. (46l.)

His data, together with some from McAdam (46t) are reproduced in Table 95.

TABLE 95.—*Endurance tests of wrought aluminum and of wrought magnesium alloys*

Composition						Working	Static tests			Endurance limit	Tested to million of cycles
Al	Mg	Cu	Fe	Si	Mn		Tensile strength	Elongation	Reduction of area		
Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*		*Lbs./in.*²	*Per cent*	*Per cent*	*Lbs./in.*²	
Bal.	------	0.12	0.49	0.15	------	Rolled	22.500	16	65	±10,500	80
------	Bal.	------	.02	.02	------	Extruded	32,500	6	4	±7,800	100
8.68	Bal.	.03	.04	.02	------	Forged	41,000	4	------	±15,000	60
8.68	Bal.	.03	.04	.02	------	Longitudinal forged	30,000	3	------	±13,000	35
4.20	Bal.	------	.03	------	------	Transverse extruded	35,000	22	28	±12,000	100
4.40	Bal.	------	.03	------	0.26	do	39,000	15½	31	±15,000	100
6.70	Bal.	------	.04	------	------	do	41,000	16	20	±13,000	20
6.80	Bal.	------	.04	------	.26	do	44,500	14	17	±15,000	80
9.65	Bal.	------	.04	------	------	do	39,000	3	4	±11,000	60
Bal.	------	.12	.30	.22	------	Hard	20,500	18	64	±[1] 8,500	200
Bal.	------	.12	.30	.22	------	Half hard	16,000	23½	75	±[2] 7,200	100
Bal.	------	.12	.30	.22	------	Annealed	12,500	48	81	±[3] 6,000	40
Bal.	------	.16	.29	.35	1.22	Hard	29,500	12½	46	±[4] 10,800	80
						Half hard	24,000	19½	57	±[5] 10,000	100
						Annealed	16,500	44	70	±[6] 7,000	100

[1] In a stream of fresh water a specimen stressed at ±5,000 lbs./in.² broke after 20 million cycles; one in salt water at ±6,000 lbs./in.² broke after 50 million cycles.

[2] In a stream of fresh water a specimen stressed at ±6,000 lbs./in.² broke after 60 million cycles; one in salt water at ±5,000 lbs./in.² broke after 20 million cycles.

[3] In a stream of fresh water a specimen stressed ±3,500 lbs./in.² broke after 30 million cycles; one in salt water at ±5,500 lbs./in.² broke after 1½ million cycles.

[4] In a stream of fresh water a specimen stressed at ±5,500 lbs./in.² broke after 40 millions cycles; one in salt water at ±4,000 lbs./in.² broke after 50 million cycles.

[5] In a stream of salt water a specimen stressed at ±3,300 lbs/in.² broke after 70 million cycles.

[6] In a stream of salt water a specimen stressed at ±2,200 lbs./in.² broke after 25 million cycles.

Archbutt and Jenkin (100s) obtained the following endurance and impact results on hot-rolled magnesium and its alloys:

	Commercial magnesium	6 per cent aluminum alloy
Endurance limit on basis of 20 million reversals ... lbs./in.²	±10,000	±14,500
Impact, Charpy ... ft.-lbs.	[1] 4.3	[2] 5.1
Impact, Izod ... do.	3.8	4.6

Specimen 10 by 10 mm, notch 45°, 2 mm deep, ¼ mm root radius.

[1] Rose to 4.75 on annealing 100 hours at 350° C.

[2] Rose to 8.6 on annealing 100 hours at 350° C.

The bulk of the recorded data on various aluminum piston alloys tested in England at ordinary and elevated temperatures, has to be discarded because of the method of testing which did not take account of the likelihood of error due to strengthening by understressing. Other early data have to be discarded because tests were carried to too small a number of cycles, and also, in some cases, because of improper fillets on test bars. The remaining data available are included in Table 96.

The data of Welter (46d) are taken from his plotted values, with certain assumptions as to the meaning of some conventions he used in plotting which are not explained in his paper.

It appears that the endurance limit (if a true limit exists for these alloys) of sound sand castings of No. 12 alloy (8 Cu, 92 Al) is not above ±7,000 lbs./in.^{2}, and that the endurance properties of the statically stronger Cu-Zn-Al light alloys are no better than and probably slightly inferior to those of No. 12.

TABLE 96.—*Endurance properties of light cast alloys, not heat-treated, sand-cast unless noted*

Nominal composition					Static properties			Safe at—	Tested to, millions of cycles	Source
Cu	Zn	Mn	Si	Mg	Tensile strength	Elongation	Reduction of area			
Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Lbs./in.*^{2}	*Per cent*	*Per cent*	*Lbs./in.*^{2}		
8	------	------	------	------	21,000	2½	1	Less than ±7,000	100	46v
1.75	------	1.75	------	------	23,000	8	8	Less than ±5,000	37	
3	14	------	------	------	36,000	2	2	Less than ±6,000	68	
8	------	------	------	------	23,000	1½	------	Less than ±8,500	20	46n
3.50	8	------	------	------	29,500	5	------	Less than ±8,500	20	
12	------	------	------	------	------	------	------	±7,000	15	46u
8	6	------	------	------	20,000	2	------	±5,000	6	
2	12	------	------	------	27,000	1½	------	±5,000	8	
------	------	------	10–12.50	(1)	21,500–23,000	3–14	3½–15	±5,800–±6,300	20	46t
------	------	------	[2] 8.50	------	28,000	17	------	±9,200	20	46a
------	------	------	12.50	------	28,000	5	------	±5,700	73	46d
8	------	------	------	------	21,000	2	------	±7,100	5	
2	10	------	------	------	22,500	5	------	±7,100	5	
.50	------	------	12.50	------	29,000	2	------	±7,100	5	
8.50	------	------	------	Bal.	28,000	4	------	±12,500	1	46h

NOTE.—All alloys except the last are alloys of aluminum, the last contains 91½ per cent magnesium.

[1] Alloys "modified."

[2] Chill cast.

Unpublished tests by the Aluminum Co. of America are stated by Dr. Z. Jeffries to indicate that the endurance limit of the heat-treated, sand-cast "No. 195" alloy (4.5 per cent Cu, 0.8 per cent Si) (see p. 258) is approximately 50 per cent higher than that of No. 12.

Although Grogan's test (46a) on an alloy of 8½ per cent silicon in chill castings would indicate slight superiority to No. 12, this is not borne out by the tests on sand castings of Gwyer and Phillips (45a), nor by those of Welter, who says that the silicon alloy (12½ per cent silicon) is inferior in endurance properties unless from ½ to 1 per cent of copper is added when it becomes equal to or better than No. 12.

The cast magnesium aluminum (8½ Al, 91½ Mg) alloy shows good endurance properties in comparison with the light aluminum casting alloys. A comparison of the test on magnesium alloys in Tables 95 and 96 with those on aluminum alloys shows that the magnesium alloys give practically as good an endurance limit as all but the best heat-treated duralumin. No tests have yet been recorded to show how the magnesium alloys will behave in the "corrosion-fatigue" test.

As a basis for comparison of the light alloys with ferrous alloys, it may be noted that the rotary beam endurance limit of steel generally runs about half the tensile strength, varying from, say, 40 per cent to, say, 55 per cent. Moore and Lyon (46u) have recently studied cast iron and find the rotary beam endurance limit to run from ±7,000 to ±12,000 lbs./in.^{2} The ordinary cast aluminum alloys show values of the same order of magnitude while the magnesium alloys and the heat-treated duralumin type alloys, at least in wrought form, are quite definitely superior in endurance limit to cast iron.

C. MAGNESIUM

I. METALLIC MAGNESIUM

1. SOURCES

Magnesium constitutes approximately 2 per cent of the earth's crust, occurring as magnesite ($MgCO_3$), dolomite ($MgCO_3.CaCO_3$), carnallite ($MgCl_2.KCl6H_2O$), kieserite ($MgSO_4H_2O$), kainite ($MgSO_4.KCl3H_2O$), brucite ($MgOH_2O$), and in various silicates (100q). Carnallite and magnesite, both used as sources of metallic magnesium, occur in Stassfurt, in Germany. Magnesite occurs in Greece and Austria, in the northern part of South America and in the western part of the United States. The bittern obtained as a by-product in the purification of common salt may also be used as a source of magnesium.

2. HISTORY, PRODUCTION, AND PRICES

The element magnesium was first isolated in 1808 by Sir Humphrey Davy (100q) nearly 20 years before aluminum was obtained in metallic form, but it was not until 1859 that attempts were made to produce the metal on a commercial scale. In America the earliest commercial production of magnesium was from 1865 and intermittently to 1892, but the European War (1914–1918) stimulated the output for war purposes.

In Table 97 are shown statistics for domestic metallic magnesium sold or used in the United States from 1916 to 1926.

TABLE 97.—*Domestic metallic magnesium sold or used in the United States, 1916–1926* [1]

Year	Number of producers	Pounds	Value	Year	Number of producers	Pounds	Value
1916	4	75, 400	$311, 462	1922	2	[3] 60, 000	[3] $89, 000
1917	5	115, 813	233, 626	1923	2	[3] 125, 000	[3] 155, 000
1918	4	284, 118	615, 217	1924	2	[3] 128, 000	[3] 150, 000
1919	3	127, 465	247, 302	1925	2	245, 000	274, 400
1920	2	(2)	(2)	1926	2	322, 650	390, 400
1921	1	48, 000	86, 000				

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[1] Mineral Resources of the United States in 1925, Bureau of Mines.
[2] Bureau of Mines not at liberty to publish figures.
[3] Estimate.

The statistics for magnesium imported for consumption in the United States are shown in Table 98, and the average price per pound from 1919 to 1925, inclusive, is shown in Table 99.

TABLE 98.—*Magnesium imported for consumption in the United States, 1918–1925*

Year	Pounds	Value	Year	Pounds	Value
1918, July to December [1]	11,899	$16,259	1922	182,939	$54,448
1919	13,239	13,583	1923	13,974	11,576
1920	29,275	25,055	1924	8,738	6,561
1921	39,913	30,592	1925	8,326	7,070

[1] Prior to 1915 the entire domestic supply was imported, but such imports are not separately shown until July, 1918.

TABLE 99.—*Average price per pound of magnesium imported* [1]

Year	Price	Year	Price
1919	$1.02	1923	$0.83
1920	.85	1924	.75
1921	.77	1925	.85
1922	[2].30		

[1] Mineral resources of the United States, 1923, 1925.

[2] This price was abnormal, importations were largely scrap metal from Germany with the dollar at a premium.

According to a Department of Commerce bulletin, dated April 1, 1927, over 73 per cent of the magnesium produced in the United States in 1926 was sold in ingot form at prices ranging from 69 to 98 cents a pound, and such sales increased nearly 19 per cent as compared with 1925. Sales of castings in 1926 were 36,940 pounds and were over 11 times greater than in 1925. Sales of wire and tubing increased fourfold as compared with 1925, but sales of sheet were nearly 9,000 pounds less than those in the previous year. The average price of domestic ingot metal in 1926 was 80 cents a pound, that of powder $1.64 a pound, and of castings $2.57 a pound.

3. COMMERCIAL FORMS

Magnesium may be obtained commercially as ingot, sheet, rods, tubes, powder, wire, ribbon, and castings.

The ingot is offered by one manufacturer in three grades, grade No. 0 containing 99.99 per cent (minimum) magnesium, grade No. 1, 99.85 per cent (minimum) magnesium, and grade No. 2, 98.00 to 99.00 per cent (98 per cent minimum) magnesium. Grade No. 0 is an extra pure metal for special purposes. No. 1 is a commercially pure metal used largely as a base for alloys to be fabricated. No. 2 is a grade suitable for deoxidizing or for alloying, when the elements included in the maximum of 2 per cent impurities, mainly silicon, iron, and aluminum, are permissible in the amounts present.

These grades are listed in the following sizes of ingot all 12 inches long.

	Pounds
0.816 inch square	½
0.922 inch diameter	½
1.312 inch diameter	1
Triangular section	2

Another manufacturer lists one grade only, classed as 99.8 per cent minimum magnesium content, and states that improvements in process now under way are expected to raise this purity to about 99.95 per cent. This grade is marketed in square pigs 3 by 3 by 15 inches, weighing about 8 pounds and in round bars 1⅜ inches diameter and 27 to 32 inches long.

There are no standard sizes for sheet and plate, but they can be obtained in any thickness from ¾ inch to No. 30 B. & S. gauge, in widths up to 12 inches, and in lengths to 10 feet for sheet. From 14 to 20 B. & S. gauge, 24-inch widths are obtainable.

Tubing is difficult to manufacture and has to be obtained on special order. Rod is produced in any size or shape from ⅜ inch to 1¼ inches maximum dimension, in random lengths. Wire is sold from No. 22 B. & S. gauge (0.025 inch diameter) to No. 00 (0.3648 inch diameter). Ribbon can be obtained in any size. Powder is graded by mesh and sold as in grades 35, 48, 65, 100, 150, 200, and 200 and finer, or in combinations of these sizes.

Castings in several alloys can be made from patterns suitable for aluminum alloys.

4. METALLURGY, IMPURITIES, METHODS OF ANALYSIS

Magnesium is prepared commercially by two processes—the chloride process and the oxide process.

The chloride process, used in Europe, makes use of $MgCl_2.6H_2O$, which is mixed with sodium chloride or potassium chloride to prevent decomposition of the material into the oxide or oxychloride (100d). After careful dehydration the molten mixture is decomposed electrolytically, the electrolysis being usually carried out in an iron pot, which serves as the cathode, with a centrally located graphite anode (100q). Magnesium is plated out at the cathode and rises to the surface of the bath in small globules which must be protected from the chlorine evolved at the anode. The magnesium obtained contains some electrolyte and must be refined by remelting and skimming, which must be very carefully carried out to eliminate chlorides, which are detrimental in accelerating corrosion. The batch process used in the electrolysis of the chloride in European practice has been supplanted in this country by the continuous process using dehydrated or partially dehydrated magnesium chloride. Detailed accounts of the present process are lacking. The chloride process is used in the production of the greater part of the magnesium produced in the United States.

