DEPARTMENT OF COMMERCE

CIRCULAR

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, Director

No. 73

COPPER

ISSUED JUNE 25, 1918

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CONTENTS

I. INTRODUCTION

The Bureau is constantly in receipt of requests for detailed or general information concerning the properties, statistics, etc., of metals and of alloys, coming from other departments of the Government, technical or purchasing agents of manufacturing firms using the metal or alloy in question, or from persons engaged in special investigative work in universities and private technical institutes. Such information is rarely to be found in systematic form; generally the different sources of such information are difficult of access, and their accuracy not always certain; much quoted information of this sort is valueless either for the reason that the data upon which it is based are actually incorrect, or that the data have not been properly interpreted in quoting.

The Bureau plans to issue from time to time circulars on individual metals or alloys, with the idea of grouping in these circulars all of the best information which the Bureau has as a result of its tests and investigations together with that available in all records of published tests and investigations of such materials.

The circulars deal primarily with the physical properties of the metal or alloy; all other factors, except a few statistics of production, such as methods of manufacture, presence of impurities, etc., are discussed only in their relation to these physical properties; it must be realized that the physical properties of metals and alloys are often in great degree dependent upon such factors, so that the statement of values for such properties should include an accompanying statement regarding those factors by which the properties are affected.

The endeavor in the circulars, therefore, is to reproduce only such data as have passed critical scrutiny, and to suitably qualify in the sense outlined above all statements, numerical or otherwise, made relative to the characteristics of the metal.

This circular is the first one issued on the metals;[1] copper has been chosen for the reason that much of the accurate information regarding copper has been obtained at this Bureau, and that, in general, our knowledge of the properties of this metal is more complete than of any other. Furthermore, commercial copper has a very high degree of purity. The data and information have been put in the form of tables and curves; the curves have been reproduced in such dimensions that accurate interpolation of values on them is possible by the use of a rule graduated in decimal parts of a centimeter. The probable degree of accuracy of data is indicated, or implied, by the number of significant figures in the values given.

II. COMMERCIAL COPPER

1. SOURCES, METALLURGY, REFINING

Copper is, relatively speaking, a quite widely distributed metal, and occurs in a number of minerals, of which the most important are the following:

(1) The sulphide copper ores, such as chalcopyrite ($CuFeS_2$), chalcocite (Cu_2S), bornite (Cu_3FeS_3), tetrahedrite (4 Rs. Sb (As_2) S_3; $R = Cu_2$, Fe, Zn, Ag_2, Hg_2) and a number of other complex sulphides. The principal copper deposits are of this type, occurring in Montana, Utah, Nevada, California, Hungary, Russia, Chile, and Australia.

(2) Native copper, occurring in large amounts only in the Lake Superior district in the State of Michigan.

(3) The oxide ores, such as cuprite (Cu_2O), malachite ($CuCO_3$) and $Cu(OH)_2$). These ores are found both in the West, Southwest, and abroad in Chile, Australia, and Ural.

From these ores copper is extracted by pyro, hydro, or electrometallurgical processes, or by combinations of these. Low-grade ores are generally first leached; medium and high grade ores directly smelted. Electrolytic processes are used only in refining crude metal; they "have so far been a failure with ore" (8)*. The actual process used in smelting and refining copper varies greatly with the type of ore.

The smelting of copper ores consists, broadly speaking, of two operations:

(1) The production from the ores of "matte," containing copper, iron, and sulphur in the following proportions: Copper,

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[1] Circular No. 58 of this series relating to invar and similar nickel steel has already been issued. There is in preparation a similar circular on iron.

* These numbers in parentheses throughout text refer to numbered bibliography references, p. 96.

20 to 80 per cent; iron, 10 to 40 per cent; and sulphur, 18 to 24 per cent.

This "matte" is produced by the roasting of the ore in heaps, in shaft, or reverberatory furnace, or in automatic multiple-hearth furnaces, followed by a reducing fusion in the blast or reverberatory furnace.

(2) The conversion of "matte" into a crude copper, generally in the converter but also in the blast furnace (abroad) or in the reverberatory furnaces (for matte containing 70 to 80 per cent copper). The product obtained is converter or blister copper, containing from 98 to 99.4 per cent copper, and, as impurities, small amounts of iron, nickel, lead, antimony, arsenic, selenium, tellurium, sulphur, silver, gold, and at times bismuth, zinc, platinum, and palladium. It receives the name "blister" copper from the cavities and excresences on the surface caused by the evolution of gases, principally sulphur dioxide (SO_2) during solidification.

Oxide ores were formerly reduced in blast furnaces to "black" copper varying from 95 to 98 per cent copper, but are now mixed with sulphides and smelted for matte, which is then converted.

Native copper ore is subjected to oxidizing fusion in a reverberatory furnace, slagged and reduced either in the same or in a different furnace. The product is refined copper, which is cased into anodes or commercial forms.

The leaching process consists of two operations:

(1) The copper of the ore is converted into a soluble form. Oxide ores are dissolved directly in acids (sulphuric acid, H_2SO_4); sulphide ores are changed to sulphate by oxidizing roasting or to chloride by chloridizing roast with addition of salt.

(2) The copper is then precipitated by iron or otherwise, the product being called "cement" copper, analyzing from 70 to 95 per cent copper, and containing lead, silver, bismuth, arsenic, antimony, iron oxide (Fe_2O_3), aluminum oxide (Al_2O_3), sulphur trioxide (SO_3), water (H_2O), sodium sulphate Na_2SO_4), sodium chloride (NaCl), and other impurities. This product, depending on its purity, may be smelted for blister copper or added to a matte charge.

The products of the leaching and smelting operations are blister, black copper, and refined copper (from native ores, lake). These may be fire refined or electrolytically refined and remelted.

The fire refining of copper consists in an oxidizing fusion in a reverberatory furnace (melting, fining, or rabbling), which volatilizes some impurities (sulphur, zinc, lead, arsenic, antimony), and scorifies others (manganese, iron, lead, nickel, cobalt, bismuth, arsenic, antimony). The slags are skimmed and fining continued until about 6 per cent of cuprous oxide (Cu_2O) is held in solution. The oxide is then almost, but not entirely, reduced by poling; that is, the introduction through the furnace door of a green wood pole into the molten metal. About 0.04 to 0.05 per cent oxygen (0.45 to 0.56 per cent Cu_2O) is generally left in the copper to prevent the reduction of the oxides of arsenic, antimony, etc., to the metallic state in which they would again dissolve in the copper.

In electrolytic refining the blister or raw copper is cast into anodes, about 36 by 36 by 1 inch in dimensions. These are dissolved by the aid of the (direct) electric current in a solution of sulphuric acid and copper sulphate and redeposited in the same operation on cathode sheets. The behavior of the impurities depends upon their electrochemical behavior relative to copper:

(1) Nickel, cobalt, iron, manganese, zinc, lead, and tin are electropositive to copper and hence dissolve at the anode; they will, however, not deposit at the cathode, but concentrate in the solution.

(2) Gold, silver, platinum, selenium, and tellurium are electronegative to copper and do not dissolve at the anode, but are mechanically separated and form part of the anode slime.

(3) The compounds Cu_2O, Cu_2Se, Cu_2Te, and Cu_2S are also not dissolved at the anode, but form part of the anode slime.

(4) Arsenic, antimony, and bismuth are partly dissolved and partly deposited at the cathode; they stand near copper in their electrochemical behavior under these conditions. This deposition is largely of a mechanical nature; the metals are carried over by drifting anode slime.

It is to be understood that the above division of the elements is only approximate, as actually some variation of behavior is noted; for example, nickel, cobalt, and lead dissolve only partially, the remainder going into the anode slimes.

The cathodes as so produced, although very pure, are not mechanically suitable for commercial use, and are remelted into wire bars, slabs, ingots, etc. This is done in a large reverberatory furnace, in the same manner as was described under fire refining.

2. COMMERCIAL GRADES—USES

There are produced in the United States three well-defined grades of copper: Lake copper, electrolytic copper, and casting copper. The former, as its name indicates, is electrolytically or fire refined from the Lake Superior native copper ores and is of two grades, high conductivity and arsenical. The electrolytic copper is that which has been electrolytically refined from blister, converter, black, or lake copper. Casting copper is the most impure grade and may consist of either (1) furnace-refined converter bar or black copper from smelters whose ores carry insufficient silver and gold to pay for refining, (2) by-product copper not up to grade, or (3) copper produced by the melting up of scrap.

British B. S. or Best Selected copper is made by the old Welsh best selecting process, the "bottoms" method, and was the purest brand of copper known until the lake ores were found and the electrolytic refining method used. Table 1 gives an idea of the analysis of different grades of commercial copper produced both here and abroad. It will be observed that the continental grades, particularly the Mansfeld copper, usually contain some nickel.

On the London Metal Exchange copper was sold according to certain standard regulations, and from this practice has arisen the term "Standard" copper. This latter is not a brand of copper but a specification for copper, and is a substitute for the former term, G. M. B. (Good Merchantable Brand). "Standard" copper was grouped into four classes:

A. Refined copper, copper not under 99 per cent, and not over 99.3 per cent, selling at contract price.

B. Refined copper, copper 99.8 to 99.3 per cent, selling at 10s. per ton over contract price.

C. Refined copper, copper not less than 99.8 per cent, selling at £1 per ton over contract price.

D. Rough copper, copper less than 99 per cent, subject to a rebate of £1 and over per ton.

Standard copper, therefore, may be looked upon as that analyzing between the limits 99 and 99.3 per cent copper.

The following groups may therefore be recognized:

American:

Electrolytic copper.......	99.90 per cent (99.88 A. S. T. M.) copper and over.
Lake (high conductivity)..	99.90 per cent (99.88 A. S. T. M.) copper and over.
Lake (arsenical)..........	99.40 per cent copper and over.
Casting....................	98.5 to 99.8 per cent copper.

British:

"Standard"	99.0 to 99.3 per cent copper.
B. S.	99.75 per cent copper and over.
"Tough"	99.25 per cent copper and over.

Copper appears on the market in the following forms:

Wire bars, for wire drawing; these vary in weight from 135 to 500 pounds (standard sizes 200 and 225 pounds); they will vary in section from 3½ by 3¾ to 4½ by 4¾ inches and in length from 35 to 84 inches.

"Square" cakes, for rolling sheet; these vary in weight from 150 to 6500 pounds; dimensions 14 by 17 to 48 by 48 inches, by from 2 to 9 inches thick.

Ingots, 20–22 pounds.

Ingot bars, 75 to 110 pounds.

Anodes, 25 by 36 inches, weighing about 140 pounds.

Cathodes, 2 by 3 feet by from ⅜ to ½ inch thick (also the 10 by 12 feet in series system cathodes).

Over 50 per cent of the copper produced is used in peace time for electrical purposes. In 1913 the following disposition was made of the copper consumed in the United States:

	Millions of pounds	Per cent
Copper wire	400	52
To brass mills	220	28
Copper sheets	105	14
Miscellaneous, castings, and alloys	42	5

From the standpoint of physical measurements, copper is quite a valuable metal because of its commercial purity. It is used as a calorimetric metal, as one element of base-metal thermocouples, copper-constantan, etc., as a pyrometric standard (for the calibration of pyrometers), both as a metal and as the copper-silver and a copper-copper oxide eutectic.

Table 2 gives a list of the brands of American copper, the refiners producing them, etc. (26).

TABLE 1.—Analyses of Commercial Grades of Refined Copper

	Chemical analysis														Ultimate tensile strength as hard drawn.	Elongation	Electrical conductivity as annealed—International copper standard
	Copper + silver	Copper	Silver	Arsenic	Bismuth	Iron	Nickel	Oxygen	Lead	Antimony	Tin	Selenium+tellurium	Zinc	Sulphur			
United States:	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Lbs/In.[2]	Per cent	
Electrolytic wire bar [a]	99.97	99.96	0.0027	0.0006	0.0000	0.0023	0.0030	0.0191	0.0024	0.0000	0	0.0000	0.0000	0.0026	65 000	[b] 1.6	100.8
Do.[a]	99.89	99.89	.0020	.0001	.0000	.0028	.0010	.0888	.0072	.0006	0	.0022	.0000	.0023	67 800	[c] 1.1	99.8
Do.[a]	99.95	99.95	.0018	.0000	.0000	.0038	.0028	.0315	.0010	.0009	0	.0026	.0000	.0026	66 300	[c] 1.04	100.4
Do.[a]	99.97	99.97	.0020	.0001	.0000	.0044	.0018	.0063	.0056	.0008	0	.0014	.0000	.0016	66 500	[c] 1.08	100.7
Lake wire bar [a]	99.90	99.89	.0096	.0062	.0000	.0028	.0090	.0753	.0031	.0000	0	.0020	.0000	.0016	67 600	1.03	96.5
Lake [a]	99.95	99.87	.071	.0006		.0014	.0010	.045		Trace			Trace	.0022			101.0
Do.[a]	99.93	99.87	.057	.0099		.0063	.0108	.056	Trace	Trace			.0008	.0064			95.7
Do.[a]	99.93	99.86	.068	.0004		.0027	Trace	.064	.0011	Trace			.0005	.0006			101.1
Lake arsenical, ingot [a]	99.43	99.41	.0254	.3183	.0000	.0056	.0153	.2143	.0027	.0000			.0000	.0071			
Casting copper [a]		99.50				.06	.15	Trace	.05		0.18						
Do.[a]		99.44	.01	.02	.01	.38				.05				.002			
Cathode copper [d]			.00001	.0003				.008	.00054	.001							
England:																	
Best selected [a]	99.55	99.53	.0210	.0071	.0000	.0044	.1112	.1705	.1331	.0087		.0066	.0000	.0074			
Merchant bar [a]	99.90	99.87	.034	.002		.011		.068					.013				
B. S.[e]		99.75		.025		.10	.061	.143	.024								
Refined converter [e]		99.25		.0211	.0044			.284	.0103	.0630							
Do.[e]		99.08		.0290	.0035	Trace		.12	.0085	.0254				.01			
Germany and Austria:																	
Mansfeld [a]	99.64	99.61	.0292	.0172		.0039	[f] .2112	.0752	.020	.0023				.0024			
Mansfield castings, refined [g]		99.44		.025		.024	[f] .317		.006								
Do.[g]		99.51				.037	[f] .279		.042								

Mansfeld rolling, refined [g]		99.34		.030		Trace	f.298		.204								
Do.[g]		99.19		.061		Trace	f.467		.206								
Mansfeld, refined (Garkupfer) [g]		98.4	.02			.07	f.45		.57					.01			
Oker, refined [a]	99.39	99.39	.072	.135	.052	.063	f.064	.1166	.061	.095				.001			
Stefanshütte, refined [g]			.011	.13		Trace	f.29		Trace	.08							
Agardo, refined [g]			.10	.64					.20	.04				.04			
Klausen, refined [g]			.077	.059					.39	.057							
Atvidaberg, refined [g]	99.46		.06			.01	f.11		Trace					.02			
Lend (Salzburg), refined [g]	97			1.10			f.46		.70								
Japan:																	
Furu Kawa, hard drawn [d]		99.90	.0094	.0284	.0021					.0201	h Trace						
Furu Kawa, soft (drawn) [d]		99.86	.0136	.0321	.0041					.0327	h .0032						
Sumitomo, hard drawn [d]		99.85	Trace	.0102	Trace					.0124	h .0701						
Sumitomo, soft (drawn) [d]		99.84	.0017	.0124	Trace					.0132	h .0524						
Burra-Burra (Australia) [g]				.02													
Wallaroo (Australia) [a]	99.64			Trace			.237			.0007							
Nischni-Tagilsk (Ural) [g]			.0032	.0002		.0034				.0042	.0036						
Kedaberg (Caucasus) [g]			.161	.0151						.0087							
Do.[g]	99.69		.0877			.035	.0057		.0110			i .0067	.0731				
Chile				Trace to .5	Trace	.8 to 1.64				Trace to .5							
Spain				.25 to to 3.31	Trace to .04	.35				Trace to .70							

[a] Given by Hofman (8).
[b] In 8 inches; hard drawn.
[c] In 60 inches; hard drawn.
[d] Given by Hirobe and Matsumoto (47).
[e] Peters (12).
[f] Nickel plus cobalt.
[g] Given by Schnabel (14).
[h] Nickel, cobalt, iron, lead, zinc, and oxygen.
[i] Gold.