The oxide process uses magnesium oxide as the source of the metal. The oxide is decomposed electrolytically at 900 to 1,050° C. in a bath of fused fluorides of magnesium, barium, and sodium. Since no fused commercial fluoride, save that of lithium is lighter than molten magnesium, the specific gravity of the electrolyte is made high, so that the magnesium floats and is removed from the surface of the bath.

Other suggested thermal, substitution and direct electrolytic processes have been discussed by Allen (100k).

The impurities in commercial magnesium, as stated by the producers, are as follows:

TABLE 100.—*Impurities in commercial magnesium*

CHLORIDE PROCESS [1]

Copper and nickel	0.010–0.020
Manganese	.003– .007
Silicon	.015– .025
Iron and aluminum	.020– .030
Barium	-----------
Chlorine	.010– .020

OXIDE PROCESS [1]

	Grade 0	Grade 1	Grade 2
Silicon	0.002–0.004	0.017–0.047	0.51–0.57
Iron and aluminum	.005– .007	.029– .049	.14– .81
Barium	None–Trace.	-----------	---------

ENGLISH MAGNESIUM [2]

	Ingot	Test rod	Commercial rod
Copper and nickel	0.032	0.02	0.048
Manganese	(3)	(3)	(3)
Silicon	.025	.06	.075
Iron and aluminum	.076	.03	.060
Barium	(3)	(3)	(3)
Chlorine	(3)	(3)	(3)

[1] American product. [2] Data from Archbutt and Jenkin (100s). [3] Not determined.

Method of analysis of magnesium for silicon, barium, iron, aluminum, calcium, and sodium have been described in the Handbook of the American Magnesium Corporation, by Guerin (101a), and by Pretete and Ecoffet (101b), all of which should be consulted on this point.

5. ATOMIC PROPERTIES, SPECTRUM LINES; CRYSTAL STRUCTURE, ATOMIC WEIGHT

Magnesium is readily detected by spectral methods, amounts of the order of 0.001 per cent, or even less, being revealed by characteristic spectral lines. Photographic observations, with quartz or grating spectographs, are required, since all the sensitive lines of magnesium lie in the ultra-violet. The ultimate ray for neutral atoms of magnesium (excited in flame or arc spectra) has a wave length of 2852.11 A. Lines of somewhat smaller sensitivity are represented by 3838.29, 3832.31, and 3829.36, their strength decreases in the order named. The ultimate rays for the ionized atoms of magnesium (excited in condensed spark spectra) occur at 2795.52 and 2802.70 A, the former being the stronger and more sensitive.

Magnesium crystallizes in the hexagonal system. The unit cell has the following dimensions: a, the side of the hexagonal base = 3.22 Å, and c, the height of the hexagonal prism = 5.23 Å, the axial ratio c/a being 1.62. The density calculated from these data is 1.709 g/cm^3. Data on crystal structure of magnesium and some of its alloys are given in Tables 5 and 6.

The atomic weight of magnesium is 24.32 (100c, l, o).

6. CHEMICAL PROPERTIES, CORROSION

Pure water is slightly decomposed at 100° C. by magnesium, MgO and H being formed (100l). Magnesium is unaffected by alkalies of any concentration, even when hot (100g, l); is readily attacked by saline solutions (100c), even when dilute (100l); is readily attacked by weak acids (100c), by concentrated hydrofluoric acid (100g, c), or by mixed sulphuric and fuming nitric acids at ordinary temperatures (100l). In humid air a layer of magnesium hydroxide is formed which protects it against further oxidation (100n). The oxide film formed in air is not progressive or injurious if the metal is clean (100o).

The tendency of magnesium to react to air moisture and weak acids decreases markedly as the purity of the metal increases (100q). The impurities which may exist in commercial forms of magnesium and magnesium base alloys may be metallic or nonmetallic. The general effect of the nonmetallic class of impurities is to weaken the metal through a loss of integrity of section (100q). If the impurity happens to be a hygroscopic salt, such as magnesium chloride, still greater harm results, since the chloride, as it becomes exposed, absorbs moisture and forms a saline solution which corrodes this metal very rapidly and with continuous action (100t).

The presence of metallic impurities in an exposed surface of magnesium may in several ways promote corrosion. If the impurity itself oxidizes readily, any reaction with moisture will cause local corrosion and tend to break the continuity of the protective oxide (or hydroxide) coating normally formed. The presence of sodium and potassium is especially harmful for this reason. The position of the impurity in the electromotive series is a factor of importance. Any segregated element electropositive to magnesium will, in the presence of moisture, cause a continuous electrolytic action with a consequent focus of corrosion. If the impurity readily forms solid solutions with magnesium, this tendency is reduced to a minimum, as in the case of aluminum. Iron does not alloy in any proportions with magnesium, and is an impurity to be avoided. Calcium, in small amounts, is said to have little, if any, effect.

Portevin (102a) states that there is no relation between the speed of corrosion and the chlorine content of the magnesium, but that silicon seems to be the impurity which plays the leading part in accelerating corrosion.

The effect of traces of chlorides resulting from manufacture by the chloride process is somewhat in dispute. There is no question but that the large amounts of chlorides included in the European product of, say, 10 years ago (which would disintegrate in storage unless kept from contact with moist air by a coating of paraffin or some similar device), played a considerable part in the atmospheric corrosion of such magnesium. With better methods for prevention of trapping of chlorides or for their elimination on remelting the chloride impurity in the metal sold is now generally very small. Statements as to the danger from or the harmlessness of the residual traces of chlorides do not appear to be substantiated by published accounts of impartial comparisons of the metal made by the chloride and the oxide processes. At any rate, it was not until the amount of chloride was reduced to practically nothing in the oxide process and to traces in the present chloride process that magnesium was commercially produced which was sufficiently resistant to atmospheric corrosion to be seriously considered as a material for engineering construction.

In a recent investigation of the corrosion of magnesium and magnesium aluminum alloys containing manganese, Boyer (102b) drew the following conclusions:

1. Pure magnesium of ordinary ingot grade is quite resistant to corrosion by salt water.
2. The addition of aluminum increases the rate of corrosion, but the presence of a small amount of manganese counteracts to a large extent the effect of the added aluminum.
3. No relation can be traced between the presence of undissolved constituents and the rate of corrosion of the magnesium-aluminum alloys.
4. There is a definite relation between cored structure and corrosion. The magnesium-rich dendrites are eaten out as if by direct attack.
5. Coring is not the cause of corrosion, but is merely responsible for the dendritic nature of the attack.

6. Magnesium silicide is inactive during corrosion.

7. The aluminum constituent, at least when present in small amounts, is inactive.

8. Nonmetallic inclusions are inactive during the initial corrosion attack, but the inclusions may act as nuclei for the crystallization of the magnesium-rich dendrites. The latter are attacked by salt water and give the appearance in the corroded specimen of a relation between inclusions and corrosion.

9. A critical amount of manganese is necessary to inhibit the corrosion of the magnesium-aluminum alloys. The amount increases with the quantity of aluminum in solid solution. At least three-tenths per cent manganese should be present in a 4 per cent aluminum alloy.

10. Alloys which do not contain the critical amount of manganese corrode until completely disintegrated.

11. An excess of manganese over the critical amount slightly decreases the resistance to corrosion, but does very little harm. It is better to have too much than too little manganese present.

12. Heat treatment of the aluminum alloys containing too little manganese makes them much less resistant to corrosion. If sufficient manganese is present, heat treatment has practically no effect.

13. The protective film forced on corrosion-resistant specimens does not stop electrochemical action by actual insulation. A change in potential relations of less than one-tenth volt will cause the liberation of hydrogen.

14. The electrical resistance of the film is small and is of the order of magnitude of a few ohms.

15. When a specimen covered by a protective film is connected to a metal of low overvoltage the magnesium corrodes rapidly and the film is activated so that hydrogen comes from both the magnesium anode and the metal acting as cathode.

16. Overvoltage of impurities and not their position in the electromotive series is the factor which determines whether they are active or inactive during corrosion.

17. Pitting is probably due to the activation of the film on the anodic areas by the formation of magnesium chloride during electrolysis. As long as current flows the action will be continuous.

18. Aluminum apparently lowers the overvoltage of magnesium. Hydrogen is liberated at a much lower potential during corrosion than is the case with pure magnesium.

It is concluded that manganese raises the overvoltage of the aluminum alloys back to practically that of pure magnesium.

7. PHYSICAL PROPERTIES

(a) DENSITY

The density of magnesium in different conditions and at different temperatures may be seen in the following table:

TABLE 101.—*Density of magnesium*

Mg	Temperature	Density	Form	Authority
Per cent	° *C.*	*g/cm³*		
99.99	20	1.7388	Extruded ⅜ inch diameter	Research Bureau of Aluminum Co. of America.
99.99	20	1.7388	Same, annealed 2.5 hours at 400° C	Do.
99.95	20	1.7381	Extruded ⅜ inch diameter	Do.
99.90	20	1.7381	do	Do.
99.90	20	1.737	As cast	Bureau of Standards.
99.99	650	1.642	Calculated at melting point	Research Bureau of Aluminum Co. of America.
99.99	650	1.572	Extrapolated at melting point	Do.
99.99	667	1.560		Edwards and Taylor (103d).
	667	1.565		Do.
	673	1.562		Do.
	711	1.538		Do.
	768	1.445		Do.
	822	1.478		Do.

Other writers give values for density of magensium as 1.74 (100 c, h, 106c) and 1.72 g/cm³ at 15° C. (100b, o, m).

(b) THERMAL PROPERTIES

(1) MELTING POINT.—The melting point of magnesium is 651° C. (103n). The boiling point of magnesium is 1,120° C. (100c, o, q). The low boiling point is made use of in the production of extremely pure metal by distillation in vacuo or in an inert gas.

(2) HEAT OF FUSION.—The heat of fusion of magnesium, or the heat absorbed in converting a unit weight of the metal from solid to liquid at the melting point without changing the temperature is 70.0 gram-calories per gram of metal, as determined by Roos (103e).

(3) HEAT OF VAPORIZATION.—The heat of vaporization, or the quantity of heat in calories absorbed in converting a unit weight of magnesium from a liquid state to a gas without changing the temperature, is 1,700 gram-calories per gram of metal, as determined by Nuesceleanu (103g).

(4) SPECIFIC HEAT.—The specific heat of magnesium, or that quantity of heat, in calories, necessary to raise 1 gram of a given substance through 1° C., over several ranges of temperature is given in Table 102.

TABLE 102.—*Mean specific heat of magnesium*

Temperature (°C.)	Specific heat	Authority	Temperature (°C.)	Specific heat	Authority
−190 to +17	0.2046	Schimpff (103h).	0	0.2456	Jones (100c).
	.2090	Behn (103l).	15 to 100	.248	Flusin (100o), Guillet (100m).
−85 to +20	.2220	Nordmeyer and Bemouli (103nn).		.246	Maybrey (100j).
−79 to +17	.2284	Schimpff.	20	.222	Gaillard (100l).
	.2311	Brunner (103i).	20 to 100	.2492	Stucker (103k).
	.2330	Behn.	20 to 350	.2808	
−17 to +100	.2495	Brunner.	20 to 650	.32996	
	.2460	Voight (103m).			

The mean specific heat of magnesium from 0° to any temperature is expressed by Stucker (103k) in the equation:

$$C_{(o-t)} = 0.2372 + 0.000093t + 0.000000685t^2$$

where t is expressed in degrees centigrade. Behn (103l) gives the following equation for the mean specific heat between any two temperatures, t_1 and t_2:

$$Ct_1t_2 = 0.232 + 0.000112(t_1 + t_2) - 0.000000423(t_1^2 - t_1t_2 + t_2^2)$$

The true specific heat, or the limiting value of the ratio of the increase in total internal heat of a unit mass of a substance, divided by the change in temperature thus produced, as the increase in temperature becomes infinitely small, is calculated by Behn and Schimpff from observed values of the mean specific heat over various temperature intervals. The equations are:

$$\frac{dq}{dt} = 0.232 + 0.000224t - 0.0^5 1270t^2 \text{ (Behn)}$$

and

$$\frac{dq}{dt} = 0.241455 + 0.0002058996(t - 17) - 0.0000010884(t - 17)^2$$

(Schimpff), when q represents the total interval heat of a unit mass of the substance, $\frac{dq}{dt}$ represents the true specific heat, and t the temperature in degrees centigrade.

Calculated values for the true specific heat of magnesium are given in the table below:

TABLE 103.—*True specific heat of magnesium*

Temperature (°C.)	Specific heat	Authority	Temperature (°C.)	Specific heat	Authority
−150	0.1767	Schimpff (103h).	100	0.2525	Schubel.
−100	.2025	Do.	200	.2627	Do.
−50	.2228	Do.	300	.2728	Do.
0	.2376	Do.	400	.2815	Do.
50	.2471	Do.	500	.2884	Do.
50	.2460	Schubel (103f).	625	.4352	Stucker.
60	.2492	Stucker (103k).			

(5) Linear Expansion.—The coefficient of linear expansion, or the ratio of the increase in length per degree rise in temperature to the dimension at zero degrees Centigrade may be expressed by the equation (applicable between −63 and +300° C.)

$$L_t = L_0(1 + 25.03t \times 10^{-6} + 0.00892t^2 \times 10^{-6}$$

The instantaneous coefficient a_t at any temperature t is given by

$$a_t = 23.909 \times 10^{-6} + 0.01784(t + 62.7)10^{-6}$$

(Hidnert (103o)).

The coefficient of expansion as measured at the Bureau of Standards is 25.9×10^{-6} from 0−100° C., and 25.7×10^{-6} at 40° C.

(6) Thermal Conductivity.—The thermal conductivity of magnesium, or the amount of heat in gram-calories transmitted through a cube 1 cm thick and 1 cm² in area, when the difference in temperature between the faces is 1° C., is given in Table 104.

Table 104.—*Thermal conductivity of magnesium*

Temperature (°C.)	Conductivity	Authority
0 to 100	0.376	Lorenz (103p).
101 to 250	.35	Williams.
18	.376	Jones (100c), Gaillard (100l).
	.34	Archbutt (100b).
	.38	Flusin (100o), Maybrey (100j).
		Guillet (100n).

8. OPTICAL PROPERTIES, REFLECTING POWER

The reflecting power of magnesium has been given by Coblentz (103j) as follows:

Table 105.—*Reflecting power of magnesium*

Wave length (μ)	Reflecting power
	Per cent
0.5	72
.6	73
.8	74
1.0	74
2.0	77
4.0	84
7.0	91

Both indices of refraction of magnesium are less than 0.5 in the range of wave lengths which has been studied (103b).

9. ELECTRICAL CONDUCTIVITY, RESISTIVITY

Pure magnesium has a volume conductivity equal to 38.6 per cent of copper. The mass conductivity is 197.7 per cent of copper. The specific resistivity of magnesium (or the resistance of a centimeter cube of the material) as determined by the Aluminum Co. of America are given below:

TABLE 106.—*Specific resistivity of magnesium*

Description	Specific resistivity at 20° C.
1. Magnesium, extruded, 99.99 per cent	4.4611×10^{-6} ohms/cm^3.
2. Magnesium, extruded, 99.95 per cent	4.4699×10^{-6}.
3. Magnesium, extruded, 99.90 per cent	4.4774×10^{-6}.
Magnesium-aluminum alloys: [1]	
96 per cent Mg+4 per cent Al	10.712×10^{-6}.
90 per cent Mg+10 per cent Al	16.661×10^{-6}.
90 per cent Al+8 per cent Mg+2 per cent Ni	7.72×10^{-6}.

[1] Determined by Northrup.

The volume conductivity compared with copper, mass resistivity, mass conductivity, and specific resistivity are given below:

TABLE 107.—*Conductivity and resistivity of magnesium*

VOLUME CONDUCTIVITY COMPARED WITH COPPER

	Copper standard
	Per cent
International annealed copper standard	100.00
Magnesium, extruded, 99.99 per cent	38.65
Magnesium, extruded, 99.95 per cent	38.57
Magnesium, extruded, 99.90 per cent	38.51

MASS RESISTIVITY OF MAGNESIUM, ALUMINUM, AND COPPER

	Copper standard
International annealed copper standard	0.15328 ohm (meter-gram).
Magnesium, 99.99 per cent	.07753 ohm (meter-gram).
Magnesium, 99.95 per cent	.07768 ohm (meter-gram).
Magnesium, 99.90 per cent	.07780 ohm (meter-gram).
Aluminum, conductor grade	.07640 ohm (meter-gram).

MASS CONDUCTIVITY OF MAGNESIUM, ALUMINUM, AND COPPER

	Copper standard
	Per cent
International annealed copper standard	100.00
Magnesium, 99.99 per cent	197.71
Magnesium, 99.95 per cent	197.33
Magnesium, 99.90 per cent	197.01
Aluminum, conductor grade	200.70

Temperature (°C.)	Resistivity	Authority
	μ/cm ^{3}	
−183	1.00	Dewar.
−78	2.97	Do.
0	4.35	Do.
98.5	5.99	Do.
400	11.90	Nicolai.

10. MECHANICAL PROPERTIES

The mechanical properties of pure magnesium as given by the American Magnesium Corporation are to be seen in Table 108.

TABLE 108.—*Mechanical properties of pure magnesium*

Density		Process of manufacture	Condition or heat treatment	Tensile strength	Per cent elongation in 2 inches	Per cent reduction of area	Proportional limit	Pounds per square inch for ¼ per cent extension under load	Compressive strength	Shear strength	Hardness	
Grams per cubic centimeter	Pounds per cubic inch										Brinell hardness 500 kg load, 10 mm ball	Shore scleroscope
				Lbs./in.²			*Lbs./in.²*		*Lbs./in.²*	*Lbs./in.²*		
1.739	0.0629	Casting (sand)	As cast	13,000	6	6	500	3,000	32,000	14,000	30	20
		Extrusion	As extruded	28,000	8	8	1,000	6,500	45,000	16,000	35	23
		Rolling (sheet)	As rolled	25,000	4	5	2,500	9,500	------	14,000	40	31
		Rolling (sheet)	Annealed	25,000	5	6	2,000	9,000	------	14,000	33	27
		Rolling [1] (rod)	As rolled	30,000 to 35,000	2 to 12½	------	3,500 to 6,000					
			Annealed at 350° C.	31,000	------	6½	Very low or none.					

[1] These data from Archbutt and Jenkins.

Pure magnesium has an extremely low proportional limit, and one of the important features to be considered in the choice of alloying elements is their effect on the proportional limit. Cold working improves the proportional limit.

The modulus of elasticity is also low, even the stronger alloys having a modulus of only 5 to 6 million lbs./in.^{2} against 10 million for aluminum and 30 million for steel.

11. APPLICATIONS

The density of pure magnesium is slightly less than two-thirds that of aluminum. Its selling price in ingot form varies between twice and three times that of aluminum on a weight basis, or, say, 50 per cent higher than that of aluminum on a volume basis. One producer states that the present cost is largely regulated by the relatively small output, and that production figures are in sight which may allow the sale of magnesium at a price equal to that of aluminum on a volume basis and that it is not impossible that in the future it may even compete on a weight basis.

At present the price advantage between the metals in ingot form is in favor of aluminum and is greater in the fabricated or partly fabricated condition than in the ingot because of small production plus the difficulties of fabrication. Unless some other property of magnesium brings other advantages than merely that of a slightly greater reduction of weight, aluminum alloys will be chosen under present prices for many ordinary uses, because magnesium has a somewhat greater need for protection against atmospheric corrosion, especially under salt-water conditions, and because it is attacked by organic acids. On the other hand, were aluminum not available, magnesium would be used in many of the important uses for which the former now holds the field.

No magnesium alloys are known whose mechanical properties can be brought up to those of duralumin or other heat treatable aluminum base alloys, and the availability of duralumin again limits the probable applications of the magnesium base alloys, since on a strength-weight basis the best magnesium alloys are but slightly better than duralumin.

When a given volume is essential rather than a minimum section, the advantage may be on the side of the magnesium alloys, and with further development of the alloys greater use, especially in aircraft, is expected.

For widespread commercial utilization of magnesium, applications must be found for which its various unique properties fit it, even in competition with aluminum and duralumin. The endurance properties of some of the alloys (p. 279) and their relative freedom from warping and distortion point out certain applications in aeronautical work and in production of accurate jigs and fixtures. A peculiar sonorous quality makes it applicable in certain types of automobile horns. It also finds application in some wet and dry current rectifiers.

(a) MINOR ALLOYING

An important use is as a minor but essential constituent of duralumin and certain other heat treatable aluminum base alloys.

(b) DEOXIDATION

Another large use for magnesium continues to be the deoxidizing or desulphurizing of other metals, particularly nickel amd Monel metal (100e). This field is gradually broadening as the cost of magnesium decreases. Magnesium has also been used in the deoxidation and desulphurization of copper, and a considerable quantity is used for scavenging low-grade scrap brass. Still further application is in the zinc-base die-casting alloys.

Magnesium has a greater affinity for oxygen than has any other common metal (100q). When magnesium does not alloy with the metal, mechanical agitation is desirable to bring the molten magnesium or magnesium vapor in contact with all parts of the melt. Where it does alloy readily with the metal to be deoxidized it is most successfully introduced by adding an alloy of proper proportions.

(c) POWDER

The rapidity with which finely divided magnesium removes the combined oxygen from salts such as nitrates, chlorates, and peroxides, and the high temperatures instantly effective for expanding the volumes of released gases, makes magnesium important as a constituent of explosives (100q).

(d) PHOTOGRAPHY

The flame of burning magnesium is unique in that 75 per cent of the total heat of combustion is emitted as radiant energy (100q). The light rays are of high actinic power; the spectum of burning magnesium is, in the violet, ten times as brilliant as a gas flame of equal luminous intensity, and in the yellow it surpasses the brilliancy of the electric arc. These properties make magnesium an important source of light in photography. A powder of 100 mesh and finer mixed with salts rich in oxygen is used. Uses somewhat allied to that as flash-light powder are in flare shells and tracer bullets.

(e) OTHER APPLICATIONS

Magnesium also finds use in organic synthesis as a dehydrating agent, as a cathode in electrolysis, and in thermit reactions. Magnesium-alloy castings are used for aircraft motor parts, including crank cases, oil pans, fuel-line fittings, pistons, supercharger parts, and instrument cases; also for lens holders, field glasses, parts of moving-picture machines, receivers and transmitters for radio sets, artificial limbs, motor-cycle engine parts, shuttles, bobbins, spools for weaving machinery, rotating parts of air compressors and vacuum pumps, gasoline-line and carburetor fittings, railway-signal instrument parts, and balloon-valve frames. Pistons, golf-club heads, and similar pieces are cast in permanent molds. Small flat forgings or pressed parts, such as diaphragm resonators, are also produced.

Magnesium sheet has been produced suitable for experimental development in the following uses: Moving parts of precision instruments, celluloid-covered drafting rulers, meter disks, scale pointers, chemical-balance parts, hydrofluoric-acid containers, dry-battery elements, speedometer parts, metal buttons, and portable drafting tables (100e). The principal requirement in the production of satisfactory sheet metal is an ingot free from flaws, which in turn involves special melting and alloying equipment and careful regulation of temperature. Magnesium wire has been largely used in the development of vacuum bulbs for radio work. The wire is raised to its melting point inside the bulb and eliminates the last traces of oxygen and nitrogen by chemically combining with them.

II. TECHNOLOGY

1. SOLDERING AND WELDING MAGNESIUM

Magnesium is subject to rapid surface oxidation, as is aluminum, and is electronegative to the low melting point metals ordinarily used in solders (100q). The surface of magnesium may be tinned, the molten tin being rubbed on with a wire brush, forming an alloy. The treated surfaces are then sweated together. Soldered joints should be protected; otherwise the magnesium will corrode.

Magnesium may be welded, but requires special technique because of the rapid oxidation. A flux is used that removes the surface deposit and serves as a covering that permits the flow of molten metal without burning (100q).

2. WORKING MAGNESIUM

(a) EFFECT OF WORKING AND TEMPERATURE ON MAGNESIUM

Magnesium hardens very rapidly with cold working. At normal temperatures the work hardening is permanent and can be eliminated only by heating. From 350 to 450° C. magnesium is quite plastic and deformation at this temperature can be carried on without hardening. In fabrication of magnesium the working temperature should approximate 350° C.

(b) HOT PRESSING

The flow of magnesium on hot pressing is similar to aluminum, except that in the case of magnesium a gradually increasing pressure is preferable to a sharp blow.

(c) FORGING

Magnesium can not be forged by the ordinary processes with cold metal and tools, the metal cracking along parallel planes of cleavage. Further cold work results in complete shattering. The forging may be accomplished most successfully when the blank is made roughly to the dimension of the die, with an excess of thickness. The metal is heated so that a single application of pressure is enough to fill the die completely before the heat of the metal is lowered sufficiently to cause cracking.

(d) SPINNING

Magnesium can not be spun by the ordinary processes owing to the rapid hardening of the material with cold work. Annealing the metal does not change its crystalline character, and mere heating of the metal gives no substantial improvement. When the metal, the chuck, and the tool are heated to the temperature range within which magnesium becomes plastic, a flow of metal is possible.

(e) DRAWING

Drawing offers the same difficulties as spinning. The collar, punch, and die of the press may be heated within the temperature range necessary for the metal to become plastic. This process is not as yet fully worked out.

(f) MACHINING

Magnesium is readily machined. The metal does not tear, there is no drag on the cutting edges of a tool, and a higher speed may be used than with brass. Carbon-steel tools may be used. Lubrication is unnecessary on any ordinary machining operation. In screw-machine work a mixture of lard oil and kerosene will prevent any possible overheating of the work.

(g) GRINDING

Magnesium may be readily ground, lubrication with kerosene or water being necessary to prevent clogging of the wheel.

3. SURFACE FINISH

Magnesium takes a high polish with a buffing wheel. A mat surface may be obtained either by acid dipping or by use of a scratch brush. It may be painted or lacquered, a bitumastic solution being a fairly stable protection against salt water and spar varnish or Bakelite varnish against sea water and mild acids.

Magnesium may be electroplated, the best results being obtained with alkaline, neutral, or cyanide solutions. The surface is prepared by sand blasting, and may then be plated with copper, silver, zinc, brass (100q). Just as with aluminum it is difficult to secure electrodeposited coatings that are really adherent.

It is stated that heating under pressure in the presence of, and above the boiling point of, water produces a surface coating that gives substantial protection (100u).

4. CASTING MAGNESIUM AND ITS ALLOYS

Magnesium requires special care in the foundry because of its rapid oxidation near and above its melting point, and because its extreme lightness causes a tendency to trap air and gases. Pure magnesium is more difficult to handle than most of its alloys (100q). The commercial magnesium-base alloys have lower melting points than the pure metal, and therefore do not oxidize as readily. Not only does the rapidity of oxidation decrease with temperatures but the start and spread of burning is checked by a lower temperature of the molten metal.

In casting magnesium the molds are thoroughly baked to eliminate water. A thin solution of water glass may be sprayed on the face of the mold before baking. The mold should be rammed lightly, vented freely, and poured rapidly. Cores must be baked free from moisture and should crush easily. A binder, such as water glass, should be used that will not give off gases when in contact with hot metal.

In order to avoid the use of dry sand molds, sand may be tempered with glycerine or ethylene glycol instead of water and the sand so tempered used for green sand molds (100x). The use of boric acid (100v, w) or of sulphur in green sand molds is also said to allow the avoidance of dry sand molds.

Magnesium may be melted in iron or mild steel pots which do not contain appreciable percentages of nickel. Air should be excluded as much as possible either by melting in a partial vacuum under inert gas or in a pot having a tightly fitting cover, the latter method being the most practical. The furnace should be either of a tilting or a bottom tap type.

Sufficient metal is charged in the beginning to complete the molds, as no metal should be charged after melting down. The melt is tapped as soon as it has reached the proper temperature. Some foundry men consider use of fluxes is inadvisable on the ground that they tend to mix with the metal and cause faulty castings. Others (100y) consider melting under a flux as a better and more practical method of excluding air. The flux is skimmed back and the metal may be dipped out by a hand ladle, with, it is claimed, complete separation of metal and flux if the proper flux is used.

Archbutt and Jenkin (100s) tried a mixture of 72 parts anhydrous magnesium chloride, 28 parts magnesium fluoride, but abandoned its use in favor of one of 68 parts anhydrous magnesium chloride, 24½ parts potassium chloride, 4½ parts sodium fluoride, 3 parts calcium fluoride.