TABLE 2.—Copper Smelting Works of North America (26) and Electrolytic Copper Refineries of the United States and Canada

COPPER SMELTING WORKS OF NORTH AMERICA, 1916

Company	Location	Blast furnaces	Annual capacity	Reverberatory furnaces	Annual capacity	Converters	Annual capacity of ore [a]
			Tons		Tons		Tons
American Smelting & Refining Co.	Aguascalientes, Mexico.	10	800 000	......	....	4	(b)
Do	Perth Amboy, N. J.	1	90 000	......	....	3	(b)
Do	Omaha, Nebr.	......	....	......	....	2	(b)
Do	El Paso, Tex.	3	300 000	3	435 000	3	(b)
Do	Matehuala, Mexico.	3	325 000	......	....	......	....
Do	Hayden, Ariz.	......	....	3	420 000	3	(b)
Do	Sasco, Ariz.	2	300 000	......	....	2	....
American Smelters Securities Co.	Garfield, Utah	4	800 000	6	875 000	7	(b)
Do	Tacoma, Wash.	2	375 000	1	144 000	7	(b)
Do	Velardena, Mexico.	3	250 000	......	....	......	....
Anaconda Copper Mining Co.	Anaconda, Mont.	3	1 750 000	8	1 750 000	7	105 000
Do	Great Falls, Mont.	2	280 000	2	330 000	2	49 000
Arizona Copper Co.	Clifton, Ariz.	......	....	3	360 000	3	....
Balakala Consolidated Copper Co. [c]	Coram, Cal.	3	630 000	1	52 500	2	....
Compagnie Du Boleo	Santa Rosalia, Mexico.	8	650 000	......	....	......	....
British Columbia Copper Co.	Greenwood, British Columbia.	3	912 500	......	....	2	....
Calumet & Arizona Mining Co.	Douglas, Ariz.	2	719 900	4	557 800	6	36 500
Canadian Copper Co.	Coppercliff, Canada.	7	1 000 000	1	180 000	5	60 000
Cananea Consolidated Copper Co.	Cananea, Mexico.	8	868 000	2	153 000	6	[d] 35 000
Consolidated Arizona Smelting Co.	Humboldt, Ariz.	1	70 000	2	150 000	2	10 000
Consolidated Mining & Smelting Co.	Trail, British Columbia.	5	450 000	......	....	2	10 000
Copper Queen Consolidated Copper Co.	Douglas, Ariz.	10	1 225 000	3	275 000	7	34 160
Detroit Copper Mining Co.	Morenci, Ariz.	1	140 000	......	....	3	150 000
Ducktown Sulphur, Copper & Iron Co.	Isabella, Tenn.	2	171 500	......	....	......	....
East Butte Copper Mining Co.	Butte, Mont.	2	350 000	......	....	3	5000
Granby Consolidated Mining, Smelting & Power Co.	Grand Forks, British Columbia.	8	1 440 000	......	....	4	7000
Do	Anyox, British Columbia.	4	1 080 000	......	....	3	28 000
International Smelting Co.	Tooele, Utah.	......	....	5	500 000	5	50 000
Do	Miami, Ariz.	......	....	4	700 000	5	50 000
Mammoth Copper Mining Co.	Kennet, Cal.	5	730 000	......	....	2	28 500
Mason Valley Mines Co.	Thompson, Nev.	2	520 000	......	....	2	22 000
Mazapil Copper Co. [c]	Conception del Oro, Mexico.	4	250 000	......	....	......	....
Mond Nickel Co.	Coniston, Canada.	3	600 000	......	....	3	60 000

[a] Raw ore smelted as flux.
[b] Included in furnace tonnages,
[c] Not in operation.
[d] Silicious ore.

TABLE 2.—Copper Smelting Works of North America (26) and Electrolytic Copper Refineries of the United States and Canada—Continued

COPPER SMELTING WORKS OF NORTH AMERICA, 1916—Continued

Company	Location	Blast furnaces	Annual capacity	Reverberatory furnaces	Annual capacity	Converters	Annual capacity of ore [a]
			Tons		Tons		Tons
Mountain Copper Co.	Martinez, Cal.	......	....	3	125 000	2	([b])
Nevada Consolidated Copper Co.	McGill, Nev.	1	175 000	5	900 000	4	40 000
Nichols Copper Co.	Laurel Hill, N. Y.	2	94 500	......	....	2	....
Norfolk Smelting Co.	West Norfolk, Va.	1	140 000	......	....	2	4200
Old Dominion Copper Mining & Smelting Co.	Globe, Ariz.	5	562 500	......	....	1	6062
Oxford Works, International Nickel Co.	Constable Hook, N. J.	2	94 500	......	....	3	....
Penn Mining Co.	Campo Seco, Cal.	......	....	2	96 000	1	48 000
Pioneer Smelting Co.	Corwin, Ariz.	1	60 000	......	....	......	....
Santa Fe Gold & Copper Co.	San Pedro, N. Mex.	1	45 000	......	....	......	....
Shannon Copper Co.	Clifton, Ariz.	3	500 000	......	....	2	8000
Swansea Consolidated Gold & Copper Mining Co.[c]	Bouse, Ariz.	1	190 000	......	....	2	....
Tennessee Copper Co.	Copperhill, Tenn.	7	1 000 000	......	....	4	15 000
Teziutlan Copper Mining & Smelting Co.[c]	Teziutlan, Mexico	2	350 000	......	....	3	....
Cia. Metalurgica De Torreon.	Torreon, Mexico	2	175 000	......	....	2	....
Tyee Copper Co.[c]	Ladysmith, British Columbia.	2	175 000	......	....	......	....
U. S. Metal Refining Co.	Chrome, N. J.	2	200 000	......	....	2	([d])
U. S. Smelting Co.[c]	Midvale, Utah	6	670 000	1	40 000	4	36 000
United Verde Copper Co.	Clarkdale, Ariz.	4	720 000	3	324 000	5	54 000
Wanakah Mining Co.[e]	Ouray, Colo.	2	105 000	......	....	......	....
Western Smelting & Power Co	Cooke, Mont.	1	110 000	......	....	......	....

ELECTROLYTIC COPPER REFINERIES OF THE UNITED STATES AND CANADA

Company	Location	Capacity [f]			
		1913	1914	1915	1916
		Pounds	Pounds	Pounds	Pounds
Nichols Copper Co.	Laurel Hill, N. Y.	400 000 000	400 000 000	400 000 000	450 000 000
Raritan Copper Works.	Perth Amboy, N. J.	400 000 000	400 000 000	400 000 000	460 000 000
Baltimore Copper Smelting & Rolling Co.	Canton, Md.	348 000 000	336 000 000	354 000 000	600 000 000
American Smelting & Refining Co.	Perth Amboy, N. J.	216 000 000	216 000 000	240 000 000	240 000 000
United States Metals Refining Co.	Chrome, N. J.	200 000 000	200 000 000	200 000 000	250 000 000
Balbach Smelting & Refining Co.	Newark, N. J.	48 000 000	48 000 000	48 000 000	48 000 000

[a] Raw ore smelted as flux.
[b] No raw ore charged.
[c] Not in operation.
[d] Under construction.
[e] Plant sold to Ouray Smelting & Refining Co.
[f] Official figures furnished by the respective companies.

TABLE 2.—Copper Smelting Works of North America (26) and Electrolytic Copper Refineries of the United States and Canada—Continued

ELECTROLYTIC COPPER REFINERIES OF THE UNITED STATES AND CANADA—Continued

Company	Location	Capacity [a]			
		1913	1914	1915	1916
		Pounds	Pounds	Pounds	Pounds
Anaconda Copper Mining Co. (old plant).	Great Falls, Mont...	65 000 000	65 000 000	65 000 000	65 000 000
Anaconda Copper Mining Co. (new plant).	.....do..............	....	....	....	[b]180 000 000
Tacoma Smelting Co......	Tacoma, Wash......	36 000 000	48 000 000	120 000 000	130 000 000
Calumet & Hecla Mining Co.	Buffalo, N. Y........	55 000 000	(c)	(c)	(c)
Do..................	Calumet, Mich......	....	[d]65 000 000	65 000 000	65 000 000
Consolidated Mining & Smelting Co.	Trail, British Columbia.	....	....	....	(b)
Total..............	....	1 768 000 000	1 778 000 000	1 892 000 000	2 488 000 000

[a] Official figures furnished by the respective companies.
[b] New works put in operation in 1916.
[c] Buffalo works of Calumet & Hecla dismantled in fall of 1914.
[d] New works put into operation in 1914.

3. PRODUCTION, PRICE

A general idea of the world's production of copper may be obtained from Tables 3, 4, and 5.

TABLE 3.—Production of Copper in Different Countries, in Metric Tons

Country	1911	1912	1913	1914	1915	1916
Africa	17 252	16 632	22 870	25 700	27 000	35 000
Australasia	42 510	47 772	47 325	33 782	32 512	35 000
Bolivia	2950	4681	3658	3500	3000	4000
Canada	25 570	34 213	34 880	33 248	47 202	53 263
Chile	33 088	39 204	39 434	38 270	47 142	66 500
Cuba	3753	4393	3381	6628	8836	9311
Germany	22 363	24 303	25 308	28 000	35 000	35 000
Japan	52 303	62 486	73 152	68 058	75 000	90 000
Mexico	61 884	73 617	58 323	35 436	30 969	55 160
Peru	28 500	26 483	25 487	22 876	32 410	41 625
Russia	25 747	33 550	34 316	32 000	16 000	16 000
Spain and Portugal	52 878	59 873	54 696	47 500	35 000	50 000
United States	491 634	563 260	555 990	515 164	646 212	880 750
Other countries	26 423	29 555	27 158	23 000	25 000	25 000
Total	886 855	1 020 022	1 005 978	913 162	1 061 283	1 396 609

TABLE 4.—Production of Copper and Apparent Domestic Consumption of Refined New Copper in the United States

PRODUCTION OF COPPER IN THE UNITED STATES, 1913–1916—SMELTER OUTPUT, IN POUNDS FINE

State	1913	1914	1915	1916
Alaska	23 423 070	24 985 847	70 695 286	113 823 064
Arizona	404 278 809	382 449 922	432 467 690	694 847 307
California	32 492 265	29 784 173	37 658 444	43 400 876
Colorado	9 052 104	7 316 066	7 272 178	9 536 193
Georgia	....	....	....	803 699
Idaho	8 711 490	5 875 205	6 217 728	7 248 794
Maryland	....	12 248	15 426	126 965
Michigan	155 715 286	158 009 748	238 956 410	269 794 531
Missouri	576 204	53 519	306 406	377 575
Montana	285 719 918	236 805 845	268 263 040	352 139 768
Nevada	85 209 536	60 122 904	67 757 322	100 816 724
New Jersey	....	....	....	4115
New Mexico	50 196 881	64 204 703	62 817 234	79 863 439
North Carolina	180	19 712	33 383	5961
Oregon	77 812	5599	797 471	2 433 567
Pennsylvania	245 337	422 741	....	904
Tennessee	19 489 654	18 661 112	18 205 308	14 556 278
Texas	39 008	34 272	38 971	86 463
Utah	148 057 450	160 589 660	175 177 695	232 335 950
Vermont	5771	....	23 995	324 400
Virginia	46 961	17 753	50 008	1 066 143
Washington	732 742	683 602	903 661	2 473 481
Wyoming	362 235	17 082	351 871	1 784 351
Undistributed	51 385	65 479	....	....
Total	1 224 484 098	1 150 137 192	1 388 009 527	1 927 850 548

PRODUCTION OF PRIMARY AND SECONDARY COPPER BY THE REGULAR REFINING PLANTS, 1913–1916, IN POUNDS

	1913		1914	
	Domestic	Foreign	Domestic	Foreign
Primary:				
Electrolytic	1 022 497 601	378 243 869	991 573 073	323 358 205
Lake	155 715 286	....	158 009 748	....
Casting	22 606 040	....	21 506 325	....
Pig	36 004 986	....	39 334 043	....
Total [a]	1 236 823 913	378 243 869	1 210 423 189	323 358 205
Total domestic and foreign	1 615 067 782		1 533 781 394	
Secondary:				
Electrolytic	14 862 577		27 702 928	
Casting	22 360 182		4 224 052	
Total	37 222 759		31 926 980	
Grand total	1 652 290 541		1 565 708 374	

[a] The distribution of refined copper of domestic and foreign origin is only approximate as an accurate separation at this stage of manufacture is not possible.

TABLE 4.—**Production of Copper and Apparent Domestic Consumption of Refined New Copper in the United States—Continued**

PRODUCTION OF PRIMARY AND SECONDARY COPPER BY THE REGULAR REFINING PLANTS, 1913-1916, IN POUNDS—Continued

	1915		1916	
	Domestic	Foreign	Domestic	Foreign
Primary:				
Electrolytic	1 114 345 342	246 498 925	1 579 620 513	370 635 116
Lake	[a] 236 757 062	....	269 794 531	....
Casting	21 555 129	....	12 469 050	....
Pig	15 047 990	....	26 868 105	....
Total [b]	1 387 705 523	246 498 925	1 888 752 199	370 635 116
Total domestic and foreign	1 634 204 448		2 259 387 315	
Secondary:				
Electrolytic	38 156 789		78 585 296	
Casting	21 417 901		25 838 511	
Total	59 574 690		104 423 807	
Grand total	1 693 779 138		2 363 811 122	

APPARENT DOMESTIC CONSUMPTION OF REFINED NEW COPPER, 1912-1916, IN POUNDS

	1912	1913	1914	1915	1916
Total refinery output of new copper	1 568 104 478	1 615 067 782	1 533 781 394	1 634 204 448	2 259 387 315
Stock at beginning of year	88 372 195	105 497 683	90 385 402	173 640 501	82 429 666
Total available supply	1 656 476 673	1 720 565 465	1 634 166 796	1 807 844 949	2 341 816 981
Refined copper exported [c]	775 000 658	817 911 424	840 080 922	681 953 301	784 006 486
Stock at end of year	105 497 683	90 385 402	173 640 501	82 429 666	128 055 229
Total withdrawn from supply	880 498 341	908 296 826	1 013 721 423	764 382 967	912 061 715
Apparent consumption	775 978 332	812 268 639	620 445 373	1 043 461 982	1 429 755 266

[a] Some Lake copper was refined at seaboard plants and doubtless marketed under some brand other than Lake. This has been excluded from the Lake copper.

[b] The distribution of refined copper of domestic and foreign origin is only approximate, as an accurate separation at this stage of manufacture is not possible.

[c] Exports of pigs, ingots, bars, rods, etc., reported by the Bureau of Foreign and Domestic Commerce, Department of Commerce.

Fig. 1 indicates the variation in value of commercial grades of copper since 1900. Lake copper formerly brought about one-fourth cent more per pound than electrolytic copper, but since the latter part of 1915 the premium on lake has practically disap-

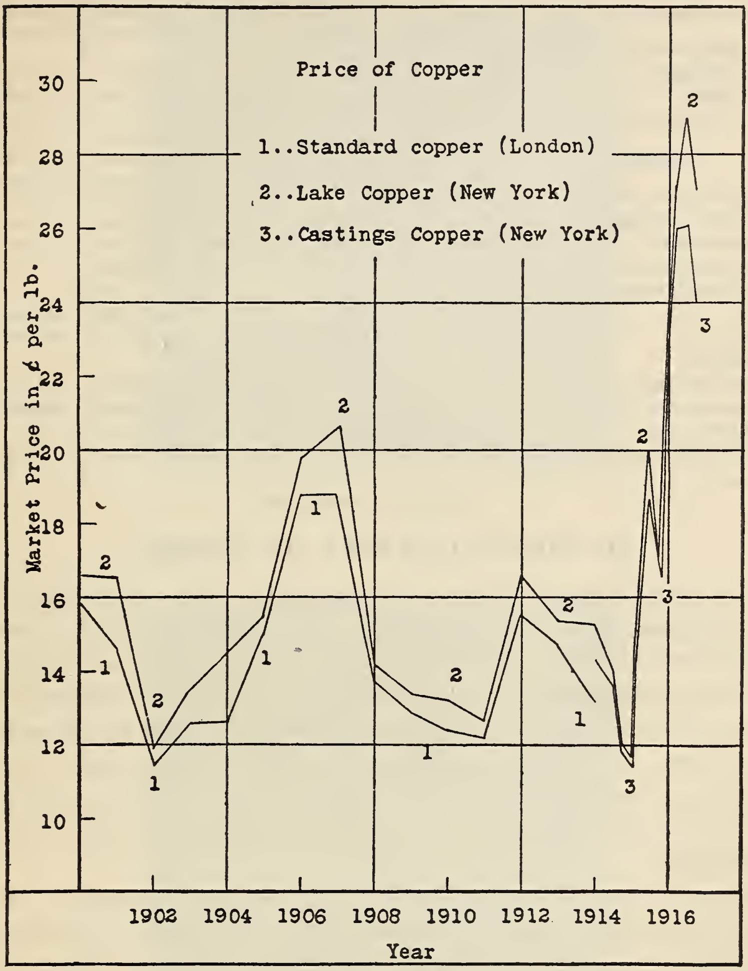

FIG. 1.—*Price of commercial copper*

peared; at times electrolytic copper has sold at a higher figure than lake. It thus seems that the old fancied superiority of lake over electrolytic copper has finally been disproved in commercial practice. (See Sec. VI, p. 39.)

TABLE 5.—Distribution of Production in United States

Copper	1911	1912	1913	1914
Production of copper:				
Smelter output..................pounds..	1 097 232 749	1 243 268 920	1 224 484 098	1 150 137 112
Mine production..................do....	1 114 764 197	1 249 094 891	1 235 569 727	1 148 432 437
Refinery production of new copper—				
Electrolytic..................pounds..	823 507 764	914 935 371	1 022 497 601	991 573 073
Lake..........................do....	218 185 236	231 112 228	155 715 286	158 009 748
Pig and casting...............do....	59 577 803	57 629 296	58 611 026	60 840 368
Total domestic..............do....	1 101 270 803	1 203 676 895	1 236 823 913	1 210 423 189
Total domestic and foreign............do....	1 433 875 026	1 568 104 478	1 615 067 782	1 533 781 394
Total new and old copper..............do....	1 648 000 000	1 843 000 000	1 888 000 000	1 790 000 000
Total ore produced ....short tons[a]..	29 994 942	35 671 028	36 361 101	35 187 118
Copper ore produced ....do.[a]....	29 988 235	35 656 414	36 336 682	35 175 541
Average yield of copper............per cent..	1.825	1.71	1.67	1.60
Imports..........................pounds..	336 607 538	410 240 295	408 778 954	306 350 827
Exports..............................do....	786 553 208	775 000 658	926 240 092	840 080 922
Consumption:				
Total new copper..................do....	681 753 279	775 978 332	812 068 639	711 624 158
Total new and old copper..........do....	895 900 000	1 051 000 000	1 085 000 000	968 000 000
World production......................do....	1 954 957 560	2 259 101 580	2 198 932 130	....
Value of production in United States.dollars..	137 154 092	205 139 338	189 795 035	152 968 246

[a] Short tons of 2000 pounds.

III. METALLOGRAPHY OF COPPER

The purest copper produced commercially, that which has been electrodeposited and not remelted, or has been remelted in vacuo, consists structurally of an aggregate of copper grains or crystals, the latter belonging to the regular or cubic system. Photomicrographs, Figs. 2 and 3, show pure electrolytic copper as deposited in the form of cathode strip, not remelted. Figs. 4 and 5 show copper as deposited in the form of electrotypes (38), and show the twinning in the columnar crystals and the etching pits inside of the grains.

When copper is remelted in practice, it takes up oxygen, only part of which is removed by poling, such that about 0.05 per cent remains in the cast ingots from the furnace. The appearance of such cast copper is shown in Fig. 6. The oxygen is present as Cu_2O, which forms a eutectic with copper of the composition of 3.45 per cent Cu_2O, melting at 1063° C; it is not appreciably soluble in solid copper. It presents under the microscope a bluish-gray appearance with a characteristic red "glow" at the center of each particle and can not be confused with other inclusions in copper. The Cu_2O content of cast copper may readily be plani-

FIG. 2.—*Cathode copper.* × 100

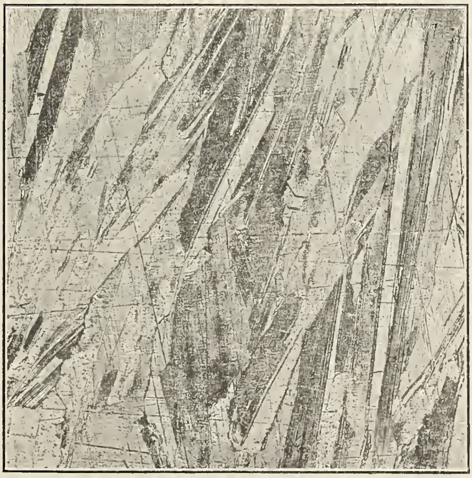

FIG. 3.—*Cathode copper.* × 100

FIG. 4.—*Electrotype copper.* × 100

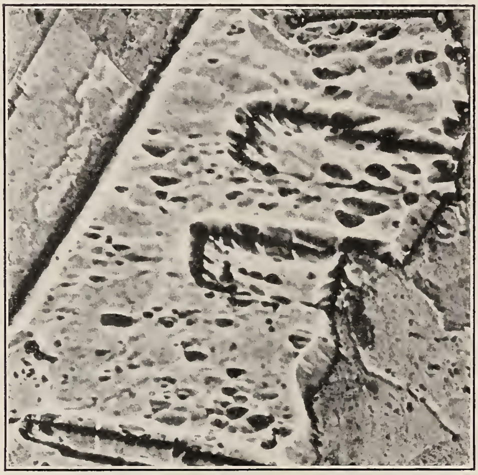

FIG. 5.—*Electrotype copper.* × 500

FIG. 6.—*Cast copper containing about 0.05 per cent oxygen.* × 100

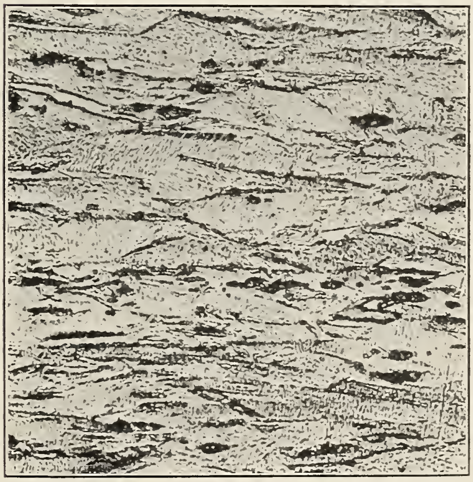

FIG. 7.—*Hard-drawn trolley wire, $\frac{23}{64}$ inch.* × 250

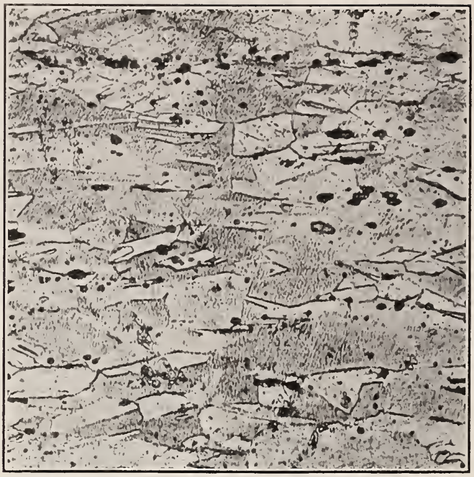

FIG. 8.—*Medium-drawn wire, $\frac{7}{64}$ inch.* × 250

FIG. 9.—*Soft wire, $\frac{1}{4}$ inch.* × 250

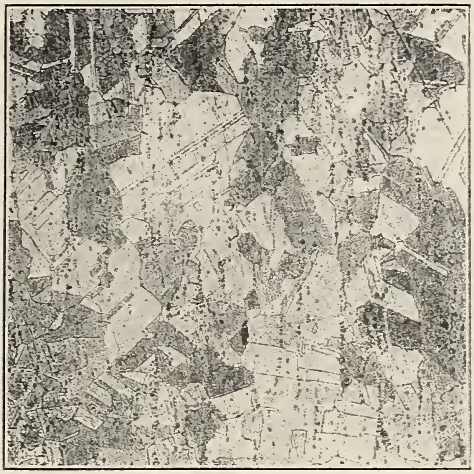

Fig. 10.—*Hot rolled, $\frac{1}{4}$-inch sheet.* × *100.*

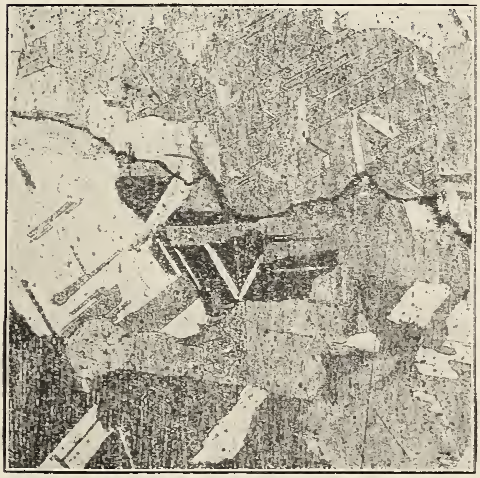

Fig. 11.—"*Gassed copper*"—*cracks.* × *100.*

metrically determined from photomicrographs or on microscope ground glass (33).

The structure of such cast copper is broken up by the mechanical and heat treatment it receives in the mill, and it recrystallizes, appearing as shown in Figs. 7, 8, 9, and 10 illustrating different forms of commercial copper.

The oxide is present in rows of fine globules, parallel to the axis of forging or working.

In the hard-drawn copper (Fig. 7) the grains are crossed by numerous etch bands, perpendicular to the direction of drawing, characteristic of hard copper; the grains are also elongated in the same direction. This is true also, but in less degree, of the medium-drawn wire, Fig. 8. When hard-drawn copper is annealed it recrystallizes; fine grains make their appearance within the larger original strained grains and generally at the border of the grains or along twinning planes and grow. The recrystallization takes place simultaneously with the softening of the metal; the temperature ranges of recrystallization coincide with those of the annealing softening (see Fig. 20); that is, from 250 to 400° C. After a full anneal, the metal assumes the structural appearance shown in Fig. 9. Figs. 10 and 11 show the appearance of hot-rolled copper plate or sheet one-fourth inch thick.

The grain size of copper may vary within wide limits. When just recrystallized, after cold drawing or rolling, the grains will have diameters of from 0.0005 to 0.003 inch, whereas after annealing at higher temperatures the diameters may go up to from 0.005 to 0.015 inch. The grain size depends upon the extent of the reduction and of annealing; this in commercial practice depends on the size of specimen, such that one may find in hard-drawn heavy sections a grain size larger than in soft smaller sections. The presence of oxide particles has been shown to hinder grain growth, in preventing coalescence of the adjoining grains.

Besides Cu_2O, bismuth and lead, when present in copper, are present in all but quite small amounts (see p. 58) as discreet particles, visible under the microscope. Other impurities, silver, gold, nickel, manganese, arsenic, antimony, zinc, phosphorus, etc., dissolve to a greater or less extent in the solid copper and leave no microscopic trace of their presence, except possibly in the cast state, when their presence gives a cored or dendritic structure to the metal.

Copper is best etched for microscopic examination with ammonium hydroxide, with ammonium-persulphate solution, or with a combination of the two; hydrogen peroxide may be used with ammonium hydroxide in place of ammonium persulphate.

Bragg (35) has shown by his method of X-ray examination that the copper atoms in crystalline copper are arranged in a face-centered cubic lattice; there is, therefore, apparently no copper molecule in solid copper smaller in size than the grain itself.

1. POSSIBLE ALLOTROPY, TRANSFORMATION

It is generally assumed that copper does not exist in any allotropic forms, but that the form which is stable at ordinary temperature persists also at lower and higher temperatures. Thermal analysis and microscopic examination disclose no evidence of any chemical transformation of any sort.

Cohen and his coworkers (42, 43), from measurements and consideration of the thermal expansion and electrical resistance, believe that they have discovered in electrolytic copper a transformation point at about 70° C. The very careful electrical resistivity measurements of Burgess and Kellberg (41) do not, however, indicate any such point; the electrical resistivity varies almost linearly in a smooth curve between 61 and 74° C. The results of Cohen are possibly to be attributed to the presence of Cu_2O in the copper tested or to the fact that the chips or wire used were in a state of initial stress or of unstable (fine) crystal structure.

Schützenberger's (45) allotropic copper has been shown by Benedicks to owe its properties to inclusions or content of Cu_2O and acetate of copper. It is harder and more brittle than copper and is made by the electrolysis of slightly alkaline solutions of copper acetate.

IV. CHEMICAL PROPERTIES

Copper is not oxidized in dry air at ordinary temperature nor in moist air in the absence of CO_2. In dry air the oxidation at temperatures under 180° C is insignificant; above that temperature are formed CuO and Cu_2O. It is not readily attacked at high temperatures below the melting point by H_2, N_2, CO, CO_2, or H_2O. Elliott claims that superheated steam makes copper brittle. In the presence of NH_4OH copper is readily oxidized in air; this reaction is utilized as a method of oxygen absorption.

Copper does not dissolve in the absence of air in dilute HCl or dilute H_2SO_4, but readily in HNO_3. In the presence of air, dilute acids, including certain organic acids, attack it slowly; at higher temperatures concentrated H_2SO_4 attacks it, forming SO_2, $CuSO_4$, etc. It is also corroded slowly by saline solutions and sea water.

Foerster (3) discusses the anodic and cathodic electrochemical behavoir of copper, characteristics of great importance to the electrolytic refining industry.

Heath (8) describes the methods in use for the analysis of copper and its alloys.

V. PHYSICAL PROPERTIES

1. ELECTRICAL, MAGNETIC

(*a*) Electrical Conductivity.—The International Electrotechnical Commission in 1913 adopted the present international standard value for the electrical resistivity of annealed copper; this is 0.15328 ohm (meter-gram) at 20° C; 0.17241 ohm (meter-square millimeter) at 20° C; 0.67879 microhm (cubic inch) at 20° C.

This value is based upon the values obtained by the various national physical laboratories (49, 60) for ordinary high-grade commercial refined copper, in the annealed state; it represents an average value for such materials. The standard density is 8.89 per cubic centimeter.