The first was viscous enough to be held back in pouring, but did not always form a perfect cover; the second was sufficiently fluid, but it was difficult to skim it back so as to prevent it entering the mold with the metal.

In general, the temperature of the metal in the furnace should range from 650 to 690° C. A safe holding temperature and one suitable for casting is 670° C. The lowest possible casting temperature should always be used.

Magnesium lends itself readily to casting in permanent iron molds or in iron molds with a sand core. The physical properties of a chill casting are better than those of a corresponding sand casting.

(a) DIE CASTING

Experiments have proved that magnesium will flow freely and fill a heated die. Owing to the reaction of air with molten magnesium, the process will probably be developed in connection with the use of a plunger type of pressure machine rather than by compressed air.

III. MAGNESIUM ALLOYS

1. MAGNESIUM-ALUMINUM

The most important alloys of magnesium are those with aluminum. The equilibrium diagram is shown on page 115. The various equilibrium diagrams for other alloys have been collected in the Handbook of the American Magnesium Corporation.

In the high-magnesium range, the alloys generally considered preferable are those having 4 to 12 per cent aluminum (100f). The mechanical properties of the 4, 6, 8, 10, and 12 per cent aluminum alloys as given by the American Magnesium Corporation (100q) are shown in Table 109.

The last alloy in the table is a 4 per cent aluminum alloy with the addition of 0.4 per cent manganese which the American Magnesium Corporation has recently advocated as combining superior average corrosion-resisting properties with maximum mechanical properties consistent with minimum foundry and fabrication difficulties.

Attention is called to the proportional-limit figures in this table. Much data on magnesium alloys, especially from foreign sources, evades or omits to bring out the fact that these low proportional limits exist, a matter which may or may not be important in engineering design depending on the structure in question, but which, if neglected in an application where it is important, may be serious.

TABLE 109.—*Mechanical properties of magnesium-aluminum alloys*

[As reported by American Magnesium Corporation]

Composition	Density		Process of manufacture	Condition or heat treatment	Tensile strength	Elongation in 2 inches	Reduction of area	Proportional limit	Pounds per square inch for ¼ per cent extension under load	Compressive strength	Shear strength	Hardness	
	Grams per cubic centimeter	Pounds per cubic inch										Brinell 500 kg load 10 mm ball	Shore scleroscope
					Lbs./in.^{2}	Per cent	Per cent	Lbs./in.^{2}		Lbs./in.^{2}	Lbs./in.^{2}		
96 per cent Mg, 4 per cent Al	1.767	0.0638	Casting (sand)	As cast	25,000	9	8	2,500	7,000	45,000	17,000	42	25
			Extrusion	As extruded	36,000	20	33	3,000	11,000	52,000	19,000	48	28
			Rolling (sheet)	As rolled	41,000	8.5	10	7,500	10,500		19,000	61	38
			do	Annealed	34,000	16	15	3,000	8,500		19,000	46	32
94 per cent Mg, 6 per cent Al	1.780	.0643	Casting (sand)	As cast	24,000	7	7	2,000	8,500	46,000	18,000	46	28
			do	Heat treat SP	25,000	5	5	2,500	9,000	46,000	20,000	50	31
			Extrusion	As extruded	41,000	16	21	5,500	15,000	58,000	22,000	54	32
			do	Heat treat SP	41,000	10	10	8,000	14,500	58,000	22,000	53	31
			Rolling (sheet)	As rolled	46,000	3	5	5,000	14,500		22,000	75	43
			do	Annealed	38,000	9.5	9	4,000	11,500		19,000	52	30
92 per cent Mg, 8 per cent Al	1.790	.0647	Casting (sand)	As cast	20,000	2	2	2,000	9,000	45,000	18,000	53	31
			do	Heat treat S	27,000	5	5	3,000	8,500	47,000	20,000	52	31
			do	Heat treat SP	30,000	1	1	5,000	12,000	53,000	22,000	73	43
			Extrusion	As extruded	46,000	9	12	10,500	15,500	61,000	22,000	59	37
			do	Heat treat SP	47,000	4	4	8,000	15,000	64,000	23,000	68	38
			Rolling (sheet)	As rolled	46,000	7	7	11,000	15,000		22,000	69	40
			do	Annealed	41,000	8.5	8	5,000	14,000		19,000	54	31
90 per cent Mg, 10 per cent Al.	1.806	.0652	Casting (sand)	As cast	19,000	1	1	2,500	10,000	49,000	19,000	57	33
			do	Heat treat S	23,000	2.5	3	3,500	9,000	48,000	21,000	55	29
			do	Heat treat SP	27,000	1	1	10,000	13,000	53,000	25,000	76	43
			Extrusion	As extruded	47,000	8	10	7,000	14,000	66,000	24,000	68	38
			do	Heat treat SP	55,000	2	2	9,000	15,000	62,000	24,000	83	50
			Rolling (sheet)	As rolled	48,000	5	5	4,000	13,000		21,000	71	41
			do	Annealed	44,000	3.5	3.5	7,000	14,500		21,000	70	40
88 per cent Mg, 12 per cent Al.	1.820	.0657	Casting (sand)	As cast	19,000	0.5	None.	4,500	11,000	47,000	18,000	65	44
			do	Heat treat S	24,000	1	1	4,500	10,000	49,000	21,000	64	43
			do	Heat treat SP	31,000	0.5	None.	12,000	16,000	56,000	22,000	94	64
			Extrusion	As extruded	45,000	7.5	8	10,500	15,000	72,000	24,000	71	46
			do	Heat treat SP	45,000	1	1	13,000	16,500	67,000	27,000	90	55
			Rolling (sheet)	As rolled	53,000	3	2	16,000	16,000		24,000	81	47
			do	Annealed	45,000	3	3	8,000	15,500		22,000	82	47
95.6 per cent Mg, 4 per cent Al, 0.4 per cent Mn.[1] Type A. M. 4.4.	1.77	.064	Casting (sand)	As cast	20–26,000	4–8.5	4–8.5	2–4,000	[2]7.5–8,000			[3] 53	
			Extrusion	As extruded	38–42,000	16–18	22–28	6–8,000	[2]18–22,000			[3] 60	
			Rolling (hot)	As hot rolled, ¼ to 1/16 inch thick.	33–38,000	16–18	16–18					[3] 56	
			Rolling (cold)	As cold rolled, 24 B. & S. gauge.	42–44,000	5–8	6–10					[3] 62	
			do	Annealed, 24 B. & S. gauge.	37–42,000	20–26	22–28					[3] 54	
			Forging	As forged	31–34,000	5–18	5–14	3–6,000	[2]18–20,000			[3] 60	

[1] 0.35 to 0.45 per cent Mn.

[2] Stress at which stress-strain curve deviates 0.1 per cent of the gauge length from line of proportionality.

[3] 1/16-inch ball, 12.61 kg load.

Archbutt and Jenkins (100s) tested the 6 per cent aluminum alloy in commercial hot-rolled rod and on an experimental lot. They obtained:

TABLE 110.—*Mechanical properties of the magnesium alloy with 6 per cent aluminum*

	Commercial 1	Commercial 2	Experimental as rolled	Experimental annealed at 350° C.	
				5 hours	100 hours
Tensile strength .... lbs./in.^{2}	52,000	41,000	40,500	38,500	37,000
Proportional limit .... do	----------	----------	5,500	5,500	4,000
Elongation in 2 inches .... per cent	3.50	11	19	15	12.50
Reduction of area .... do	4	17	----------	----------	----------

The variations are doubtless due to variations in finishing temperatures, giving different amounts of cold work.

The thermal conductivity of the alloys are given by the American Magnesium Corporation and Aitchison (105c) as follows:

TABLE 111.—*Thermal conductivity of alloys with aluminum*

	Temperature	K (calories)
	° *C.*	
4 per cent Al, 96 per cent Mg	106–250	0.17
6 per cent Al	Not stated.	.18(105c)
8 per cent Al, 92 per cent Mg	106–250	.17
11 per cent Al	Not stated.	.211(105c)
12 per cent Al, 88 per cent Mg	110–250	.15

The volume resistivity is given below:

	Specific resistivity at 20° C.
96 per cent Mg, 4 per cent Al	10.712×10^{-6}
90 per cent Mg, 10 per cent Al	16.661×10^{-6}

Aitchison (105c) gives the tensile strength of the cast 11 per cent aluminum alloy at 250° C. as 12,500 lbs./in.^{2} and at 350° C. as 10,300 lbs./in.^{2}. The mass strength or $\frac{\text{maximum stress}}{\text{specific gravity}}$ of the alloy at the same temperatures is 6,900 lbs./in.^{2} and 5,600 lbs./in.^{2}, respectively.

The effect of the addition of aluminum (as well as of Ni, Cu, and Zn) on the tensile properties of magnesium is shown in Figures 108 to 114. As will be seen by comparison of Tables 109 and 112 with Figure 108, Archbutt's data, which indicate that the tensile strength is less in the alloy with 4 per cent aluminum than in the pure metal, are not corroborated by other available data. It is generally considered that the addition of up to 4 per cent aluminum increases the tensile strength, elongation, and hardness. Above 4 per cent aluminum further addition increases the tensile strength and hardness, but at the expense of the elongation. Beyond 10 per cent aluminum both tensile strength and elongation are reduced,

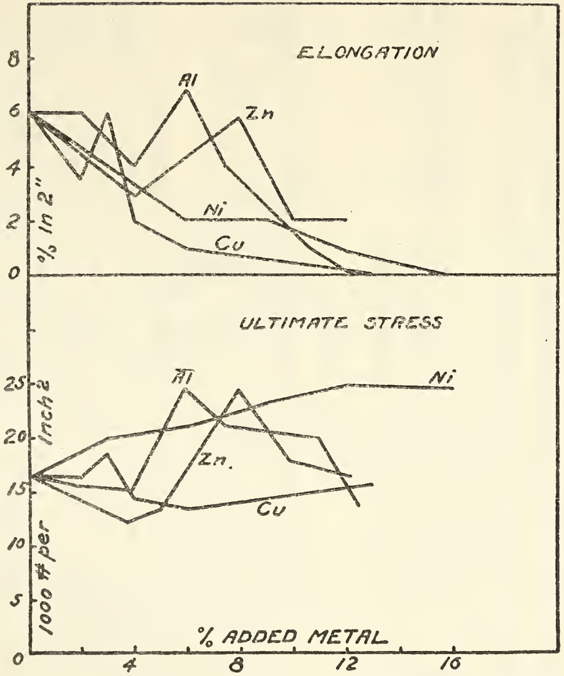

FIG. 108.—*Effect of increasing percentages of added elements on the elongation and ultimate stress of magnesium. (Archbutt 105d)*

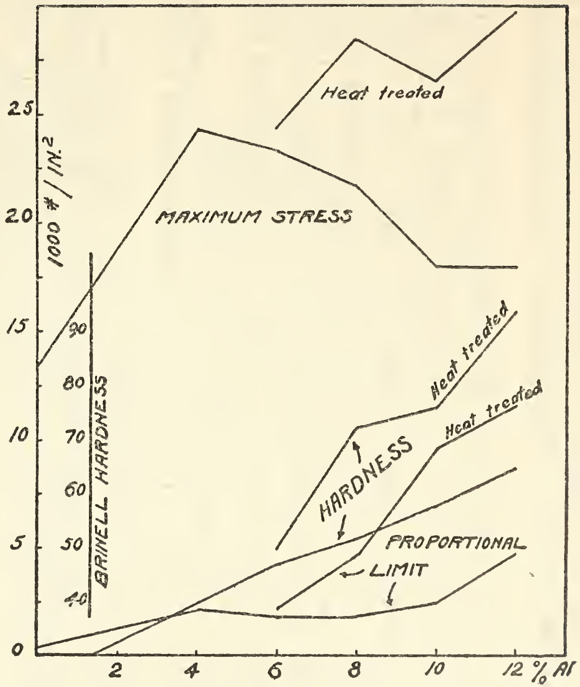

FIG. 109.—*Variation of properties of magnesium with percentage of aluminum in sand-cast aluminum-magnesium alloys. (Archbutt, 105d)*

but hardness increases. The addition of aluminum also markedly increases the proportional limit. These facts are brought out in Figure 110, after Gann (109a). The addition of 0.1 per cent Mn to magnesium-base aluminum alloys increases the proportional limit materially.

The effect of heat treatment and mechanical treatment on the magnesium-aluminum alloys is to increase the strength of the alloy and shift the position of maximum tensile strength toward higher aluminum contents. Compare Figure 111 with 112 and Figure 113 with 114. The hardness of the 12 per cent aluminum alloy is raised from 65 to 79 for the sand-cast alloy and from 80 to 100 for the chill cast by heating two hours at 430° C., quenching in water, and reheating four hours at 170° C. (107a). The alloy did not show any change on aging at room temperature for seven days.

Neither Mg nor Mg-base Al alloys yield readily to cold bending. The 4 per cent Al alloys will bend without cracking around a radius of about three times the thickness of the sheet.

These alloys are used for casting purposes when toughness is desired. The 4 to 8 per cent aluminum will give the best results; when hardness is desired the heat-treated 12 per cent aluminum alloy is best; for worked metal with good physical properties and working qualities the 4 to 6 per cent aluminum alloy is superior.

2. DOW METAL

Dow metal is used by the manufacturers as a generic term for a series of magnesium-base alloys containing aluminum or copper as the chief alloying elements (100f, k).

The properties of these alloys as stated by the manufacturers are given in Table 112. Data for the older alloy "A" (8 per cent aluminum) are taken from Gann's paper (109a).

3. ELECTRON

Electron is a German term for magnesium-base alloys containing small percentages of (1 or more of) aluminum, zinc, copper, manganese. The composition of the electron alloys varies widely and in most cases the compositions are not available.