Investigation made at this Bureau showed that for 89 annealed samples of the purest commercial copper from 14 refiners the mean value of the resistivity was 0.15292 ohm (meter-gram), the average deviation from this value being 0.26 per cent, the maximum 1.7 per cent. It is thus seen that even in the purest grades of copper the variation in purity and physical state are sufficient to cause variations in resistivity of annealed samples of about ±1.5 per cent. Some of the highest values found for the per cent conductivity of copper are the following:

Resistivity = 0.15045 ohm (meter-gram) at 20° C (annealed wire).
Conductivity = 101.88 per cent.

Resistivity = 0.15386 ohm (meter-gram) at 20° C (hard-drawn wire).
Conductivity = 99.62 per cent.

The first value (60) is for an annealed wire drawn directly from a mass of native lake copper which had never been melted. The second value is for a hard-drawn sample drawn directly from a cathode plate without remelting. The average difference between the conductivity of hard-drawn and of annealed copper is 2.7 per cent. (See p. 49.)

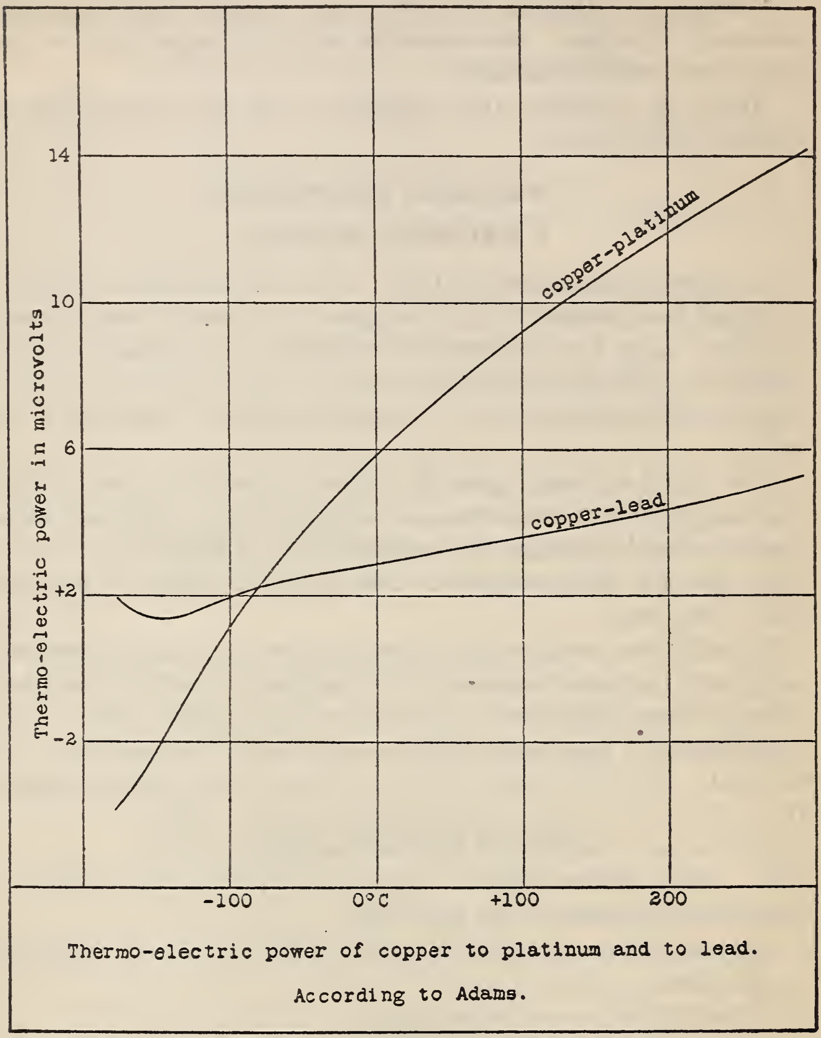

FIG. 12.—*Thermoelectric power of copper to platinum and to lead.* (*Adams*)

It may be noted that in the investigation by this Bureau of about 90 samples of commercial pure copper the electrolytic samples annealed gave a mean value of 100.3 per cent; the lake samples one of 100.02 per cent conductivity. The electrolytic samples averaged about 0.40 per cent higher than the lake samples also in the hard-drawn condition. According to Mr. Bassett, technical superintendent and metallurgist, American Brass Co., "it is not uncommon to find a conductivity in commercial wire bars of 101.3 to 101.6 per cent when soft annealed."

It may be noted that the electrical conductivity, as also its temperature coefficient, afford very sensitive criteria of the purity of copper, and are most convenient when the metal is to be tested in the form of wire or rod, etc.

Within the temperature limits 10 to 100° C the conductivity of copper is a linear function of the temperature (within 0.2 per cent) (50), and the temperature coefficient of resistance is proportional to the conductivity; for example,

$$\alpha_{20^\circ} = 0.0000393 \times \text{per cent conductivity.}$$

Thus, as a consequence of this relation the change in resistivity per degree centigrade is a constant for copper, independent of the temperature (10 to 100° C) and of the purity and is equal to 0.000597 ohm (meter-gram, 1° C).

G. K. Burgess (41) in a series of observations on the resistance of one sample of copper wire between 0 and 150° C finds that this may be represented for the sample tested to within 1 part in 1000 by the following formula:

$$R_t = R_0\ (1 + 0.00\,41151\ t - 0.0000019988\ t^2).$$

The second term, indicating the departure from linearity of the electrical resistance as a function of temperature, amounts to approximately 2 per cent at 100° C.

(*b*) Thermoelectromotive Force—Peltier Effect, Thomson Effect.—In Fig. 12 are given the curves of the thermoelectric power (dE/dt) of commercially pure copper to pure lead and platinum as determined by Adams (61), of the geophysical laboratory of the Carnegie Institution. According to Adams the thermal emf of samples of commercial copper wire to lead or platinum does not vary by more than 5 microvolts at 200° C showing a remarkable homogeneity of this metal in its commercial form. From these curves cubic equations have been derived as follows:

$$(\text{Cu} - \text{Pt})\ \frac{dE}{dt} = 5.85 + .0406t - 7.46t^2 10^{-5} + 1.096t^3 10^{-7}$$

$$(\text{Cu} - \text{Pb})\ \frac{dE}{dt} = 2.84 + .0082t - .84t^2 10^{-5} + .226t^3 10^{-7}$$

The thermal emf's are obtained by integration as follows:

$$E_{to} = \int_0^t \frac{dE}{dt} dt$$

$$(\text{Cu} - \text{Pt}) E_{to} = 5.85t + .0203t^2 - 2.48t^3 10^{-5} + .274t^4 10^{-7}$$

$$(\text{Cu} - \text{Pb}) E_{to} = 2.84t + .0041t^2 - .28t^3 10^{-5} + .0565t^4 10^{-7}$$

The emf of copper to lead was calculated from the direct data of Adams on the emf of copper-lead and of lead-platinum.

Adams and Johnston (62) give a general equation for the copper constantan couple, to be used in connection with deviation curves given by Sosman (66). The equation is:

$$E = 38.105\,t + 0.04442\,t^2 - 0.00002856\,t^3$$

The Peltier and Thomson effects may be calculated from the above equations.

(*c*) Electrolytic Solution Potential.—The electrolytic solution potential of copper to a solution containing its (bivalent) ions is given by Newman (69) who found for

$Cu/nCuSO_4$ (18° C)/normal hydrogen electrode
$E_h = -0.308$ (Cu ion concentration $= 0.11\,n$)
E_h (calculated) $= -0.329$ (Cu ions in $CuSO_4$ solution of n concentration)

Labendzinski (73) has determined with care the emf of copper to its cupric salts. His results are as follows:

	Normality	E_h
$Cu/CuSO_4$	1.0	+0.304
	.1	.284
	.01	.262
$Cu/Cu(NO_3)_2$	1.0	.331
	.1	.294
	.01	.266
Cu/Cu(acetate)	Saturated	.278
	.1	.264
	.01	.242

Cohen (69) has shown that the emf of copper amalgams of mercury content of from 1 to 16 per cent to a saturated solution of $CuSO_4$ at 25° C to Hg_2SO_4/Hg is 0.3471 volt.

The emf of copper to solutions containing cuprous ions has been studied by Bodländer-Storbeck (71). They find that the emf E_h

$Cu/0.05\,nKCl$ + saturated CuCl

is −0.194 volt.

The emf of copper to solutions of its salts (cupric) becomes less negative with increase of temperature (72). The temperature coefficient of emf between 0 and 50° C is

$$0 = 0.00066 \text{ volt per degree}$$

(*d*) Magnetic Properties.—Pure copper is diamagnetic. Its magnetic behavior is very profoundly altered by slight traces of iron present as an impurity. Thus, as little as 0.04 per cent iron makes copper paramagnetic (75, 77). Values given for K, the susceptibility, are

$K_v = -0.66 \times 10^{-6}$ (79)
$= -\ .82 \times 10^{-6}$ (electrolytic copper) (78)
$K_m = -1.22 \times 10^{-6}$ (native copper) (76)
$= -\ .086 \times 10^{-6}$ (electrolytic copper, Fe = 0.008 per cent) (80)
$= -\ .085 \times 10^{-6}$ (electrolytic copper, Fe = .0004 per cent) (81)

The value of K may thus be taken as -0.085×10^{-6} for pure copper. The temperature coefficient of K is given by the equation (78)

$$\alpha_0 = -0.0015$$

that is, the value of K decreases with temperature increase.

Cu_2O and CuO have been found to be paramagnetic (75)

$K(CuO) = \text{about} + 20.0 \times 10^{-}$
$K(Cu_2O) = +0.62 \times 10^{-6}$

2. THERMAL

(*a*) MELTING POINT, HEAT OF FUSION, BOILING POINT, VAPOR PRESSURE.—The *melting point* of copper is taken as 1083.0° C, the value adopted by the Bureau (87) in standardization of pyrometers, etc. Small amounts of oxygen lower the melting point markedly, the melting point of the eutectic $Cu - Cu_2O$ (3.45 per cent Cu_2O = 0.395 per cent oxygen) being about 1063° C.

Richards-Frazier (105) give 43.3 calories as the *heat of fusion* of copper.

It has not been possible to determine the *boiling point* of copper accurately; this has been due largely to the experimental difficulties. Greenwood (83, 84) states that there is an interval of about 100° C between the temperature at which copper first begins to form bubbles and that temperature at which ebullition is vigorous. This latter temperature he gives as 2310° C at 760 mm pressure, as measured with a Wanner optical pyrometer on electrolytic copper in an atmosphere of hydrogen, and states that it can readily be duplicated.

V. Wartenberg (87) states that the boiling point of copper lies above 2200° C, and Féry (82) places it at 2100° C.

Greenwood (84) also made three determinations of the vapor pressure of copper, his values being

At 2310° C	1.0 atmospheres
At 2180° C	.34 atmospheres
At 1980° C	.13 atmospheres

From these data Johnston (85) has given the formula

$$\log p = 9.14 - \frac{16400}{T}$$

p = vapor pressure in millimeters of mercury
T = absolute temperature

This gives a pressure of 0.001 mm at 1080° C. From this formula it follows (Johnston, loc. cit.) that the heat of vaporization of copper is about 75 000 calories.

(*b*) Thermal Conductivity.—An empirical law, approximate only, of Wiedemann-Franz-Lorenz connects the thermal conduc-

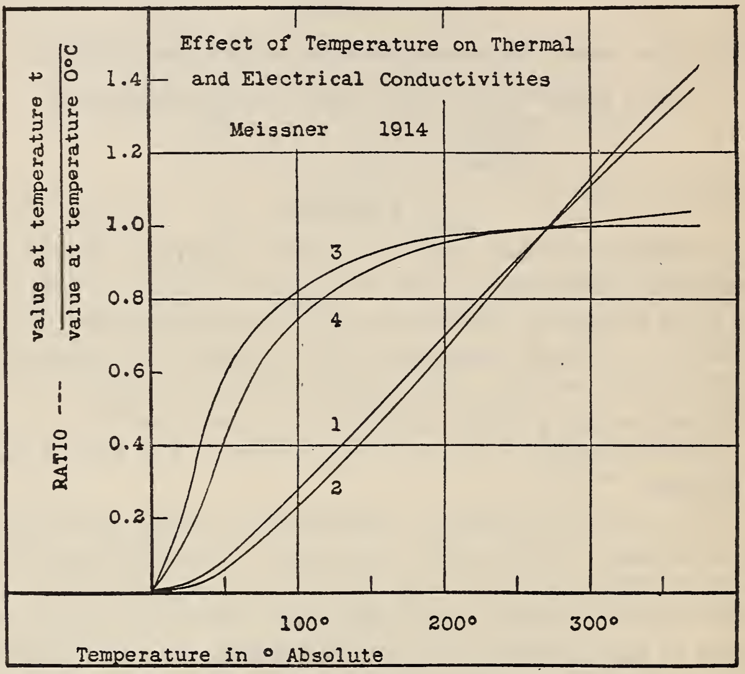

Fig. 13.—*Thermal and electrical conductivity at low and higher temperatures (Meissner, 84)*

Curve 1. $\lambda/x = \frac{\text{thermal}}{\text{electrical}}$ conductivity.
Curve 2. $1x$ = electrical resistivity.
Curve 3. $1x$ = thermal resistivity.
Curve 4. $\lambda/xT = \frac{\text{thermal conductivity}}{\text{electrical conductivity} \times \text{abs. temperature.}}$

All quantities expressed as fraction of respective values at °C. The portion of curve between 0° and 20° abs. is extrapolated.

tivity of pure metals with the electrical conductivity by the following relation:

$$\frac{\text{Thermal conductivity}}{\text{electrical conductivity}} = K \times \text{(absolute temperature)}$$

Determination of both conductivities were made in 1900 at the Physikalish-technische Reichsanstalt (90) on a "pure copper" (traces of iron and zinc together less than 0.05 per cent). The results were as follows:

Electrical resistivity (18° C) = 0.01782 ohm (meter-square millimeter) conductivity of 96.8 per cent (international standard).

Temperature coefficient of electrical resistivity at 18°C = 0.00393_8.

$$\text{Thermal conductivity } (18°\text{ C}) = 3.73 \left(\frac{\text{watt-seconds}}{\text{centimeter-second-degree}}\right)$$

Temperature coefficient of thermal conductivity $= 1.96 \times 10^{-4}$

$$\text{Ratio} - \frac{\text{thermal conductivity}}{\text{electrical conductivity}} = 665 \times 10^{-8}\ (18°\text{ C}).$$

Temperature coefficient of this ratio $= 3.67 \times 10^{-3}$

Schaufelberger (92) obtained in 1902 a value of 0.9382 $\left(\frac{\text{Calorie}}{\text{second-gram-degree}}\right)$ for "pure copper." The electrical conductivity of this material is, however, only 92.8 per cent, showing the material to be inferior in purity to that used by Jaeger and Dieselhorst.

At lower temperatures divergence from the Wiedemann-Franz-Lorenz law is still greater. The variation of the two conductivities and their ratio between 20 and 400° C absolute is given by Meissner (91) in Fig. 13.

(*c*) Thermal Expansion.—The linear thermal expansion of copper is not a linear function of the temperature but is well expressed (at least from −40 to +300° C) by a quadratic equation.

The thermal expansion of two samples of electrolytic copper furnished by the American Brass Co. has been determined at this Bureau.