Much of the comment on these alloys in the literature is of so general a character that it gives little real information, mechanical properties being claimed without statement of composition or degree of mechanical working. Some of the earlier electron alloys for casting purposes contained 5 to 6 per cent of alloying elements, both zinc and aluminum being used in varying proportions. These appear to be designated by the symbol "AZ." In the cast form these appear to have the same general order of strength as the 4 per cent aluminum alloys of Tables 109 and 112, but rather lower elongation. Few

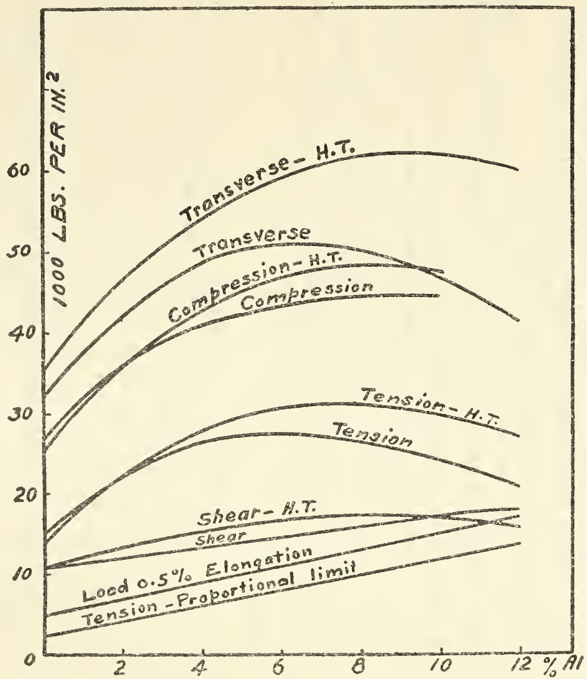

FIG. 110.—*Mechanical properties of magnesium-aluminum alloys.* (*Gann, 109a*)

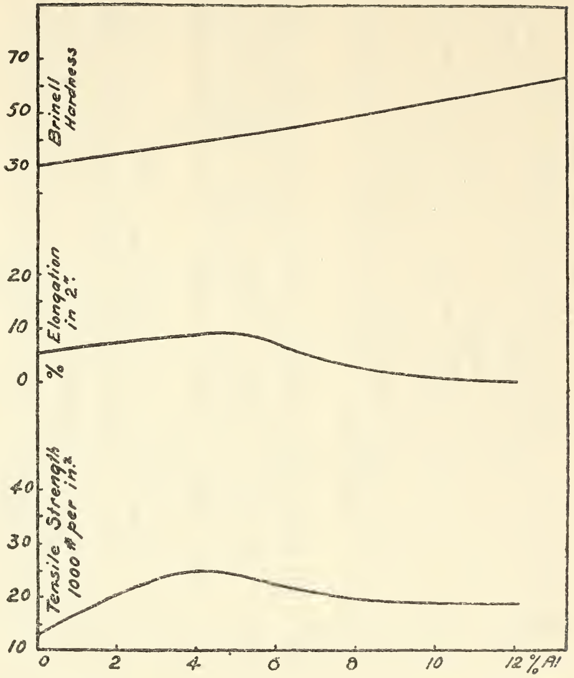

FIG. 111.—*Mechanical properties of magnesium-aluminum alloys as cast.* (*American Magnesium Corporation, 100q*)

data have been found giving both chemical composition and mechanical properties. Beckinsale (110b) examined three specimens of rod 0.31 inch diameter thought to have been extruded. They contained about 0.5 per cent copper and 4.5 per cent zinc, and showed 36,000 to 41,000 lbs./in.^{2} tensile strength, 13 to 19 per cent elongation in 0.64 inch (test pieces 0.18 inch diameter). In compression test of 0.31 inch diameter cylinders of equal length, the crushing strength was about 39,000 lbs./in.^{2}. The stress at a compression of 0.5 per cent with load on varied from about 6,700 to 18,500 lbs./in.^{2} and the permanent reduction in length at a load of 22,400 lbs./in.^{2} varied from 1 to 4 per cent.

Archbutt and Jenken (100s) studied a rod of commercial electron which contained 4.38 per cent zinc, 0.22 per cent copper, 0.15 per cent aluminum, 0.14 per cent silicon. This gave 40,000 lbs./in.^{2} tensile strength, and 11,000 proportional limit, 15 per cent elongation, 19 per cent reduction of area.

Anderson (110a) gives data for extruded rod "Z1" containing 5 per cent zinc and a trace of copper which showed tensile strength of 36,500 to 39,500 lbs./in.^{2}, elongation of 17.5 to 22.5 per cent, and reduction of area of 20 to 30 per cent. The proportional limit varied from 6,000 to 13,000 lbs./in.^{2}.

The "V1" alloy, containing 10 per cent aluminum and a trace of copper, was claimed by the maker to have a proportional limit of 24,000 lbs./in.^{2}. Anderson found that the proportional limit was 10,900 lbs./in.^{2}. Even this figure is higher than that indicated for extruded material of this composition in Table 109.

The shape of the stress-strain diagram for these magnesium alloys is of such shape that the sensitivity of the extensometer used plays a controlling part in the magnitude of the values recorded for proportional limit. The yield point, likewise, depends on the arbitrary conditions chosen for the test. Figures for proportional limit and yield point from different observers are seldom directly comparable, and any indication of superiority on the basis of such tests must be viewed with suspicion unless the tests of each alloy were made under identical conditions.

The other values reported by Anderson for the extruded 10 per cent aluminum or "V1" alloy are tensile strength 47,500 lbs./in.^{2}, elongation 13 per cent, reduction of area 12 per cent. He also gives for annealed sheet of 10 per cent aluminum and 4 per cent aluminum content, respectively, 47,500 and 33,500 lbs./in.^{2} tensile strength, 11,000 and 10,500 lbs./in.^{2} proportional limit, 13 and 17 per cent elongation. Anderson also reported on an alloy "AZM" containing 5 per cent aluminum, 3 per cent zinc, and 1 per cent manganese, which, as extruded, gave 13,500 lbs./in.^{2} proportional limit, 49,000 lbs./in.^{2} tensile strength, and 16½ per cent reduction of area.

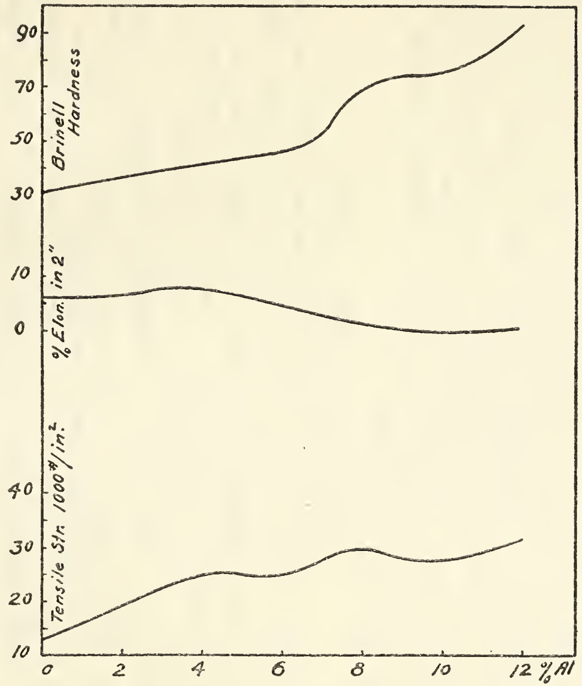

FIG. 112.—*Mechanical properties of magnesium-aluminum alloys cast, quenched, and aged. (American Magnesium Corporation, 100q)*

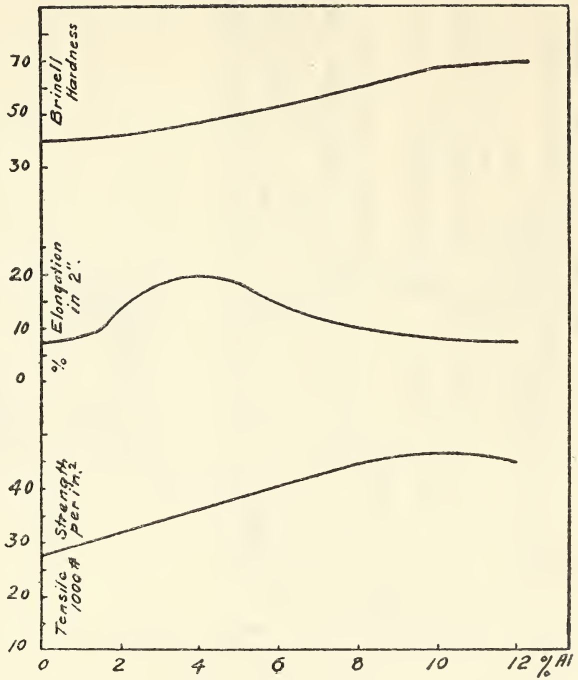

FIG. 113.—*Mechanical properties of magnesium-aluminum alloys as extruded. (American Magnesium Corporation, 100q)*

The effect of relatively large amounts of manganese is shown by tests reported by Anderson on alloys containing 96 per cent magnesium, 4 per cent aluminum, and 95 per cent magnesium, 4 per cent aluminum, and 1 per cent manganese, each rolled to sheet 0.012 inch thick and presumably annealed. The tensile strengths were, respectively, 33,500 and 28,500 lbs./in.^{2}, elongations 15 and 5 per cent, and proportional limits 10,500 and 11,500 lbs./in.^{2}. The effect of manganese upon the proportional limit seems to be less marked in annealed than in cold-worked material.

Electron alloys take on a protective film of oxide in air (100p), are not readily flammable (100l), may be soldered (103b), and may be worked and forged between 220 to 350° C. (103o). The AZ casting alloys have a shrinkage of about 1.1 per cent and are brittle above 500° C. (100g). The thermal expansion of electron is given by Disch, as follows:

Temperature range, ° C.	Average coefficient of expansion per degree centigrade, $\times 10^{-6}$
0 to 100	28.4
100 to 200	28.7
200 to 300	29.1

The material does not tend to absorb oxygen and nitrogen while in the molten condition (100o). Electron is said to be unaffected by rain water (103a), alkalines, gasoline, benzine, oils, and fats free from acids (100g), but is susceptible to acids, even organic (103c), salt solutions, or chlorides and sulphates of heavy metals and ammonia salts of river waters (103a, 100g). Electron finds use in the optical automotive, electrical, textile, and aircraft industries, for die castings, and other purposes (100g).

4. MAGNESIUM-COPPER ALLOYS

These alloys have found limited application abroad as piston alloys (100m). The strength of the 13 per cent copper alloy at moderately high temperatures is said to be higher than that of the 4 per cent aluminum alloy (100a). Cook and Jones (106d) studied the properties of copper-magnesium alloys containing 1.15 to 9.84 per cent copper. The effect of increasing percentages of copper on ultimate stress, reduction of area, and elongation are shown in Figure 115. The specific gravity of the alloys increased from 1.759 for the 1.15 per cent copper alloy to 1.871 for the 9.84 per cent copper alloy. Increasing the amount of copper caused a corresponding increase in hardness. These results show that the copper-magnesium alloys do not harden on aging. The alloys machine without difficulty, and there was little appreciable difference in the behavior of the alloys.

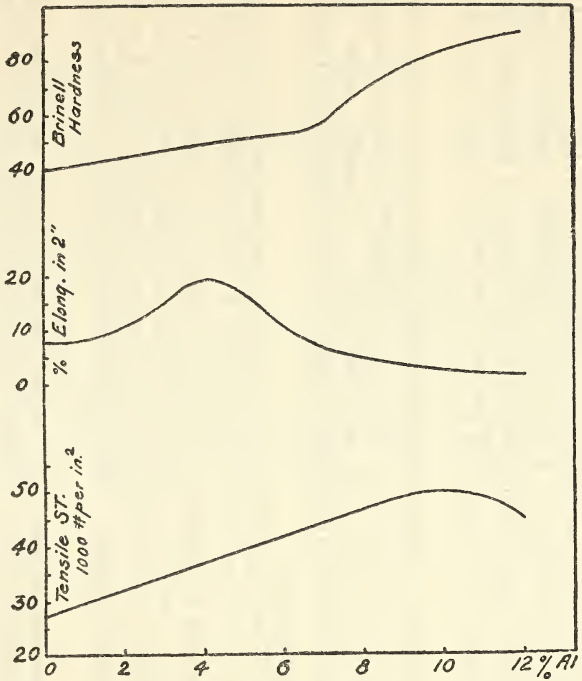

Fig. 114.—*Mechanical properties of magnesium-aluminum alloys extruded, quenched, and aged. (American Magnesium Corporation, 100q)*

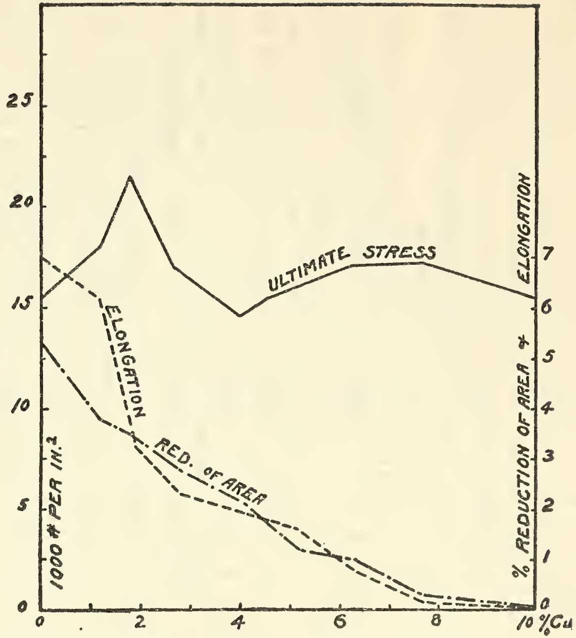

Fig. 115.—*Effect of addition of copper on the mechanical properties of magnesium. (Cook and Jones, 106d)*

Hansen (106a) also found no perceptible change of hardness on aging at room temperature in alloys of copper 5.83 to 15.44 per cent quenched from 450° C. Hansen attributes this as possibly due to the fact that the atomic mobility is sufficiently great to permit the compound to precipitate in the form of microscopical particles during quenching, slow cooling causing these particles to coagulate to larger ones, accompanied by a small decrease in hardness and a considerable decrease in elongation and reduction of area.

Cook and Jones (106d) give figures for the properties of chill castings ranging from 1.15 to 7.69 per cent copper as: Proportional limit 3,500 to 7,000 lbs./in.^{2}, ultimate stress 16,500 to 17,500 lbs./in.^{2}, elongation 7.0 to 0.2 per cent, reduction of area 5.4 to 0.3 per cent, while values given for the copper-magnesium alloys as given by other authors (100b, j, h) show a specific gravity of 1.77 to 1.90 from 2 to 13 per cent copper, thermal conductivity 0.34 for the 3 per cent copper alloy and 0.308 to 0.32 for the 13 per cent copper alloy, casting shrinkage 0.14 inch per foot for the 3 per cent copper alloy, and 0.15 inch per foot for the 13 per cent copper alloy. Brinell hardness numbers given by Cook and Jones for the 0.23 to 15.44 per cent copper alloys vary from 39 to 60 for the quenched alloys, and from 35.5 to 54.0 for the slowly cooled alloys. The strength of the 13 per cent copper at room temperature is 35,500 lbs./in.^{2}, elongation 3 inches, and reduction of area 2.77 per cent; at 400° F., about 9,000 lbs./in.^{2} higher than that of magnesium.

Archbutt and Jenken (100s) have studied commercial rolled rod of 3 and 13 per cent copper. These gave, respectively, tensile strength, lbs./in.^{2} 33,000 and 39,000; proportional limit, not determined and 7,000; elongation 4.50 and 2.50 per cent; reduction of area 5 and 2.50 per cent.

While the high thermal conductivity of magnesium alloys with copper has led to interest in them as automotive pistons, the poor mechanical properties, and especially their extremely rapid corrosion under normal atmospheric conditions, make them of little commercial importance.

Hansen (106a) finds Mg_2Cu is soluble in magnesium to the extent of about 0.4 to 0.5 per cent copper at 485° C., the solubility decreasing with decreasing temperature to about 0.1 per cent copper, and hence that solution quenching and precipitation hardening is possible in this alloy. He also gives the mechanical properties of alloys with 6, 8, 10, and 15 per cent copper. The alloys also contained 0.1 to 0.2 per cent silicon.

A magnesium-copper alloy with the addition of aluminum and cadmium (see alloy "T") Table 112, which may be used in the cast or forged condition, is preferred in this country for pistons, and is considered by its makers to be the most successful magnesium alloy yet developed for the purpose.

TABLE 112.—*Properties of magnesium alloys ("Dow metals")*

[As reported by Dow Chemical Co.]

Composition						Commercial designations	Density	Condition	Tensile strength	Elongation in 2 inches	Yield point [1]	Compressive strength	Hardness		Impact [2]	Impact fatigue,[3] 4-pound blow	2½-pound blow	1-pound blow	Melting point	Thermal conductivity
Mg	Al	Mn	Cu	Cd	Zn								Brinell 500-kg 10-mm ball	Scleroscope						
									Lbs./in.²	*Per cent*	*Lbs./in.²*	*Lbs./in.²*							*° F.*	
99.9	------	------	------	------	------	------	1.74	As cast	14,000	5	4,000	25,000	38	20	77	610	1,600	4,400	1,204	0.38
								Forged	30,000	7	19,000	43,000	40	17	104	1,000	2,600	22,000	------	------
Balance.	4.0	0.3	------	------	------	"F"	1.76	As cast	24,000	8	9,000	40,000	48	22	56	600	3,000	16,000	1,160	.23
								Forged	38,000	16	22,000	48,000	54	23	------	1,300	5,000	38,000	------	------
Balance.	6.0	.25	------	------	------	"E"	1.78	As cast	26,000	7	11,000	43,000	52	24	50	580	2,400	11,000	1,135	.21
								Forged	42,000	11	27,000	52,000	58	27	114	2,400	10,000	130,000	------	------
Balance.	2.0	.15	4.0	2.0	------	"T"	1.82	As cast	21,000	3	13,000	40,000	45	22	32	400	2,300	23,000	1,185	.30
Balance.	8.5	.15	2.0	1.0	0.5	"D"	1.84	do	22,000	2	14,000	45,000	58	28	23	190	2,500	35,000	1,100	.18
Balance.	8.0	------	------	------	------	"A"	1.80	do	25,000	4	12,500	44,000	55	------	------	------	------	------	1,139	.20

[1] Yield point taken as load at 0.5 per cent elongation of gauge length under load.

[2] Dow impact test. Figures comparable among themselves. See Warwick, C. L., Résumé of American practice in notched bar impact tests of metals. Proc. A. S. T. M., **22** (2), p. 78; 1922.

[3] Eden-Foster machine, test specimen not described. Figures comparable among themselves.

5. MAGNESIUM-CADMIUM ALLOYS

The 1 per cent Cd alloy is suitable for rolling, extruding, forging. The properties of this alloy are given by Aitchison (103c) as follows:

TABLE 113.—*Mechanical properties of magnesium-cadmium alloys*

Condition	Elastic limit	Proof stress	Maximum stress	Elongation	Reduction of area
	Lbs./in.^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Per cent*	*Per cent*
Cast bar	2,700	6,500	9,900	3.5 ($4\sqrt{A}$)	3.1
Forged bar	----------	25,500	31,500	5.0 ($3\sqrt{A}$)	6.9
Rolled strip	13,000	25,000	26,000	1.0 (2 inches)	----------
	13,000	25,000	25,500	.75 (2 inches)	----------
Extruded rod	----------	----------	26,000	----------	----------
	----------	----------	21,500	----------	----------

6. MAGNESIUM-NICKEL ALLOYS

Aitchison (100h) gives the properties of magnesium-nickel alloys as follows:

TABLE 114.—*Mechanical properties of magnesium-nickel alloys*

Nickel (per cent)	Maximum stress	Elongation in 2 inches	Specific gravity
	Lbs./in.^{2}	*Per cent*	
3	19,500	4	1.78
6	21,000	2	1.82
9	23,500	2	1.86
12	24,500	1	1.90
16	24,000	0	1.94
20	25,000	0	1.97

7. MAGNESIUM-ZINC ALLOYS

Stoughton and Miyake (106c) give the following properties for the magnesium-zinc alloys:

TABLE 115.—*Mechanical properties of magnesium-zinc alloys*

Zinc (per cent)	Maximum stress	Specific gravity	Zinc (per cent)	Maximum stress	Specific gravity
	Lbs./in.^{2}			*Lbs./in.*^{2}	
4	12,300	1.78	9	21,300	1.85
5	13,500	1.79	10	18,000	1.87
6	17,200	1.81	11	17,200	1.89
7	21,000	1.82	12	16,600	1.91
8	25,000	1.84			

Values for the strength of these alloys as given by Aitchison (100h) are somewhat lower. A $\frac{13}{16}$-inch chill-cast bar of 3 per cent zinc alloy has a yield point of 11,200 to 12,200 lbs./in.^{2}, maximum stress 27,800 to 24,000 lbs./in.^{2}, elongation 4 to 6 per cent, Brinell 36 to 39 (103c). The forged bar had a yield point of 26,400 lbs./in.^{2}, maximum stress 28,400 lbs./in.^{2}, elongation 1.5 per cent, Brinell 38. The alloy did not forge well. It is easily corroded.

The mechanical properties of magnesium-zinc alloys may be improved by heat treatment, Stoughton and Miyake stating that the alloys may be hardened materially by quenching from a temperature below the solidus, followed by reheating to a temperature higher than room temperature (artificial aging). The effect is especially great in high-zinc chill-cast alloys.

8. GENERAL COMMENT

Accurate data on the properties and behavior of magnesium alloys in commercial production from other sources than the producers of magnesium itself are scarce, and, hence, many of the data given above for the various alloys are not so thoroughly checked up as is the case with the more common alloys of aluminum. Much of the published data from foreign sources are given for "Elektron," and as that term covers a range of alloys of various compositions, such information is of little definite value.

The low proportional limit and the tendency toward corrosion of magnesium have had to be remedied in order to make its alloys applicable to many engineering uses. Much has been done along both lines so that these drawbacks are somewhat under control. The good endurance properties, which are discussed on pages 279 to 281, offer a counterbalancing advantage over some of the aluminum alloys for some uses. The question whether combined corrosion and repeated stress will, in practice, minimize this apparent advantage over aluminum alloys can not yet be answered, as no work on corrosion fatigue of magnesium alloys has so far been reported.

The Army Air Service specification No. 11301 for Magnesium Alloy Castings, is as follows:

United States Army Air Service, No. 11301. Any composition containing not less than 85 per cent magnesium shall be acceptable, provided the manufacturer states the composition he intends using and the chemical requirements he can maintain.

The specific gravity of this alloy shall not exceed 1.85.

This alloy shall have the following physical properties:

Tensile strength (minimum)	lbs./in.^{2}	20, 000
Elongation in 2 inches (minimum)	per cent	4
Brinell hardness (500 kg)		40–50

IV. SILICON, BERYLLIUM, AND THEIR ALLOYS

Aluminum and magnesium are both ductile and capable of being wrought, even when not very pure. These light metals therefore early came into use in wrought form. Two other light metals—silicon and beryllium—would have, were they ductile, possibilities not exceeded by those of aluminum and magnesium, since the specific gravities of the metals are, aluminum 2.68, silicon 2.34±, beryllium 1.84±, magnesium 1.74. The atomic weights are, beryllium 9.02, magnesium 24.32, aluminum 26.97, silicon 28.06. Silicon and beryllium are both very resistant to atmospheric corrosion and to attack by many chemical reagents. Their melting points are much higher than those of the ductile metals, the order being silicon 1,420 ± 15° C., beryllium 1,280 to 1,300° C., aluminum 660° C., magnesium 651° C. Silicon is volatile at temperatures above its melting point, and this fact has to be taken into account in electric smelting of the metal. The actual boiling point is not known; estimates range from those of Mott (111g) at 1,600 to 1,800° C. to those of Zimmerman at 2,000 to 2,500° C.

Light high-melting metals resistant to corrosion are, however, of little industrial use in the pure state unless they can be wrought or at least cast. Silicon, even in purest form, such as that prepared at the National Physical Laboratory by Tucker (111a) by chemical purification of the commercial metal, is brittle, and no method of fabrication hot or cold, other than casting, has been found possible. While attempts have been made (111i) to develop cast silicon vessels for chemical use, its brittleness has made it so unpromising that in spite of the widespread distribution of very pure silica that would serve as ore and of the comparative ease of preparation by smelting silica with carbon or carborundum in an electric furnace (111p), silicon to-day finds use as a pure metal chiefly as electrode in wet or dry electrolytic rectifiers. In attempting to make castings the use of a slag on the metal to avoid oxidation and the avoidance of too high a solicon content are advisable. Castings with 85 to 88 per cent silicon are made with less difficulty than those of higher silicon content. Silicon also serves as a source of hydrogen, since it reacts with caustic soda to give hydrogen and sodium silicate (111h).

The production of ferrosilicon is large and of fundamental importance in the steel industry, but discussion of ferrosilicon has no place in a description of light alloys. Calcium-silicon and other alloys of silicon intended for use as deoxidizers are on the market.

In similar fashion to the use of aluminum as a reducing agent in the thermit reaction, the high heat of oxidation of silicon, given as 6,400 to 7,600 calories per gram (111n, m, o), makes it suitable for use as a metallurgical reducing agent (111f, 113a, b). A multitude of patents for processes of manufacture of various chromium alloys and "stainless steels" involve as one step the reduction of chromium oxide by silicon. In such uses extreme purity of the silicon is required only when its impurities would be detrimental in the alloy to be produced.

Beryllium also has a high heat of oxidation, about 14,500 to 15,000 calories per gram (112i, j, k), but is still too expensive for use as a reducing agent.

Silicon is peculiar among metals in that its temperature coefficient of electrical resistance may change sign in some temperature range, the exact behavior varying with the impurities. At red heats, the resistance changes in such fashion that it was at one time planned by Weintraub (113c) to use graphite or tungsten rods coated with silicon to make a resistor which would have the same resistance regardless of temperature, the change in resistance of the silicon with temperature being calculated to balance that of the other material. While this plan did not succeed, cast silicon resistors were tried in experimental use (111e) and the fact established that oxidation of the metal is slow even at high temperatures because of the protective oxide coating which forms.

Some attempts have been made to utilize silicon or ferrosilicon as a coating (111b, c, d), to give corrosion-resisting properties to the surface of another metal or alloy and, in a finely crushed state, as a pigment.

None of these actual or suggested applications, however, depend primarily upon the low specific gravity of the metal. In its applications to light alloys, the chief use and a very large one, of silicon is in the aluminum silicon casting alloys which have been described on page 170 and for addition in case the aluminum used does not carry a sufficient amount of silicon in itself, to alloys of the duralumin type which are hardened in whole or in part by the precipitation of magnesium silicide during aging, as described on page 238.

As the detrimental action of iron upon some of the aluminum alloys has become better known, and the fact that the iron could be brought into a form less harmful to these alloys by causing it to combine into complex iron-aluminum-silicon compounds (see p. 240), a small use of pure silicon has developed for addition to commercial aluminum in order to raise the silicon content to the proper amount to balance or control the iron content when such control is desirable on account of the use to which the aluminum is to be put.

Obviously for such uses the silicon should be as free as possible from iron. Hence, the purity is controlled, first by selection of raw material, and second by a refining process which presumably consists of chemical treatment after crushing to dissolve undesirable impurities, followed by remelting, along the general lines described by Tucker (111a). A complete analysis of a typical commercial silicon is—

	Per cent		Per cent
Silicon	92.42	Manganese	0.05
Iron	4.24	Phosphorus	.025
Silicon carbide	.41	Titanium	.15
Aluminum	1.48	Sulphur	.02
Calcium	.02	Copper	Trace.
Magnesium	.04		

One lot of a higher grade showed 94.5 per cent silicon, 2.8 per cent iron, and 1.7 per cent aluminum.

Treatment of silicon 90 to 95 per cent pure with hydrofluoric acid followed by remelting the purified material produces refined silicon such as is used for making aluminum-silicon alloys.

Commercial silicon, before refining, may contain as main impurities about 8 per cent iron, 2 per cent aluminum in the 90 per cent grade used for generation of hydrogen (111h), and in the 95 per cent grade, about 5 per cent iron plus aluminum (111f).

Refined commercial silicon contains 98 per cent or higher silicon, the chief impurities being up to about 0.7 per cent iron, up to about 0.6 per cent aluminum and up to about 0.4 per cent calcium.

Tucker produced metal of 99.94 per cent purity containing only 0.02 per cent each of iron and aluminum, about 0.01 per cent calcium and a trace of nonmetallics.