One sample was in the form of hot-rolled and cold-drawn trolley wire of N. E. C. copper wire bar, of the following analysis:

	Per cent		Per cent
Copper	99.956	Nickel	0.0001
Silver	.0005	Selenium, Tellurium	.0000
Iron	.0006		
Lead	.0007	Sulphur	.0017
Arsenic	.0025	Zinc	.0000
Antimony	.0011	Oxygen	.0364 (diff)

This sample showed between −24 and +64° C, a unit linear expansion expressed (within 0.000003) by the following equation:

$$\frac{\Delta l}{lo} = (16.48t + 0.00382t^2)\ 10^{-6}$$

Another sample of electrolytic copper (battery assay 99.968 per cent Cu) hot rolled, drawn, and annealed, showed between −49 and +305° C an expansion expressed (within 0.000009) by the equation:

$$\frac{\Delta l}{lo} = (16.34t + 0.00413t^2)\ 10^{-6}$$

Dittenberger (95) gives the following equation from results determined between 0 and 625° C on a sample of copper of "good conductivity."

$$\frac{\Delta l}{lo} = (16.07t + 0.00403t^2)\ 10^{-6}$$

Henning (96) has determined the expansion at low temperatures of the same material used by Dittenberger. He finds a contraction between 0 and −191° C of 2.917 mm per 100 cm, which does not fit Dittenberger's formula.

Lindemann (97) finds Grüneisen's law, that the ratio:

$$\frac{\text{coefficient of thermal expansion}}{\text{specific heat}} \text{ is a constant,}$$

independent of the temperature, verified by determination of the coefficient at low temperature. He finds

$$\frac{1}{l}\frac{dl}{dt} \cdots \text{ from 85 to 292° C (absolute)} = 124 \times 10^{-6}$$

$$\frac{1}{l}\frac{dl}{dt} \cdots \text{ from 80 to 90° C (absolute)} = 75 \times 10^{-6}$$

$$\frac{1}{l}\frac{dl}{dt} \cdots \text{ from 20 to 80° C (absolute)} = 49 \times 10^{-6}$$

(*d*) Specific Heat.—The specific heat of copper is not constant but varies with the temperature. In Fig. 14 are given curves taken from various observers, indicating the effect of temperature on the specific heat of copper.

The results of determinations made at the Bureau (100) show that between 0 and 50° C the specific heat of copper (99.87 per cent pure, 100.5 per cent electrical conductivity, Mattheissen standard, is a linear function of the temperature and may be represented by the formula

$$C = 0.0917 + 0.000048\ (t - 25)\ \frac{\text{calorie}_{20°c}}{\text{gram-degree}}$$

This value agrees well with a probable value deduced from the om results any previous investigators.

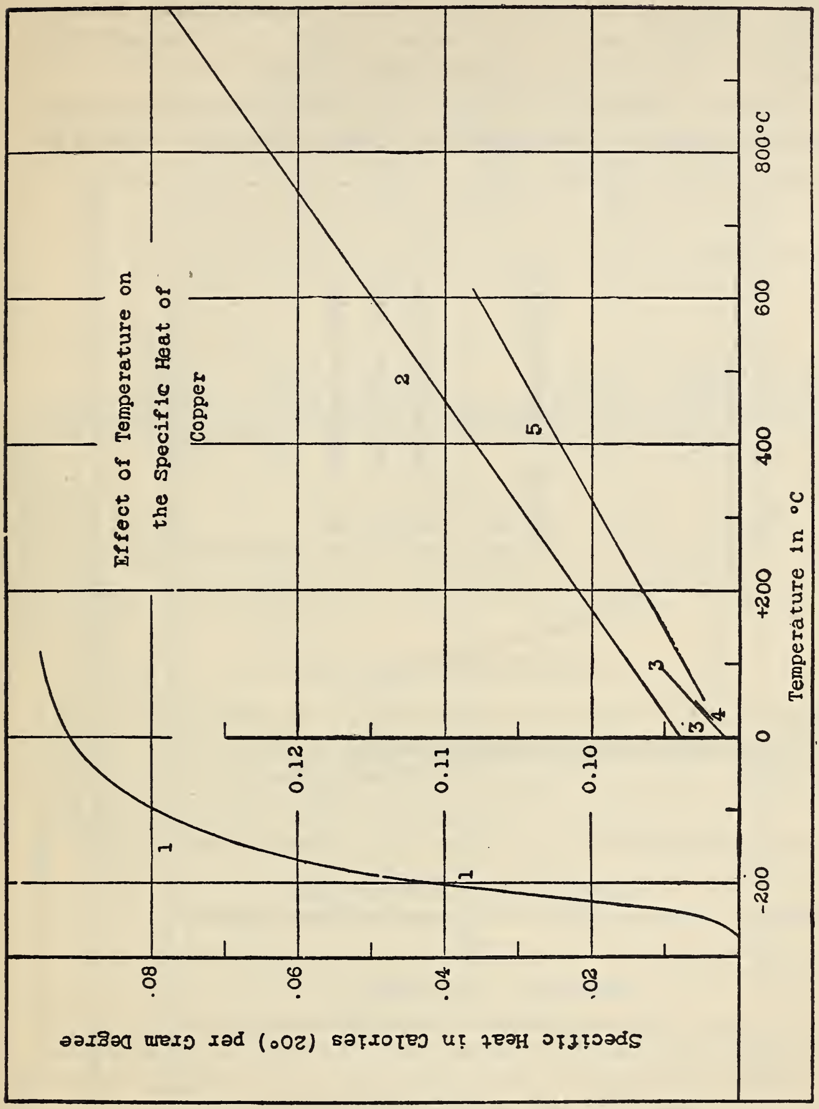

FIG. 14.—*Effect of temperature on specific heat (constant pressure)*

Curve 1. Nernst (102), electrolytic copper; Nernst and Lindemann (103); Keesom and Ormes (101).
Curve 2. Richards and Frazier (105).
Curve 3. Griffiths and Griffiths (99), electrolytic copper.
Curve 4. Harper (100), electrolytic copper.
Curve 5. Schübel (106).

3. OPTICAL

Copper is a red metal, which takes a fairly high polish and reflects well. The reflecting power and the refractive and absorption indices are given by the curves of Fig. 15. The selective absorption and reflection are strikingly indicated.

The relative emissivity of copper and of cuprous oxide at different temperatures, as determined by various observers, is given in

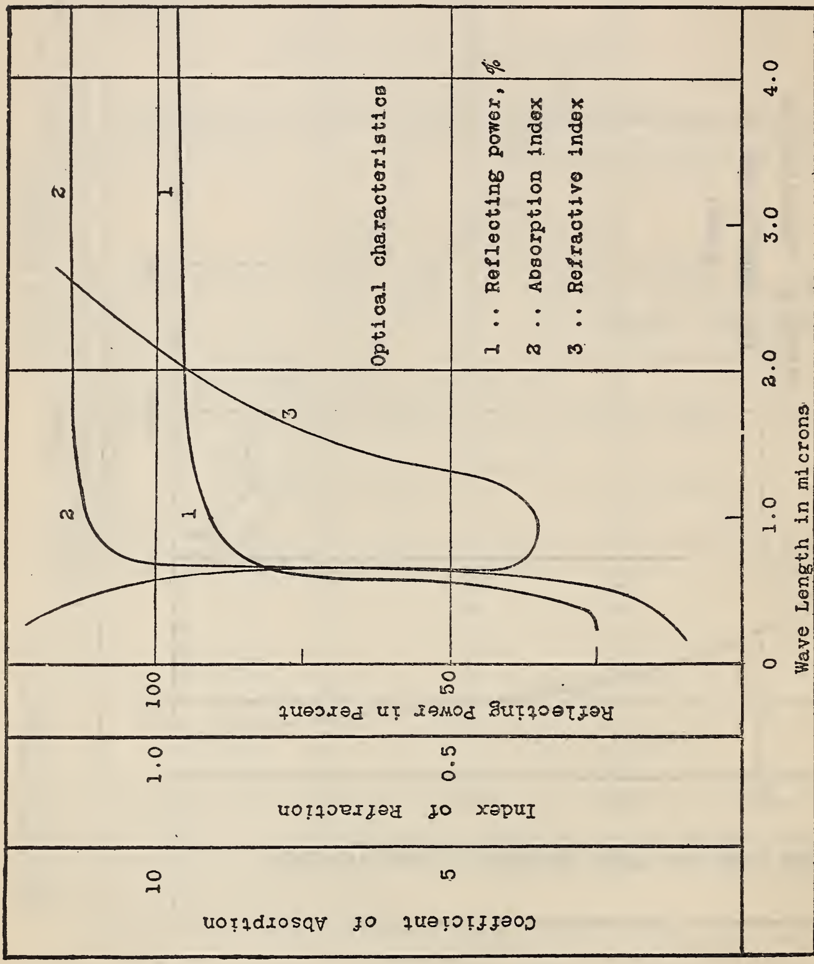

Fig. 15.—*Optical characteristics of copper*

Curve 1. Reflecting power (perpendicular incidence) in per cent. | Curve 2. Absorptive index—k. Curve 3. Refractive index—η.

Curve 1 from data by Hagen and Rubens (110, 111). Curves 2 and 3 from data by Minor (113) and Ingersoll (112).

Table 6. The selective emissivity is clearly shown, the copper absorbing or emitting strongly at the blue end of the spectrum. According to Bidwell (107), Stubbs (114), and Burgess and Waltenberg there is practically no temperature variation of E_λ between 20° and 1500° C.

TABLE 6.—Relative Emissivity of Copper

λ in microns	1—coefficient of reflection, Hagen and Rubens (110) 20° C (111)		Relative emissivity, Stubbs (114)			Relative emissivity, Tate (115) 20° C	Relative emissivity of Cu_2O, Burgess (108) 1100° C
	Electrolytic copper	Commercial copper	1090° C	1127° C	1174° C		
0.450	0.512	0.63	...	...	...	...	...
.475	...	...	0.374	0.473	...	...	...
.500	.467	.56	.374	.381	0.402	0.51	0.68
.550	.405	.52	.330	.340	.349	...	...
.560	...	...	...	...	...	.42	...
.600	.165	.28	.210	.210	.197	.29	...
.650	.110	.20	.148	.152	.146	...	.60
.660	...	...	...	...	...	.22	...
.700	.093	.17	.106	.130	.124	.21	...

Temperature, degrees centigrade	Relative emissivity for λ=0.65, Burgess and Waltenberg (109)	Relative emissivity for λ=0.55, Burgess and Waltenberg (109)	Relative emissivity for λ=0.66, Bidwell (107)	Temperature, degrees centigrade	Relative emissivity for λ=0.65, Burgess and Waltenberg (109)	Relative emissivity for λ=0.55, Burgess and Waltenberg (109)	Relative emissivity for λ=0.66, Bidwell (107)
700	...	...	0.11	1100	0.150 *l*	0.36 *l*	...
930	0.096 *s*	...	...	1200	...	...	0.11
1025	.105 *s*	...	...	1400	...	...	.11
1080	.117 *s*	0.38 *s*	...	1800	...	...	.124

s=solid. *l*=liquid.

4. MECHANICAL PROPERTIES

In any discussion of the mechanical properties of any material it must be constantly be borne in mind that most of the characteristics determined are more or less dependent upon the method of their determination, the size and shape of test piece used, the rate of loading, etc., as well as upon the previous mechanical and heat treatment of the material. This is much less true of the elastic properties and the moduli than of the ductility and strength. In general, therefore, it is not possible to assign definite values to these mechanical characteristics; only the range of values given by pure material treated in different ways can be given.

Martens, in an article of great value to those interested in the testing of copper (140), has shown that in the case of copper a variation of testing speed amounting to from 0.5 to 40 per cent elongation per minute causes a difference in the value of the ultimate tensile strength of less than 2 per cent.

Ludwik (139) has shown, however, that for longer periods the effect of time in testing is quite large. He found that a one-half millimeter diameter electrolytic copper wire which sustained a load of 4958 g for five minutes sustained a load of only 4500 g for 90 hours and one of 3950 g for one and one-fourth years.

Martens also showed that although the form of the test piece (ratio of test length to cross section, distance of test length from shoulder of test specimen, etc.) had practically no effect on the values of the ultimate strength and yield point of copper, it exerted a marked effect on the elongation and reduction of area in the tensile test; variations of 15 to 30 per cent were obtained on the same material by varying the ratio: $\frac{\text{length}}{\text{cross section}}$ from 1/20 to 1/2.

(*a*) ELASTICITY.—There is some divergence among the results of determinations of Young's modulus for copper. Values of 12 100 to 12 300 kg/mm² (17.2 to 17.5×10^6 lbs./in.²) for electrolytic copper have been obtained by careful investigators. Determinations by Searle (121) showed a value of 17.6×10^6 lbs./in.² for drawn and of 18.3×10^6 lbs./in.² for annealed copper. The temperature coefficient of E at ordinary temperature for copper is given by Wassmuth (125) as $\alpha = 3.59 \times 10^{-4}$ $[E = E_0\ (1 + \alpha t)]$ and is negative; that is, the modulus decreases with rise of temperature. Some values for the moduli at different temperatures are given in Table 7.

TABLE 7.—Influence of Temperature on the Elastic Moduli of Copper

Temperature, degrees centigrade	Mean modulus of torsion (124)	Young's modulus (144) *a*	Young's modulus (144) *b*	Temperature, degrees centigrade	Mean modulus of torsion (124)	Young's modulus (144) *a*	Young's modulus (144) *b*
	Lbs./in.²	Lbs./in.²	Lbs./in.²		Lbs./in.²	Lbs./in.²	Lbs./in.²
0	....	....	....	350	....	....	....
20	6.02×10^6	17.8×10^6	18.1×10^6	400	....	10.1×10^6	....
100	5.82×10^6	....	18.1×10^6	500	3.96×10^6	....	....
150	....	....	....	600	....	....	....
200	5.58×10^6	14.3×10^6	15.6×10^6	800	2.72×10^6	....	....
250	....	....	....	1000	2.10×10^6	....	....
300	4.85×10^6	11.8×10^6	13.5×10^6				

Poisson's ratio for copper is 0.33 ± 0.01; its temperature coefficient (0° to 150° C) about 0.00023.

The modulus of torsion for copper as given by Koch and Dannecker (124) is 4240 kg/mm² (6.15×10^6 lbs./in.²)

The modulus of hydrostatic compression for copper is approximately 12 000 kg/mm² (20).

(*b*) TENSION TEST.—Pure copper may best be normalized by casting, rolling, and drawing, followed by annealing for one-half to one hour at about 500° C, and then by slow or quick cooling; after this treatment there is less variation between different samples in the results of the tensile test than in any other condition. The tensile characteristics of copper in this state may be summarized as follows:

Ultimate tensile strength	35 000±5000 lbs./in.^{2}
Elastic or proportional limit	Not determinable
Elongation in 2 inches	40 to 60 per cent
Reduction of area	40 to 60 per cent

It will be noted that no value is given for the elastic or proportional limits; the usual method of determination of these

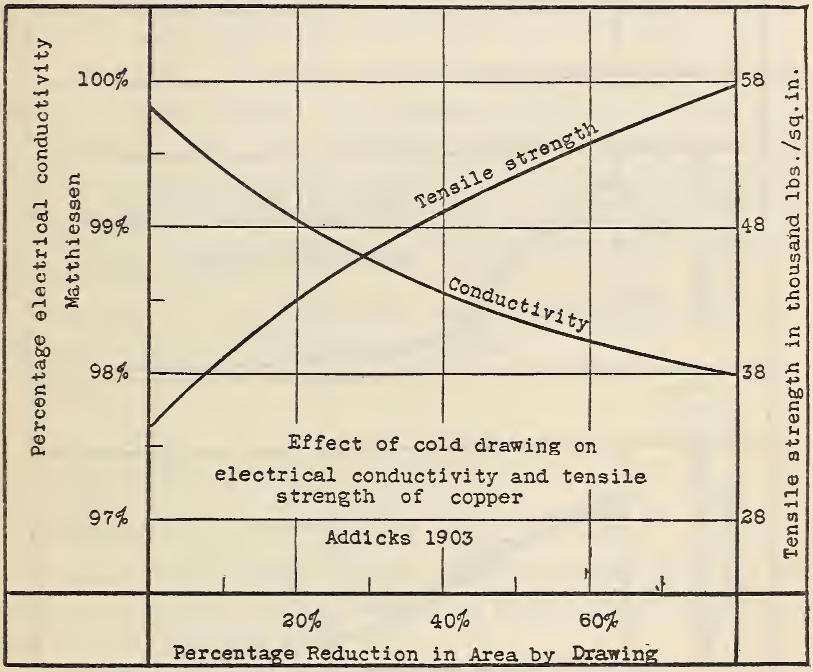

FIG. 16.—(184). *Effect of cold work on tensile strength and electrical conductivity of pure copper.* (*Addicks*, 243.)