The physical properties of material of this last grade have not been fully described. Many properties, such as are given in previous sections of this circular for aluminum and magnesium, can only be satisfactorily determined upon wrought metals. This and the knowledge that the mechanical brittleness of the material would bar it from most industrial uses, account for the lack of accurate data upon the pure material.

In its uses for alloying with aluminum the low specific gravity of silicon is an advantage. The commercial aluminum silicon alloys are lighter than aluminum itself.

The alloys of silicon have been studied to some extent (111k, l), the more recent work being chiefly on the magnesium silicon system in connection with Mg_2Si and its behavior in duralumin. Nothing of commercial promise seems to have been found in the binary systems.

The possibilities in light alloys which might consist of a high percentage of silicon and a small one of some heavy metal, may not have been exhausted, but, in general, the brittleness of silicon is not destroyed in such combinations. Hence, the story of the light silicon alloys is a short one to date, and there seems to be no immediate likelihood of the development of such alloys.

Beryllium, or glucinum as it is sometimes called, has approximately the same specific gravity as magnesium. Hence, one does not look to alloys of beryllium because of exceptional lightness, but because of the possibility of other useful properties. Although beryllium has been described by some writers as a ductile metal, this statement can not yet be accepted as correct. Metallic beryllium, manufactured by the Beryllium Corporation of America, has been upon the American market for a year or so at a price of about $200 a pound, in purity of around 98.7 per cent, the chief impurities being about 1.1 per cent iron, 0.20 per cent barium, and a little silicon. The density of this material is 1.86 g/cm^3. This material is far from ductile in the cold. It is, instead, coarsely crystalline, reminding one of antimony or bismuth, is hard and brittle, and apparently incapable of being wrought cold.

Metal more recently produced is said to be better than 99.5 per cent pure, with about 0.2 per cent iron and 0.1 per cent silicon. Some lots are semimalleable cold, and can be rolled hot into thin sheet.

Cooper[8] states that it is expected to be possible to lower the price to not far from $50 per pound in the near future, and that in the more distant future, with the development of a market for large quantities, substantial reductions from this figure may be looked for.

Stock and coworkers (112g) and Hopkins and Meyer (112h) studied the preparation of the metal, while Burgess (112f) discussed other methods. Vivian (112e) has prepared beryllium by electrolysis of sodium beryllium fluoride plus barium fluoride, quite analogous to the methods used for production of aluminum and magnesium, and has made metal of 99.8 per cent, or better, purity. The impurities are ordinarily iron, carbon, aluminum, and magnesium, each in amounts approximating 0.05 per cent. Nitrogen is present to about 0.005 per cent. Some material practically free from carbon and with only about 0.02 per cent iron has been produced by sublimation in a vacuum. Analytical difficulties prevent accurate statement of the purity obtained, but all Vivian's products were brittle, and had a Brinell number of 90 to 112.

Cooper[8] states that while the process of Stock and Goldschmidt is one of the outstanding developments in the history of beryllium, operation at about 1,300° C. with molten fluoride is difficult because of the corrosive action of the fluoride and the loss by volatilization. He says that in the Cooper process (not described) the voltage required is but 5 to 6, the temperatures low and yields high, better than 80 per cent even in the present stage of development.

Uyman (114a) has claimed that beryllium, even when quite impure, can be drawn down to fine wire, and Corson (112d) also claims it to be ductile. It is probable that with proper methods hot working of the pure metal can be done.

The pure wrought metal would be interesting because of the claim by Negru (112l) that the metal has very high electrical conductivity. A study of the thermal and electrical conductivity of beryllium is under way at Cornell University, but results are not yet available. Cooper[8] states that the electrical conductivity is 18 μ per cc or about the same as that of lead. Bassett (112a) has found that small amounts of beryllium strengthen copper, with relatively little reduction in the electrical conductivity of the copper so that, with sufficient beryllium available at a price that would allow its use, electrical conductors of superior properties might be produced. The modulus of elasticity of beryllium, and, hence, of the alloys high in beryllium,

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[8] H. C. Cooper, personal communication.

is expected to be high. According to Corson (112d) the modulus of the pure material may be higher that that of steel.

Another interesting property is the coefficient of thermal expansion. Tests at the Bureau of Standards (112b) also—Hidnert and Sweeney (112m)—upon cast material of the commercial grade, probably about 98.9 per cent, and having a density of 1.835 at 20° C., indicate the expansion coefficient to be about the same as that of cast iron (see Table 116). Could the casting and machining difficulties be overcome and the price be brought down to a point where the material could be used, a light piston for automotive engines might be produced which might have advantages over present light alloy pistons.

TABLE 116.—*Coefficients of thermal expansion of impure metallic beryllium*

Temperature range (° C.)	Coefficient expansion
	$\times 10^{-3}$
−100− 50	7.0
−120+ 20	8.1
− 50+ 20	9.8
+ 20 100	12.3
+ 20 200	13.3
+ 20 300	14.0
+ 20 400	14.8
+ 20 500	15.5
+ 20 600	16.1
+ 20 700	16.8

The melting and casting of beryllium is not easy, but by melting with a flux of 90 per cent barium chloride and 10 per cent barium fluoride it is possible to handle such melts in fairly satisfactory fashion, although experience is required.

Alloys of silver and beryllium have been claimed to resist tarnish, but experiments at the Bureau of Standards (112m, n) have not substantiated this claim.

Both Corson (112d) and Kroll (112n, o) suggest that beryllium might serve in duralumin, either as an inhibitor of grain growth or as a magnesium beryllide or beryllium silicide precipitable on aging after quenching, but Kroll's data on such alloys (p. 247) indicate no advantage over ordinary duralumin. Cooper [9] expects increased resistance to salt-water corrosion and better physical properties. No proof of the value of beryllium in duralumin has yet been adduced.

Corson (112d) claims that it is difficult to alloy more than a few per cent of beryllium with aluminum. This is obviously incorrect. Kroll (112p) has made and rolled to sheet an alloy with 20 per cent beryllium. Alloys up to about 50 per cent beryllium are being tested for thermal expansion at the Bureau of Standards and will be reported on later; and it is reported that an alloy of 70 per cent beryllium and 30 per cent aluminum, rolled to very thin sheet, is being studied for its possibilities as a diaphragm for a radio loud speaker. It is said that this hard-rolled 70 per cent beryllium alloy, in thin sheet, has a

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[9] H. C. Cooper, personal communication.

tensile strength of about 100,000 lbs./in.^{2} in the direction of rolling, but only about 70,000 lbs./in.^{2} in the transverse direction. This is said to have a specific gravity of 2 and to be unaffected by salt water. An alloy of 90 per cent beryllium 10 per cent aluminum has been rolled.

Kroll (112p) gives the following for a series of aluminum-beryllium alloys rolled to sheet and annealed at 420° C. The alloys contain about 0.10 per cent silicon as impurity, besides iron.

TABLE 117.—*Mechanical properties of aluminum-beryllium alloys in sheet form (Kroll, 112p)*

Beryllium	Iron	Tensile strength	Elongation
Per cent	*Per cent*	*Lbs./in.^{2}*	*Per cent*
None.	0. 25	9, 500	22½
0. 30	. 40	11, 000	34½
1. 30	. 45	12, 500	29
2. 06	. 55	13, 000	30½
6. 06	. 84	16, 500	33
9. 87	2. 70	17, 000	36
20. 23	1. 35	23, 000	39

Webster (58a) reports a tensile strength of 26,500 lbs./in.^{2} and an elongation of 10 per cent for an aluminum alloy with 2 per cent beryllium.

Kroll (112.) does not see much future in beryllium or the aluminum-beryllium alloys, stating that beryllium is more of a metalloid than a metal and that it greatly resembles silicon. He even states that, in whatever way alloyed with light metals, it is doubtful if it has properties that silicon does not equally possess. He says, "A good deal of the confidence with which beryllium was regarded either as a metal for use in construction or for its properties on being alloyed with aluminum or magnesium, has already proved misplaced."

Cooper (personal communication) states that there is no parallel at all between the alloying action of silicon and that of beryllium with aluminum and feels that the industrial future of beryllium lies in the development of the beryllium-aluminum alloys.

Kroll estimates that the cost of production could hardly be reduced in the near future, at least, to less than about $45 a pound.

The ores of beryllium would be gadolinite and beryl, more probably the latter, which contains, in the crystalline beryl, free from gangue, only around 5 per cent of the element itself and which must be separated from the impurities of the ore by tedious and costly chemical processes. Beryl is not a very rare mineral, and were uses found for the metal to justify mining the mineral where it is now found and prospecting for other deposits sufficient ore deposits could presumably be located to provide for a considerable supply of the metal. Nevertheless, the scarcity of the ore in comparison to the sources of aluminum and magnesium, the low metallic content of the ore, the certainly greater difficulties in purification, and the probably greater difficulties in electrolytic reduction to metal, made it obvious that whatever the future price of the metal may be it will always, as far as one can predict, be essentially much more costly than the other light metals.

In view of the great scarcity of accurate data upon the properties of beryllium and its alloys and because of the relatively small amount of scientific work being done upon them, no definite idea can yet be had as to whether or not beryllium and its alloys will find commercial use. No immediate large-scale use seems probable, yet the chances of securing the pure metal or its alloys in usable form and with properties quite different from most other light alloys seem good enough to justify brief mention of a few of the scanty data so far published on them, because any alloy of unusual or unique properties is likely to be of service for some application or other.

Data on the average coefficients of expansion of beryllium and aluminum-beryllium alloys and chemical analyses and densities of beryllium and aluminum-beryllium alloys are given in Tables 118 and 119.

TABLE 118.—*Résumé of average coefficients of expansion of beryllium and aluminum-beryllium alloys*

Material	Average coefficients of expansion per degree centigrade				
	20 to 100° C.	20 to 200° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.
	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
Beryllium (98.9 per cent)	12.3	13.3	14.0	14.8	15.5
Aluminum-beryllium alloy (4.2 per cent beryllium)	22.2	23.2	24.4	25.1	26.5
Aluminum-beryllium alloy (10.1 per cent beryllium)	21.4	22.5	23.3	24.1	25.4
Aluminum-beryllium alloy (18.6 per cent beryllium)	20.0	20.8	22.1	23.0	24.0
Aluminum-beryllium alloy (27.5 per cent beryllium)	18.8	19.8	21.1	22.0	23.0
Aluminum-beryllium alloy (32.7 per cent beryllium)	17.9	19.2	20.6	21.3	22.3

TABLE 119.—*Chemical analyses and densities of beryllium and aluminum-beryllium alloys* [1]

Sample	Material	Chemical analyses [2]						Density [3] in g/cm [3] at 20° C.
		Aluminum	Beryllium	Silicon	Copper	Iron	Manganese	
		Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
1223 [4]	Beryllium [5]	(6)	98.9	0.18	0.06	0.90	0.20	1.835
1224	Aluminum-beryllium alloy	66.3	32.7	.11	.09	.84	.06	2.225
1225	do	71.9	27.5	.10	.08	.58	.05	2.202
1226	do	81.0	18.6	.12	.11	.36	.05	2.242
1227	do	89.7	10.1	.12	.09	.19	.01	2.401
1228	do	95.7	4.2	.10	.10	.12	.01	2.416

[1] The chemical analyses and the densities were determined after the expansion measurements were made on the samples.

[2] Determined by J. A. Scherrer, of this bureau. Magnesium, calcium, lead, zinc, nickel, and selenium were not detected.

[3] Determined by Miss E. E. Hill, of the volumetric section of this bureau.

[4] Dr. W. F. Meggers, of this bureau, made a spectrochemical analysis of this sample by means of its spark spectrum. The following additional impurities were found: Chromium, selenium, aluminum, magnesium, calcium, silver (trace), and bismuth (doubtful).

[5] The electrical resistivity of this rod of beryllium was found to be 10.2 microhm-cm at 21.5° C. by Dr. F. Wenner, of this bureau. Assuming the resistivity temperature coefficient to be 0.004 per degree C., the resistivity at 20° C. is 10.1 microhm-cm. The value given is probably not in error by as much as 5 per cent.

[6] Not detected.

V. APPENDIX

A. DEFINITIONS OF PHYSICAL TERMS

Absorption index.—When monochromatic light traverses a distance equal to its own wave length, λ, in a material the ratio of the amplitude of the emergent J'_λ to that of the entering light, $J_\lambda{}^\circ$, is

$$\frac{J_\lambda{}'}{J_\lambda{}^\circ}=e^{-2\pi\kappa}$$

when κ is the absorption index.

(A variety of usage prevails regarding the definition of this term. This definition is used in the Smithsonian physical tables.)

Density.—The density of a substance is the mass per unit volume. It is usually expressed in terms of grams per cubic centimeter.

Electrical conductivity and resistivity (χ, ρ).—There are two methods of expressing electrical resistivity in common use, each being defined quantitatively in terms of the resistance of a unit specimen. The volume resistivity is ρ in the equation

$$R=\frac{\rho l}{s}$$

in which R = resistance, l = length, and s = cross section. The volume resistivity thus defined may be expressed in various units, such as microhm-cm (microhm per centimeter cube), ohms per foot of a uniform wire 1 mil in diameter, etc. The commonly used units, in abbreviated terminology, are:

microhm-cm.
microhm-inch.
ohm (meter, mm).
ohm (meter, mm^2).
ohm (mil, foot).

The other kind of resistivity is mass resistivity, and is defined as δ in the equation

$$R=\frac{\delta l^2}{m}$$

in which m = mass of the wire. The usual units of mass resistivity are:

ohm (meter, gram).
ohm (mile, pound).

Per cent conductivity.—The term "conductivity" means the reciprocal of resistivity, but it is used very little in wire calculations. In connection with copper, however, extensive use is made of the per cent conductivity, which is calculated in practice by dividing the resistivity of the International Annealed Copper Standard at 20° C.(×100) by the resistivity of the sample at 20° C.

Temperature coefficient of resistance.—The temperature coefficient of electrical resistance is the fractional change of resistance per degree change of temperature. Its value varies with the temperature, and hence the temperature from which the resistance change is measured must always be stated or understood. For a temperature t_1, the temperature coefficient t_1 is defined, for a metal like copper, by

$$R_t = R_{t_1}[1 + \alpha_{t_1}(t - t_1)],$$

in which R_{t_1} = resistance at the temperature t_1 and R_t = resistance at any other temperature t. The temperature coefficient that is usually used at 20°, for example, is

$$\alpha_{20} = \frac{R_t - R_{20}}{R_{20}(t-20)}.$$

Boiling point.—The boiling point of a liquid is the temperature at which it boils under atmospheric pressure, or better the temperature at which its vapor pressure is equal to the external pressure.

Brinell test.—An indentation is made, by pressure, on a polished plane surface of the material, by using a hardened steel ball. There are several ways of expressing the hardness:

The most common definition of the Brinell hardness is the pressure in kilograms per unit area (square millimeters) of the spherical indentation. (Hardness numeral = H. N.)

$$\text{H. N.} = \frac{\text{Pressure}}{\text{area of spherical indentation}} = \frac{P}{t\pi D}$$

where

$$t = D/_2 - \sqrt{D^2/_4 - d^2/_4}$$

P = pressure used,
t = depth of indentation,
D = diameter of sphere,
d = diameter of indentation.

Electrolytic solution potential (E).—At the junction of a metal and any conducting liquid there is developed an electrical potential, which is a measure of the free energy change of the chemical reaction which is possible at the surface of the metal liquid. In particular if the chemical reaction consists in the solution of the metal, forming ions, the e.m.f. is given by the formula.

$$E=\frac{RT}{nF}\log_e\frac{P}{p}$$

R = the gas constant,
T = absolute temperature,
n = valence of metal,
F = 96,500 coulombs, the Faraday constant,
P = solution pressure of metal,
p = osmotic pressure of metal ion formed in solution.

In any electrolytic cell the sum or difference of two such potentials is measured, one of which may be a standard electrode; for example, the hydrogen or the calomel electrode. The e. m. f. of an electrolytic cell of the following type: Metal–solution–normal hydrogen electrode is often called the single potential (e_h) for the metal in the solution; that is, the e. m. f. of the normal hydrogen electrode is taken as the zero of reference. These potentials are expressed in terms of the potential of the metal with respect to the solution. Thus, the normal potential of zinc/zinc ions is -0.76 volt and of copper/cupric ions is $+0.34$ volt.

Emissivity (E *or* E_λ).—The coefficient of emissivity E for any material represents the ratio $\frac{J'_\lambda}{J_\lambda}$ of the intensity, J'_λ, of radiation of some particular wave length or color, λ, emitted by the material at an absolute temperature T to that, J_λ, emitted by a black body radiator at the same temperature.

The coefficient of total emissivity E for any material represents that ratio $\frac{J_1}{J}$ of the intensity of radiation of all wave lengths, J_1, emitted by the material at an absolute temperature, T, to that, J, emitted by a black body radiator at the same temperature.

This coefficient is always less than 1, and for metals is equal to 1 minus the reflection coefficient for normal incidence (Kirchhoff's law).

For any optical pyrometer using monochromatic light a value of the observed or "black body" temperature of any substance (not inclosed) is reduced to the true temperature by the following formula:

$$\frac{1}{T}-\frac{1}{T_0}=\frac{\lambda\log 10\,E_\lambda}{6232}$$

T = true absolute temperature,
T_0 = observed absolute temperature,
λ = wave length in microhm (0.001 mm),
E_λ = relative emissivity of substance for wave length.

Erichsen test.—This test is carried out to determine the ductility of sheets. An indentation is made in the sheet with a die with hemispherical end. The greatest depth of indentation which can be made without incipient cracking of the sheet, measured in inches or millimeters, is known as the Erichsen value for the sheet.

Heat of fusion.—The heat of fusion of a substance is the quantity of heat absorbed in the transformation of unit mass (1 g) of the solid substance to the liquid state at the same temperature.

Magnetic properties.—The usual magnetic characteristics of a substance are given either by the permeability, μ, or the susceptibility, κ. Permeability is the ratio of the magnetic induction (B: in maxwells per square centimeter) to the magnetizing force (H: in gilberts per centimeter). This is indicated by the relation

$$\mu=\frac{B}{H}$$

Susceptibility is given, in corresponding units, by

$$\kappa=\frac{\mu-1}{4\pi}$$

For all materials except iron and a few other ferromagnetic metals μ is very nearly unity and κ is only a small decimal. When κ is negative in sign the substance is diamagnetic. The susceptibility as thus defined is sometimes called volume susceptibility and indicated by κ_v. A quantity called mass susceptibility is also used, and is equal to the volume susceptibility divided by the density of the material; it is represented by κ_m.

Melting point.—The melting or fusing point of a substance is the temperature at which it fuses (under atmospheric pressure), or, more accurately, the temperature at which the solid and the liquid substance are in equilibrium with each other.

Peltier effect (π).—When at the junction of two metals current flows from one to the other, heat is, in general, absorbed or liberated (see "thermoelectromotive force" below); the coefficient, the amount of heat liberated when a unit quantity of electricity flows across the junction, is known as π (measured either in calories per coulomb, or in volts), the Peltier effect.

Refractive index.—The ratio of the velocity of light in vacuum to that in any material is called the refractive index (η) of that material. (This physical quantity ceases to have a meaning at or near an absorption band in the material.)

Scleroscope test (*Shore*).—A hardened hammer falls from a constant height onto a polished surface of the material, and the distance of rebound is measured on a scale 10 inches long, divided into 140 equal parts. The scleroscope hardness is expressed as the distance of rebound on this arbitrary scale, the value 100 representing the hardness on this scale of hardened (martensitic) steel.

Specific heat (σ).—The true specific heat of a substance is $\frac{du}{dt}$ when u is the total internal heat or energy of unit mass of the substance. The mean specific heat is defined as $\frac{q}{t_1-t_2}$ per unit mass when q is the quantity of heat absorbed during a temperature change from t_2 to t_1. It is generally considered as the quantity of heat (calories) required to raise the temperature of unit mass (grams) by unity (degrees centigrade), either at constant volume or at constant pressure. Unless otherwise noted the specific heat of solids refers to that at constant (atmospheric) pressure. The true specific heat (constant pressure) of metals may usually be expressed sufficiently by an equation of the type

$$\sigma = A + Bt + (Ct^2 \ldots\ldots)$$

Tension test.—The quantities in the tension test are the following:

The *ultimate tensile strength* is the maximum load per unit area of original cross section borne by the material.

The "*yield point*" (American Society for Testing Materials) is the load per unit of original cross section at which a marked increase in the deformation of the specimen occurs without increase of load. Without further definition, "yield point" is a vague value upon alloys of the class described in this circular. There is no true yield point comparable to that found in mild steel. In commercial testing of aluminum alloys yield point is usually taken as the stress at which a given extension occurs under load, the extension being chosen so as to lie somewhere on the knee of the stress-strain curve. The extension chosen varies with the experimenter and the equipment he has available. Yield-point values cited from various sources in this circular are only roughly intercomparable because of failure of most investigators to report in sufficient detail the exact criterion chosen for yield point. (See p. 64.)

The *elastic limit* (American Society for Testing Materials) is the greatest load per unit of original cross section which does not produce a permanent set.

It is seldom determined on aluminum alloys. Values given for it in the literature usually refer to some yield point well above the true elastic limit.

The *proportional limit* (American Society for Testing Materials) is the load per unit of original cross section at which the deformations cease to be directly proportional to the loads.

The *percentage elongation* is the ratio of the increase of length at rupture between arbitrary points on the specimens to the original length between these points.

The *percentage reduction of area* is the ratio of the decrease of cross section at the "neck" or most reduced section when ruptured, to the original section.

Thermal conductivity (λ).—The coefficient of thermal conductivity (λ) expresses the quantity of heat (small calories) which flows in unit time (seconds) across a unit cube (centimeter) of the material whose opposite faces differ in temperature by unity (1° C.). The mean *temperature coefficient* of thermal conductivity is expressed as

$$a_{\ to}=\frac{\lambda_t-\lambda_{to}}{\lambda_{to}(t-to)}$$

Thermal expansion.—If l_t is any linear dimension of a solid at any temperature, $\frac{I}{l}\frac{dl}{dt}$ is the linear thermal expansivity of that solid in the direction of *I*. It is not in general proportional to the temperature except approximately over small temperature intervals, but may be expressed in the following manner:

$$\frac{I}{l}\frac{dl}{dt}=a+bt+ct^2\cdot\ \cdot\ \cdot$$

For small temperature intervals a mean coefficient (a) is often determined; that is,

$$a_{to}=\frac{l_t-l_{to}}{l_{to}(t-to)}$$

Thermoelectromotive force (E).—In an electric circuit composed of two dissimilar conductors, the two junctions being at different temperatures, there exists in general an electromotive force, called the thermoelectromotive force, between the two metals, the value of which is a function both of the temperature and the difference of temperature between the two junctions. It is shown thermodynamically that this emf is related to the Thomson and Peltier effects in the following manner:

$$\left.\begin{aligned}\pi&=\frac{T}{J}\frac{dE}{dt}\\ \sigma_1-\sigma_2&=-\frac{T}{J}\frac{d^2E}{dt^2}\end{aligned}\right\}\text{ and expressed in calories per coulomb}\quad J=\frac{418\text{ dynes}\times10^6}{\text{calories}}$$

when E is the thermal emf, T the absolute temperature, $\frac{dE}{dt}$ the thermoelectric power (see below), and $\sigma_1-\sigma_2$ the difference in the Thomson effect of two materials. The form of the function $E=E(T)$ is not known. In general, the equation $\frac{dE}{dt}=A+BT$

satisfactorily fits the experimental data over a limited range of temperature of a few hundred degrees.

It has been shown that the Thomson effect for lead is practically zero. This metal has served as a comparison metal in studying the thermoelectric forces of others.

Thermoelectric power.—If E is the thermoelectromotive force of any two dissimilar metals, $\frac{dE}{dt}$ = the thermoelectric power; it is at any temperature therefore approximately the thermal emf of a couple of which the temperatures of the two junctions differ by 1° C.

The Thomson effect.—When a current flows in a conductor from a point at one temperature to one at another, heat is in general liberated, or absorbed, and an emf or counter emf is produced. The coefficient of the Thomson effect is the amount of heat liberated or absorbed when unit quantity of electricity flows from a point at temperature, t, to one at a temperature, $t+dt$, and is equal to σdt calories per coulomb where σ is the so-called Thomson specific heat of electricity. It is called positive for any material when heat is generated in that material as a current flows from a region of higher to one of lower temperature.

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ll	--------	Krause, Das aluminium.
mm	--------	Ecole Centrale des Arts et Manu., Correspondence.
nn	--------	Bureau of Standards analysis.
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96. PATENTS

Aluminum Chloride

UNITED STATES

1165065
1354818
1422560
1445082

Binary Alloys

UNITED STATES

451405
662951
662952
697544
1083903
1224362
1254987
a1410461
p1508556
1518760
1553298
1557431
1570893
b1572459
1572487
1572488
c1572489
q1572502
1578979
1579481
1583549
1584688
1595218
1596020
1606616

BRITISH

171996
171997
219346
231185
252160

Castings

UNITED STATES

528181
586095
624605
936339
1098137
1476192
1147398
1156093
1247977
1293426
1305166
1318702
1333965
1350891
1352271
1352272
1453254
1480846

BRITISH

d244441

96. PATENTS—Continued

Commercial Aluminum

British

e211027

Heat Treatment

United States

1394534
1562269

Light Aluminum Alloys

United States

44086
633743
652833
867194
451406
684207
1212374
1227174
1223362
1175655
1146185
1130785
1092500
1095653
1099561
1102618

British

252028

German

144777
113935
119643
125334
204543
244554
112546
170085
218970
230095
[1] 231060
242313
137003
134582
268515
203557
257868

Manufacture of Articles

United States

139678
1261987
1431237
1625598
1518190
1526701
1534322
1537540
1572253
1614684

British

221873
237341
240594
244478

Canadian

267484

Plating and Coating

United States

1011203
1077480
1515658
1526127
1535492
f1540766
1551613
1565495
1565496
1591983
1594061
1627900
1607676
1608775

British

223994
226776
233648
237072
245746
252070

Production

United States

220149
580711
1292582
1321684
1348458
1442773
1512420
1512462
1518872
1519648
1524470
1534031
1534315
1534316
1534318
1534319
1534321
1535458
1550192
1552728
1562654
1566694
1569483
1576080
1578044
1585786
1591798
1630361
1599869
1612642
1615009
1636881

British

224488
225494
232549
g242958
254050
258560

Canadian

251381
267264

Solders

United States

1323520
1416924
1550987
1556022
1584219

British

265733

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[1] Describes the properties of alloys of aluminum, copper, manganese, and silver.
[2] Describes the properties of alloys of aluminum with cobalt and tungsten.

Rübel (Krause, (2 p. 129)) describes the properties of alloys of aluminum with phosphorus.

Uyeno (Krause, (2) p. 132)) describes alloys of aluminum with mercury and zinc which are used to generate hydrogen (with hot water) for balloons.

96. PATENTS—Continued

Surface Treating, Etc.

UNITED STATES

1011203
1077480
1540766
1573825
1573826
1584647

BRITISH

223995
252070

Ternary and Complex Alloys

UNITED STATES

38301
373221
443943
446351
451406
480445
501553
611016
629084
633743
639600
646442
652833
684707
699216
721814
743566
759617
856392
867194
886597
938422
995113
1019963
1072017
1076137
1080155
1080156
1092500
1095653
1099561
1102618
1104369
1117308
1121267
1121268
1121269
1130785
1146185
1175656
1175658
1212374
1277174
1254854
1261987
1280706
1300058
1304229
1310309
1365178
1418303
1422591
1508556
1510242
1518321
1540006
1546657
1553298
1555959
1556953
1558066
1560845
h1563079
1572357
1572382
1572502
1572489
1572490
1572593
1595058
1595219
1606616
1606752
1612642
[3] 539740
r1629699

BRITISH

220602
221082
228143
230326
244478
252028

CANADIAN

242938

Welding

UNITED STATES

1538355
1542753
1550280
1552443
1604698
1636656

BRITISH

226187
227471
239413
241058

Miscellaneous

UNITED STATES

j868383
k1387000
l1387900
m1412280
n1453928
o1464625

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[3] Serial application number.

MAGNESIUM

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Text references	Year	Name and title
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