The ultimate tensile strength and the per cent electrical conductivity are plotted as a function of the per cent reduction in area. The wires tested were drawn to No. 12 B. & S. gage from different sizes of annealed copper rod.

quantities does not yield any value; that is, annealed copper takes a slight permanent set with the slightest loads which are applied in testing. The values of the moduli given above are determined generally on hot-rolled material in which a practical proportionality exists for very small loads.

When copper is cold worked, rolled, or drawn the hardness is increased and the ductility is decreased. At the same time it

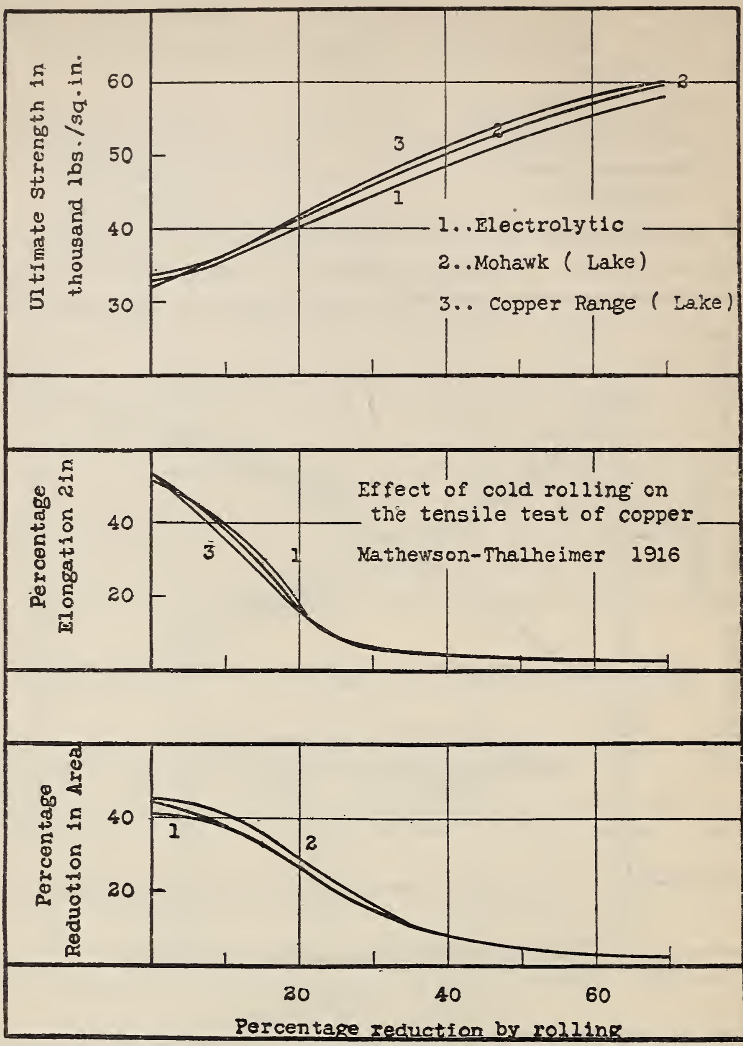

Fig. 17.—*The effect of cold work on the mechanical properties of copper (tensile test). Matthewson and Thalheimer (191)*

There are plotted the ultimate tensile strength, the elongation in 2 inches, and the reduction of area of copper strips rolled to different gages from an annealed strip 0.128 inch in thickness, as functions of the percentage reduction of section.

	Oxygen	Arsenic	Silver
Curve 1. Electrolytic copper	0.071	0.000	0.0005
Curve 2. Mohawk copper (Lake)	.052	.096	.069
Curve 3. Copper Range copper (Lake arsenical)	.055	.296	.052

acquires a limit of proportionality. The hardness and ductility of such material depend on the amount of cold work or reduction (rolling or drawing) it has received. Figs. 16 and 17 give a good idea of the changes in these quantities in copper strips with various degrees of cold reduction.

Experiments made at this Bureau have shown that modern hard-drawn copper wire is equally affected by drawing throughout the section, and that no hard or exterior skin exists. This has been corroborated by Peirce (141).

A good indication of what tensile test values are to be expected in commercial copper wire, hard, medium, drawn, and soft, may be obtained from the Amercian Society for Testing Materials specifications. (See p. 78.)

By increasing the current density and employing a rapidly rotating cathode Bennet (133) has been able to produce electrodeposited copper of a hardness approaching that of hard-drawn copper; that is, of a tensile strength of 68 000 lbs./in.^{2} Some experiments indicating the effect of varying current density upon the mechanical properties of copper were earlier obtained by Von Hübl (137).

Thurston (147) and others give values of the results of the tensile test on copper in different conditions.

	Ultimate strength, pounds per square inch
Cast copper	22–36 000
Copper, forged	34 000
Copper, bolt	36 000
Copper, sheet	36 000
Copper, wire	62 000

(*c*) Compression Test.—Copper of good quality does not fail in the compression test by fracture; it merely yields indefinitely and becomes flattened out.

Thurston (147) states that the resistance of copper to compression may be calculated (within the limits $e<\frac{1}{2}$) from the formula

$$C = 145\ 000\sqrt[3]{e}$$

c = resistance in pounds per square inch of original area

e = fractional compression.

This formula holds, according to him, for compressions up to 50 per cent for cylinders of three diameters length.

(*d*) Torsion Test.—Thurston (147) states that copper shafts will break under load when

$$d' = \sqrt[3]{\frac{Fl}{4000}} \text{ or } d' = \sqrt[3]{\frac{Fl}{8000}}$$

according as they are of cast or worked copper

d' = diameter in inches
F = torsional moment
l = lever arm.

He also gives the equation

$$d' = \sqrt[3]{\frac{5.1\ Fl}{S'}}$$

where S' for copper should be from 15 000 to 30 000 pounds.

(*e*) Shear Test.—The shearing stresses for copper are given in the Ordnance Manual of the United States War Department. The shearing resistance of copper may be taken (Thurston, 147) as equal to that of the ultimate strength in tension and subject to the same variations—that is, in the annealed or cast condition, from 22 000 to 36 000 lbs./in.^{2} The work done in shearing copper (for punched holes) is (147).

W = 96 000 dt
W = work in foot-pounds
d = diameter of hole
t = thickness of plate or sheet.

(*f*) Transverse Bending Test.—Thurston (147) gives the modulus of rupture as varying between 20 000 and 40 000 lbs./in.^{2}

(*g*) Hardness Test.—It is well known that this property is expressed in many different ways, many of them quite arbitrary.

On the Mohs or mineralogic scale copper has a hardness of 2.5 to 3. Tammann (146) states that soft and hard copper give the same values of sclerometer hardness. A hardened steel needle (Martens sclerometer) gave a scratch of 0.014 to 0.016 mm width when loaded with 10 g, and one of 0.022 to 0.027 mm when loaded with 17 g.

The scleroscope hardness of annealed copper varies from 6 to 7 (universal hammer), whereas that of hard copper (cold reduction, 66 per cent) varies from 22 to 24 (186).

The Brinell hardness of annealed or cast copper is 35 ± 5 (500 kg load, 10 mm ball); when hardened by cold work the ball hardness thus defined may become as high as 100. Guillet (189) has determined the ball hardness and the tensile strength of copper in various states of hardness, produced by pressing annealed copper in a steel die to different thicknesses. His results are given below.

TABLE 8.—Brinell Hardness of Copper

Per cent cold reduction of section	Brinell hardness numeral, 500 kg		Tensile strength	Elongation in 11 cm
	10 mm ball	5 mm ball		
			Lbs./in.^{2}	Per cent
0, soft annealed	42	50	33 600	46
10	70	74	36 000	24
20	81	81	40 000	13
30	86	90	45 000	5
40	94	92	47 800	4.5
50	96	95	52 600	4.2

It is seen that that ratio of $\frac{\textit{tensile strength}}{\textit{Brinell hardness}}$ is variable with the hardness of the copper.

(*h*) Impact Test.—Impact tests of copper have been so few that no final or typical values for copper could be chosen from the data. Baucke (132) has carried out a number of tests according to Frémont, using rectangular bars 10 by 10 mm, with a sharp saw notch of 3 mm depth; the specific impact work was measured. Some of the results are given in Table 9. He compares the tensile strength, reduction of area, and elongation (in (?) inches). For certain special brands carrying arsenic, nickel, and iron (98.5 to 99.9 per cent copper) giving tensile strengths of from 20 to 31 kg/mm^2 (28 400 to 44 000 lbs./in.^{2}) elongations of 40 to 50 per cent, reductions of area of from 50 to 77 per cent, the specific impact work (S. I. W.) varies from 10 to 33 kg-m (72.4 to 239 feet-pounds) in longitudinally cut specimens and from 9 to 31 kg m (65.2 to 224 feet-pounds) in transverse specimens. For ordinary brands, oxygen content 0.11 to 0.06 per cent, copper 99.5 to 99.8 per cent, having tensile strengths of from 21 to 24 kg/mm^2 (30 000 to 34 000 lbs./in.^{2}), elongations of 30 to 47 per cent, reductions of area of 33 to 70 per cent, the specific impact work varied from 10 to 15 kg-m (72.4 to 108.6 feet-pounds) in longitudinally cut specimens and from 3 to 11 kg-m (21.7 to 79.6 feet-pounds) in transverse specimens.

TABLE 9.—Impact Tests of Copper. Baucke (132)

COMMERCIAL FIRE-BOX PLATES

S. I. W.[a]		Chemical composition. Impurities in 0.01 per cent										
Longitudinally taken specimens	Transverse taken specimens	Antimony	Tin	Arsenic	Lead	Bismuth	Iron	Zinc	Nickel	Manganese	Oxygen	Per cent copper
Kg-m	Kg-m											
11.0	10.5	......	3	33	2	<1	11	1	......	......	6	99 44
11.0	5.5	......	......	......	1	1	2	......	9	......	8	99.80
9.0	6.1	......	......	......	11	......	4	12	......	......	8	99.57
10.9	3.1	......	......	1	3	1	5	......	23	......	10	99.57
10.8	9.1	......	2	......	5	1	3	22	10	......	10	99.48
10.4	5.3	......	1	......	......	<1	2	......	1	......	11	99.81
10.5	......	......	......	1	5	......	5	9	22	......	11	99.47
8.3	5.3	1	......	......	35	1	1	......	2	......	11	99.50
13.6	10.1	......	......	......	2	<1	19	1	......	......	11	99.66
19.0	6.6	......	1	......	3	<1	2	......	1	1	11	99.81
8.3	5.3	......	......	14	7	......	4	14	......	......	12	99.50
SPECIAL COPPER (HECKMANN) FOR PLATES												
28.6	26	......	201	......	......	......	......	45	......	......	......	......
28	......	......	82	......	......	......	......	40	......	......	......	......
18	......	......	......	7	......	......	3	......	4	......	......	......

[a] Baucke gives S. I. W. in kilos, but it is assumed that he means kilogram-meters.

(*i*) Fatigue or Alternating Stress Test.—Very little data of this sort are available. A few tests have been carried out by Johnson (259, 261), the results of which are embodied in Tables 10 and 14; he used the Arnold type of testing machine, which applies very high fiber stresses, above the elastic limit.

5. MISCELLANEOUS

(*a*) Density.—The density of pure copper, rolled, forged, or drawn, and afterwards annealed, may be taken as 8.89 at 20° C. This value was accepted by the International Electrotechnical Commission in 1913. Samples of high conductivity copper will vary (149) usually between 8.87 and 8.91; in some cases samples have shown densities as high as 8.94 and as low as 8.83. Variations in density may be due to microscopic flaws or seams (low density) or to the variation in the percentage of oxygen present

(0.03 per cent oxygen lowers the density by about 0.01). The density of cast copper will be about 8.89 when no blowholes are present; otherwise, lower densities will be found.

According to experiments by G. L. Heath (148), there is but an extremely small difference between the density of hard-drawn and drawn and annealed copper. No difference in density is detected between the two high grades of copper. The mean density of 10 hard-drawn samples of wire was 8.898; after these samples had been annealed their mean density was 8.900, showing an increase of density upon annealing of approximately 0.02 per cent. Similar values of the increase in density of hard copper upon annealing have been found also by Gewecke (187) and by Kahlbaum-Sturm (150); these ranged from 0.001 to 0.10 per cent, and averaged about 0.02 per cent.

VI. PHYSICAL PROPERTIES AT HIGHER AND LOWER TEMPERATURES

1. ELECTRICAL CONDUCTIVITY

Northrup (54) has determined the electrical resistivity of a sample of high conductivity copper from 20 to 1450° C. His curve is reproduced in Fig. 18.

Dewar-Fleming (161) have determined in terms of platinum resistance temperatures the resistance of copper at low temperatures, using an electrolytic copper, drawn into wire without melting or heating but subsequently annealed in hydrogen. Their results are as follows:

Temperature, degrees centigrade, calculated by Dickson (162)	Temperature, degrees centigrade, on the platinum-resistance scale	Resistance of copper, ohms (meter-square millimeters)	Temperature, degrees centigrade, calculated by Dickson (162)	Temperature, degrees centigrade, on the platinum-resistance scale	Resistance of copper, ohms (meter-square millimeters)
201.7	....	0.029269	− 81.9	− 78	0.010243
.55	....	.015639	−197.1	....	.002887
−39.4	....	.012975	−206	−223.2	.001436

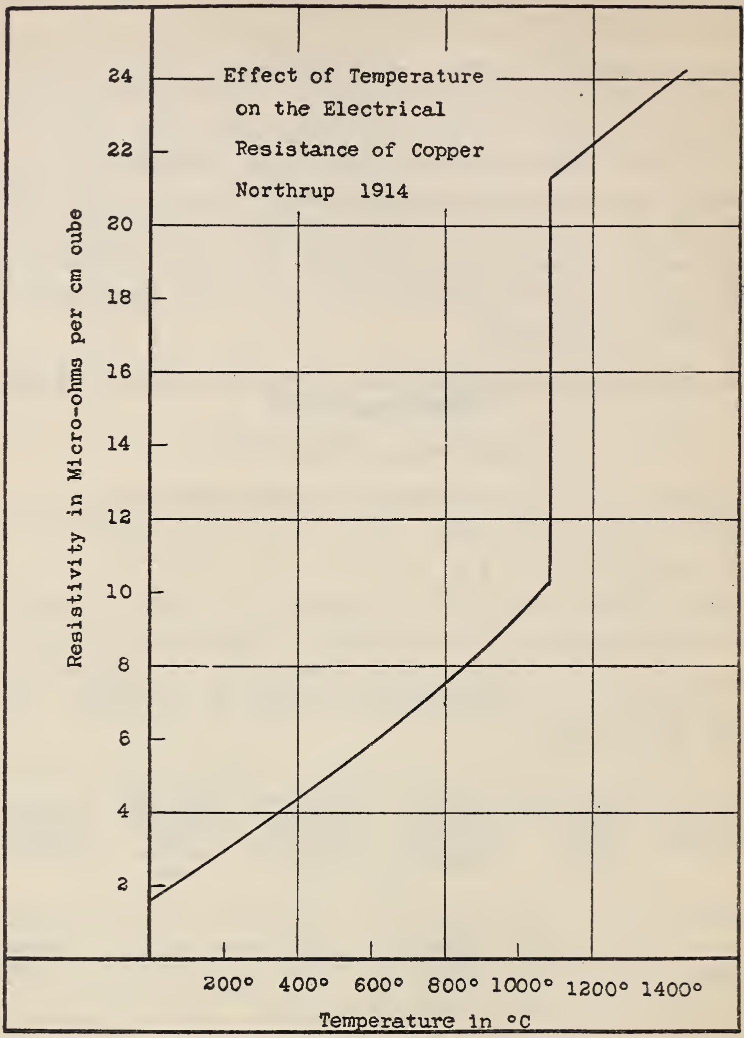

FIG. 18.—*The electrical resistivity of copper at higher temperatures.* (*Northrup, 54*)

2. MECHANICAL PROPERTIES

The mechanical properties which have been investigated at higher temperatures are chiefly those determined in the ordinary tensile test. Such determinations are complicated by several facts; the results are dependent on the rate of loading and on the

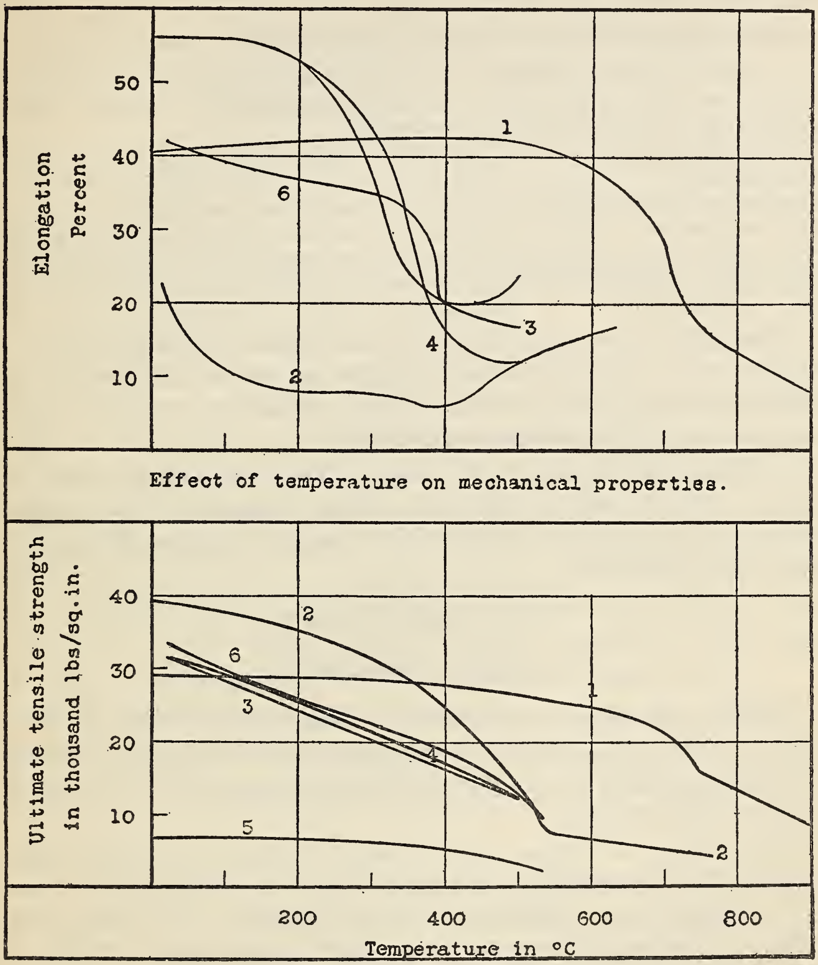

FIG. 19.—*Effect of higher temperatures on the mechanical properties of copper*

Curves 1 and 2 (152) are for annealed electrolytic copper (oxygen, 0.08 per cent; arsenic, 0.003 per cent; and iron, trace) and rolled arsenical copper (oxygen, 0.13 per cent; arsenic, 0.13 per cent; iron, 0.02 per cent; lead, 0.10 per cent; and tin, 0.08 per cent), respectively. The former was tested in air, the latter in CO_2; in both tests a constant rate (1.120 lbs./in.^{2} per minute) of loading was used. Curves 3 and 4 (156, 157) are for annealed electrolytic copper (arsenic, antimony, selenium, tellurium less than 0.05 per cent; bismuth, 0.0005 per cent) and for arsenical copper (arsenic, 1.2 per cent), respectively, tested in air. Curve 5 gives the yield point for the electrolytic copper; rate of loading was not constant nor given. Curve 6 is for "pure" copper (159).

atmosphere in which the tests are carried out. It is not surprising, therefore, to find considerable variation in the results of different observers. An idea of the range of results may be obtained from Fig. 19, in which elongations in 2 inches and ultimate tensile strengths are plotted as a function of temperature at which the tests were made.

Bengough and Hanson (152) come to the following conclusions:

(1) The nature of the atmosphere has an important influence on the results of tensile tests at high temperatures. An oxidizing atmosphere gives high ductility (at least with B. S. copper) at high temperatures.

(2) The existence of a range of low ductility in the neighborhood of 250 to 450° C is confirmed.

(3) Oxygen and arsenic lower the ultimate strength and increase the ductility at high temperatures. (This last deduction is perhaps not in accordance with the well-known fact that arsenical copper softens upon annealing at higher temperatures than pure copper. However the yield point, not the ultimate strength, determines the latter characteristic.)

Huntington (156, 157) has carried out alternating stress tests on copper up to 500° C and finds that the number of alternations to failure decreases with the temperature of test in much the same manner as does the ultimate strength.

Guillet and Bernard (153) have carried out impact tests on copper up to 1000° C, and find a linear decrease of the specific impact work required to bend the specimens (none of the test specimens fractured).

VII. TECHNOLOGY

1. CASTING, DEOXIDATION

Copper can be cast successfully in sand molds although difficulty is often encountered in the formation of blowholes, caused by disengagement of gas during solidification or in the oxidation of the molten metal.

The casting of copper from a large reverberatory furnace into chill molds for rolling ingots has already been described. (See p. 7.) The same difficulties are encountered in the casting of copper into sand molds; the metal may be cast porous, owing to the absorption of gas during melting and its disengagement during solidification or the molten metal may become overoxidized. The casting of copper into sand molds, therefore, is a much more difficult undertaking than that of brass or bronze.

Commercially copper is generally cast from a reverberatory furnace such as one of the down-draft Schwartz type; it may also however, be cast from a crucible with equally good results. If a melting furnace is used, the metal can be poled to pitch exactly as it is for chill-mold casting; small test ingots may be taken during poling to ascertain whether the copper is "tough-pitch" or not. Since poling can not be readily accomplished in a crucible, care must be taken during melting to prevent overoxidation of the copper, which can not subsequently be deoxidized as in the melting furnace. This is generally done by covering the copper with charcoal; often a handful of common salt is thrown upon the metal to form a protective layer.

In either case a low pouring temperature is not to be recommended; copper may safely be heated to 1300° C, particularly when a deoxidizing agent such as silicon copper or boron carbide is used.

The majority of copper castings are made in green sand, although for some purposes dry sand may be used.

Although good castings can be made with copper alone, modern practice in the casting of copper favors the use of a deoxidizing agent added to the molten copper before pouring; the deoxidizer removes the oxygen and prevents also either the gas absorption or its later disengagement during solidification, such that sound castings are produced with no oxygen. Such deoxidizers are phosphorus, silicon, calcium, boron suboxide or carbide, zinc, titanium, magnesium, etc. Generally speaking, it is intended to add just sufficient of the deoxidizing agent to remove the oxygen, such that none of the added element remains dissolved in the solid copper; in practice an excess of the element usually remains.

Many castings of copper are required to have high electrical conductivity such that in using or choosing a deoxidizing agent the effect of this agent upon the electrical conductivity must be considered. Most elements lower the conductivity of copper. (See Sec. IX.)

Phosphor copper (containing about 15 per cent phosphorus) is one of the most common deoxidizing agents used for copper. It is added to the molten copper in the proportion of about 1 to 2 per cent. An excess of phosphorus hardens the copper and diminishes the electrical conductivity markedly; except for the latter effect, phosphorus is a most efficient deoxidizer.

Zinc may be used as a deoxidizer (0.5 per cent), but offers no advantages over phosphorus; the mechanical properties of the casting are satisfactory but the conductivity is decreased.

Deoxidation by means of silicon copper (containing about 10 per cent of silicon) is quite generally practiced and is found satisfactory.

An excess of silicon affects neither the mechanical properties or the conductivity as markedly as phosphorus or zinc.

A number of tests made by one firm using 0.4 per cent of 10 per cent silicon copper, melting in a Schwartz furnace, gave the following range of values:

Tensile strength	23 000–26 000 lbs./in.^{2}
Elongation in 2 inches	25–45 per cent
Conductivity	78–84 per cent

This company expects the following values from remelted selected copper scrap using silicon copper:

Tensile strength	23 000 lbs./in.^{2}
Elongation in 2 inches	27 per cent

Castings have been made having conductivities of 90 to 96 per cent by the addition of 0.25 per cent of titanium copper. One firm states that sand castings of 71 per cent and chill castings of 91 per cent conductivity had been obtained by them using titanium copper.

Perhaps the latest deoxidizer for copper is boron carbide (superseding boron suboxide) developed by Dr. E. Weintraub, of the General Electric Co. (170, 171). This may be added as such or without separating it from the reaction product in which it is formed; if the suboxide, from 0.08 to 0.1 per cent should be added. It is claimed that in the foundry using scrap, castings will be obtained having a conductivity of about 90 per cent, although if pure metal is used, a conductivity of 97 per cent may be obtained. The other properties of such boronized castings are as follows:

Ultimate tensile strength	25 000 lbs./in.^{2}
Elongation in 2 inches	48 per cent
Reduction of area	74 per cent

The advantage claimed for this deoxidizer (which is also true of silicon copper) is that it is not so necessary to guard against an excess of the element remaining in the copper, as the suboxide does not remain in the copper but is removed with the dross; thus the material as cast is always as pure (free from metalloids) as the materials melted up.

With magnesium, conductivities between 75 and 85 per cent may readily be obtained in sand castings. This deoxidizer is readily handled, having a low melting point. A difficulty with this metal (as well as with titanium) is that the oxides do not separate readily from the copper.

A recent product, "boronic copper," widely advertised as a deoxidizing agent for copper and brass, does not show chemically the presence of boron or of any element which would deoxidize copper. Actual foundry tests made at this Bureau and elsewhere have failed to show any effect of the prescribed addition of such "boronic copper" upon the properties of the copper castings.

Copper has a fairly high shrinkage coefficient, which makes careful foundry practice necessary in avoiding shrinkage cavities, etc. Wüst has determined the shrinkage coefficient of copper (163) to be about 1.42 per cent (roughly, one-fourth inch per foot).

Copper may be remelted without deterioration in its properties if care is taken either to protect it from oxidation (in a crucible) or to pole it back to pitch (in a melting furnace). When it has become oxidized the mechanical properties of the cast material are inferior (155); such material can be regenerated after several remelts by the addition of boron carbide and other deoxidizers, giving castings whose mechanical characteristics (tensile strength and ductility) are 100 per cent and over of the original virgin metal.

2. WORKING

Copper of commercial purity is in practice worked either hot or cold, and most articles of copper are produced or formed by both hot and cold work, the metal usually being worked hot during the initial heavy reductions and finished cold. The actual detailed operations of producing such articles as sheet, wire, and rods vary somewhat in different plants.

Rods are rolled hot in one operation from wire bar to approximately one-fourth inch above the finished diameter desired, pickled, and "cleaned up" by drawing cold through steel dies to size.

Fine wire is, in general, rolled hot in one operation to one-fourth or three-eighths inch, pickled, drawn to about 0.048 inch, annealed, drawn to 0.025 inch, annealed, and drawn to smaller sizes. The full drawing operation is generally performed on a 9-die machine and may, of course, be earlier interrupted for intermediate sizes of wire; finishing draws may be made on single blocks.

Coarse wire, such as one-eighth inch, would be rolled from wire bar at three-eighths inch, pickled, and drawn to size without annealing, leaving the wire hard; the latter would then be annealed if soft wire were desired.

Wire bar may also be hot-rolled only to approximately 1 inch in diameter, cold-rolled on the looping rod mill to smaller sizes, and then finished by drawing as described above.

The wire bar is heated to from 750 to 800° C for hot rolling; annealing is carried out at incipient red heat—about 600° C.

Hard-drawn copper wire below one-fourth inch in diameter receives from 8 to 12 B. & S. gage numbers reduction subsequent to the last anneal; medium-drawn wire, about 2 B. & S. numbers; soft wire is annealed after the last draw. A one-fourth inch soft wire will stand a cold reduction to about one-thirtieth of its sectional area in the dies; a finer wire, annealed, will stand less; for example, a wire 0.05 inch in diameter can be readily reduced only to one-fourth of its area. Copper wire can be drawn as fine as 0.001 inch in diameter.

Copper sheet is made from cast cakes, 3 or 4 inches in thickness, by hot or cold rolling. For tanks, pipes, etc., these cakes are hot-rolled nearly to size, pickled in acid, and cold-rolled to size. The smaller gages of sheet are usually made by cold rolling; the furnace cake is hot rolled to about one-fourth or three-eighths inch, annealed, pickled, and rolled to size cold with intermediate annealing as necessary, in much the same manner as wire.

Seamless tubes are made by casting a hollow cylindrical billet and drawing down cold over a mandrel, or by piercing a solid cylindrical billet (the Mannesmann process). This is done at a temperature of about 850° C; the pierced tube is quenched in water, and may thereafter be further reduced or finished by cold drawing over a mandrel.

3. WELDING

Although copper can be welded either by the ordinary smith-welding process, by the oxyacetylene or by any of the electric processes, this method of joining copper has hitherto been little used; it has been preferred to solder, rivet, or braze the metal. This has been due to the fact that this metal is undoubtedly difficult to weld, owing to its rapid oxidation at welding temperatures, to its high thermal conductivity, and to the fact that impurities have such a marked effect on the mechanical properties at high temperatures.

A smith weld is made in the usual manner, using a flux of borax, borax plus sodium phosphate, or borax plus potassium ferrocyanide.

In making a weld by the oxyacetylene process, a larger size blowpipe is required than for iron and a lower temperature flame.

Copper can not be cut by the oxyacetylene flame as can iron and steel.

In arc welding two or three times the power is required for a weld than with iron.

Copper may also be "resistance" welded. Thomson contact copper-wire welding machines for this purpose are on the market.

In making a weld by any of these methods, the weld should be hammered in order to break up the cast structure and to restore the strength and ductility of the welded portion.

Carnevali (178) has made tests on welds of copper and finds that the strength in impact and static tests may be reduced 50 per cent, the toughness 30 per cent, and the ductility to 10 per cent of its original value. He used copper welding wire containing phosphorus and shows that within the welded zone a porous structure is produced due to disengagement of gas during solidification.

Thompson advocates the use of boronized copper as welding material or in making "burn-ins."

4. HARDENING

The popular interest in the so-called "lost art" of hardening or "tempering" copper is evidenced by the numerous inquiries on this subject received by this Bureau, together with samples of copper treated by some "secret" process in the endeavor to render the metal similar or equal to steel in many of its properties. The rather numerous patents covering such processes may also be cited as evidence of the interest in this field, the directions given in some of these patents for the treatment of the metal being very suggestive of the methods of working metals used in medieval times. The following may be quoted as typical:

> Heat the copper to 260° to 315° C and subject it while hot to the fumes of burnt sugar and animal fat at a temperature below that necessary to form carbon monoxide.

There are but two well-recognized methods for hardening copper: (1) By mechanically working it, and (2) by the addition of some alloying element. All of the samples of so-called "hardened copper" submitted to this Bureau showed that the superior qualities which were attributed to them were due to one or both of these causes. One method, used more frequently than any other, is to manipulate the melting of the charge so that the metal when cast is thoroughly impregnated with cuprous oxide, which renders the metal quite different from the purer copper in its mechanical properties. Inasmuch as cuprous oxide alloys with metallic copper in exactly the same sense that some other metals do, such a product is properly to be considered as an alloy and thus should be included under the second cause given above.

Gowland (183) makes the following authoritative statement regarding the "tempering" of copper as practiced by primitive peoples. "The castings (knives, swords, etc.) generally were hammered at their cutting edges and it is to this hammering, and to it only, that the (increased) hardness of the cutting edge is due, and not to any method of tempering." Most of the "copper" tools and knives of ancient origin contain considerable amounts of tin introduced by the smelting of mixed ores of the two metals so that resulting alloy can not fairly be compared with copper. Gowland further states "that the ordinary bronze of to-day can be made as hard as any, in fact harder than most, of prehistoric times by simple hammering alone."

5. ELECTRODEPOSITION OF COPPER

The principal industries utilizing the electrodeposition of copper are (1) electrolytic refining of copper, (2) electroplating, and (3) galvanoplasty, viz, electrotyping.

(1) The process of electrolytic copper refining has already been described above. (See Sec. II.)

(2) Electroplating.—Since most metals to be plated are more electropositive than copper, plating from the acid-sulphate bath is not satisfactory because of the initial deposition of the copper in a spongy form. On this account, an alkaline cyanide bath is used containing from 3 to 8 per cent of the double potassium copper cyanide.

In order to obtain thick copper plating, the article is first plated in the cyanide bath, and then transferred to an acid-sulphate bath where a deposit of any desired thickness may be obtained. The cyanide bath is usually operated at 50° to 60° C, using a sufficiently high current density to produce rapid evolution of gas.

(3) Galvanoplasty is the act of reproducing the forms of objects by the electrolytic deposition of metal upon a wax or metal surface which serves as a matrix for receiving the impression of the object to be reproduced. When deposited metal reaches the desired thickness, the wax or metal may be removed by melting. The process is extensively used for making electrotypes, copper tubes, and parabolic mirrors.

In electrotyping, the impression of the original type is taken in wax or lead. In case wax is used, its surface is made conductive by means of powdered graphite, while if lead is used, a greasy film is necessary to allow separation of the deposited "shell."

In the production of tubing, the metal is deposited upon a rotating cylinder, with or without simultaneous polishing.

In producing parabolic mirrors the surface of a glass form is made conductive by the ordinary "silvering" process. Copper is then deposited upon the silvered surface to give mechanical strength.

VIII. HEAT TREATMENT OF COPPER; EFFECT ON PHYSICAL PROPERTIES

Cold-worked copper is softened by annealing, the ultimate tensile strength being decreased, and the ductility increased. The temperature range within which this softening takes place most rapidly is from 200 to 325° C for pure copper reduced 66⅔ per cent (186, 193), but is markedly affected by two factors: (1) Extent of previous cold reduction and (2) presence of impurities.

Fig. 20 shows the annealing characteristics of three commercial grades of copper the same, of which the characteristics were described on page 34 and in Fig. 17, and of which the analyses were then given. It is noticed that the presence of arsenic raises the annealing range of the copper.

Impurities such as arsenic and silver raise the annealing temperature range of hard copper, oxygen lowers it. This is seen from the curves in Fig. 21.

The range of softening temperatures for copper is lower the greater the previous cold reduction. This is shown in the curves of Fig. 22.

Bardwell has studied the effect of annealing in raising the conductivity of hard-drawn copper wire. His curves are given in Fig. 23.

The properties of copper are not affected by a rapid cooling after annealing or rolling as are steel and certain copper alloys. It is generally held that quenching copper in water after annealing produces a softer metal than if it were slowly cooled; there is, however, little evidence either for or against this view.

Martens (140) found that two similar bars of copper, cold worked, and annealed, of which one (*a*) was quenched and the other (*b*) was slowly cooled, possessed the following properties:

Specimen	Tensile strength		Elongation in 10 cm	Reduction of area
	Lbs./in.²	kg/mm²	Per cent	Per cent
(a)	30 900	21.7	47.1	57
(b)	30 800	21.6	51.8	60

32618°—18——4

Johnson (261) also finds that his specimen, *EE*, Table 14, which was cooled slowly after hot rolling, has a greater ductility than two specimens of similar composition which were quenched.

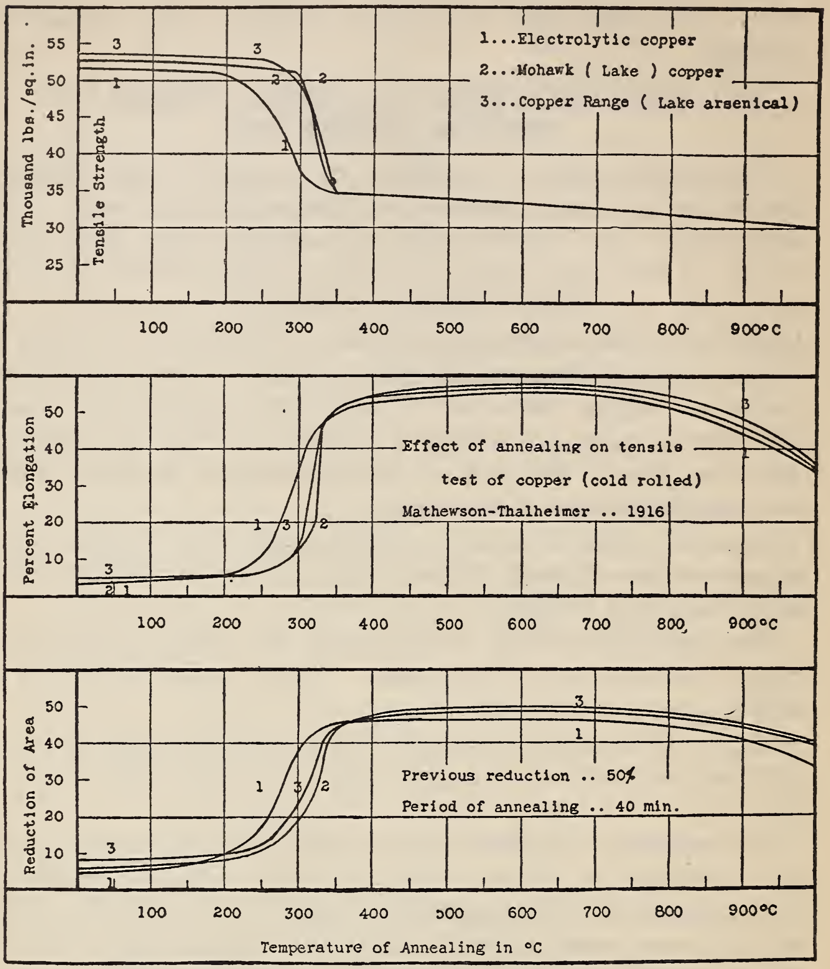

FIG. 20.—*Effect of annealing on mechanical properties (tensile test) of commercial varieties of copper (191)*

	Oxygen	Arsenic+ antimony	Silver
Curve 1. Electrolytic copper	0.071	0.000	0.0005
Curve 2. Mohawk copper (Lake)	.052	.096	.059
Curve 3. Copper Range copper (Lake arsenical)	.055	.296	.052

Previous reduction 50 per cent.

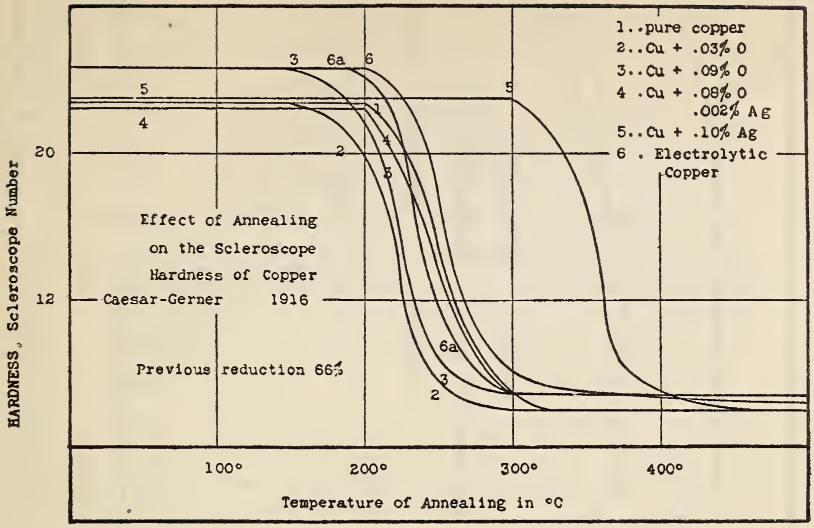

FIG. 21.—*Effect of impurities on the annealing properties of copper (186)*
Ordinates, scleroscope hardness; abscissas, annealing temperature.

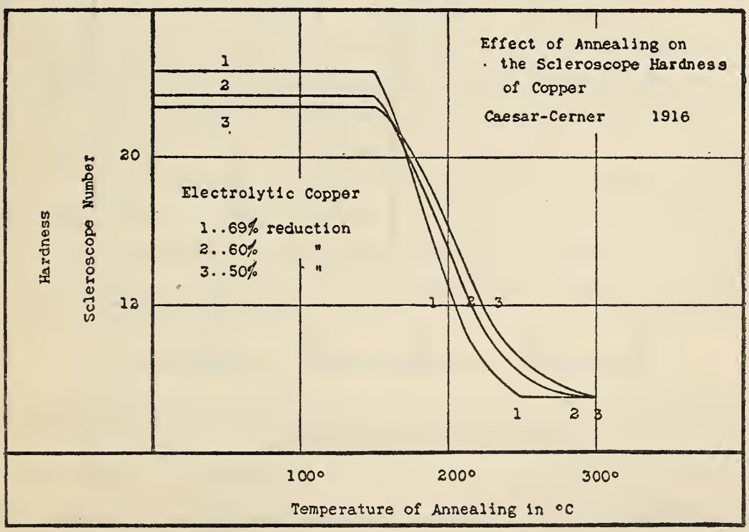

FIG. 22.—*Effect of extent of previous reduction on temperature annealing range for copper (186)*

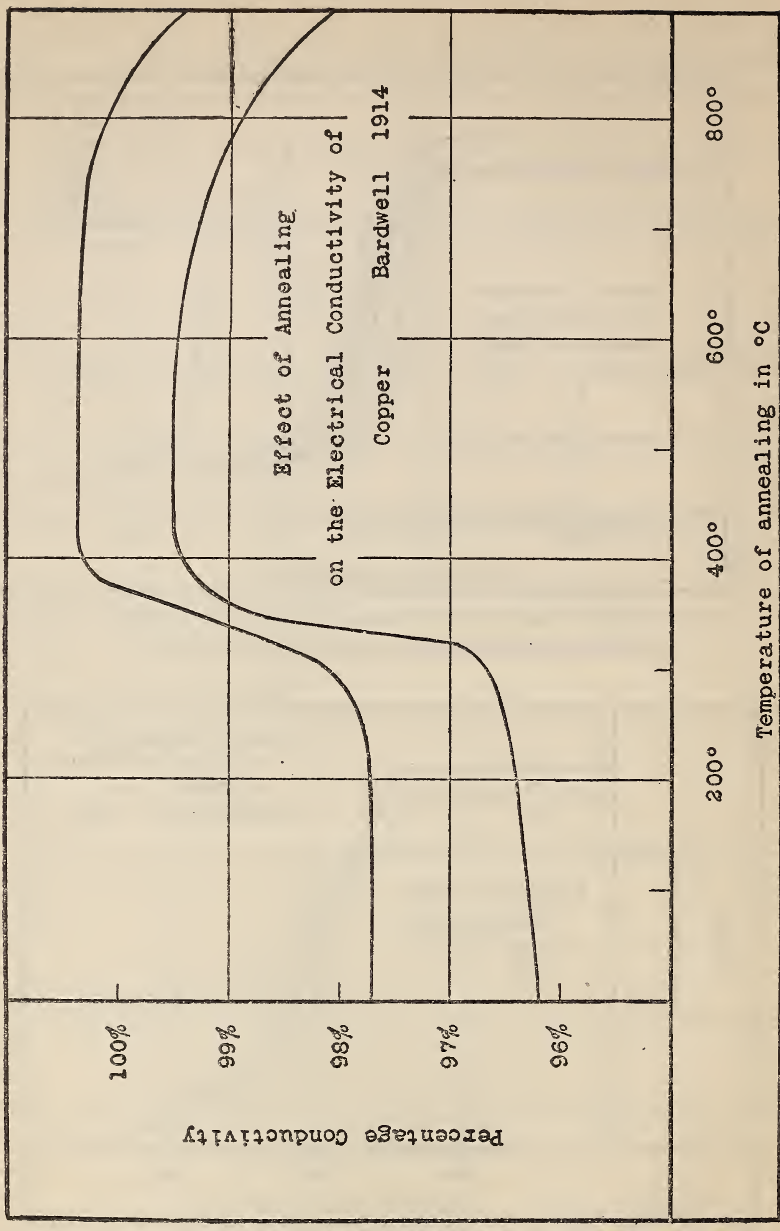

FIG. 23.—*Effect of annealing upon the electrical conductivity of hard-drawn copper (185)*

Ordinates, per cent conductivity, abscissas, temperature of anneal.

	Oxygen	Arsenic+ antimony	Copper+ silver
Material 1	0.070	0.0038	99.92
Material 2	.046	.0038	99.945

Previous reduction not given.

IX. IMPURITIES IN COPPER; EFFECT ON PHYSICAL PROPERTIES

The various physical and other characteristics of copper are affected in quite varying degree by the presence of impurities. Most markedly sensitive are the electrical and probably also the thermal conductivities and the mechanical properties (particularly ductility), especially at high temperatures, to the presence of impurities. The melting (also boiling) point is also changed by the presence of impurities; information concerning this is given by the equilibrium diagrams of these elements and copper. It has been noted that the magnetic susceptibility is very profoundly altered by the presence of slight amounts of iron. Otherwise the effect of impurities in the amounts ordinarily found in good commercial grades of copper have but little influence on it. The specific heat, for example, is an additive constant. Practically no data are now available concerning the effect of small amounts of impurities on the characteristics of copper other than those mentioned above.

1. ELECTRICAL CONDUCTIVITY

Addicks (243) has investigated systematically the influence of impurities on the electrical conductivity of copper. He used high-conductivity wire (99.5 to 101 per cent) in making up his alloy ingots; this was melted in a reducing atmosphere under charcoal with the added impurity. The ingot was cast in a heated iron mold, swaged down, and drawn cold to No. 12 B. & S. gage. The wires were then all annealed by passing 110 amperes through them, and tested. Fig. 24 gives a summary of the results of his tests. The presence of all these impurities lowers the conductivity; arsenic, phosphorus, and aluminum being particularly effective in this direction.

2. MECHANICAL AND "WORKING" PROPERTIES

A great deal of investigation has been made of the effect of individual impurities on the mechanical properties of copper, not all of which has been conducted with a full recognition of the factors which must be considered in manufacturing conditions. A knowledge of the effect of an impurity in small amounts on the otherwise pure copper is undoubtedly valuable, but such copper is not a commercial product. From the practical viewpoint, the effect of such impurities should always be considered in conjunction with that of the other usual impurities, principally oxygen.

It is a fact that the effect, particularly of lead, antimony, and bismuth, is most markedly altered by a variation of the presence of oxygen, arsenic, and other elements.

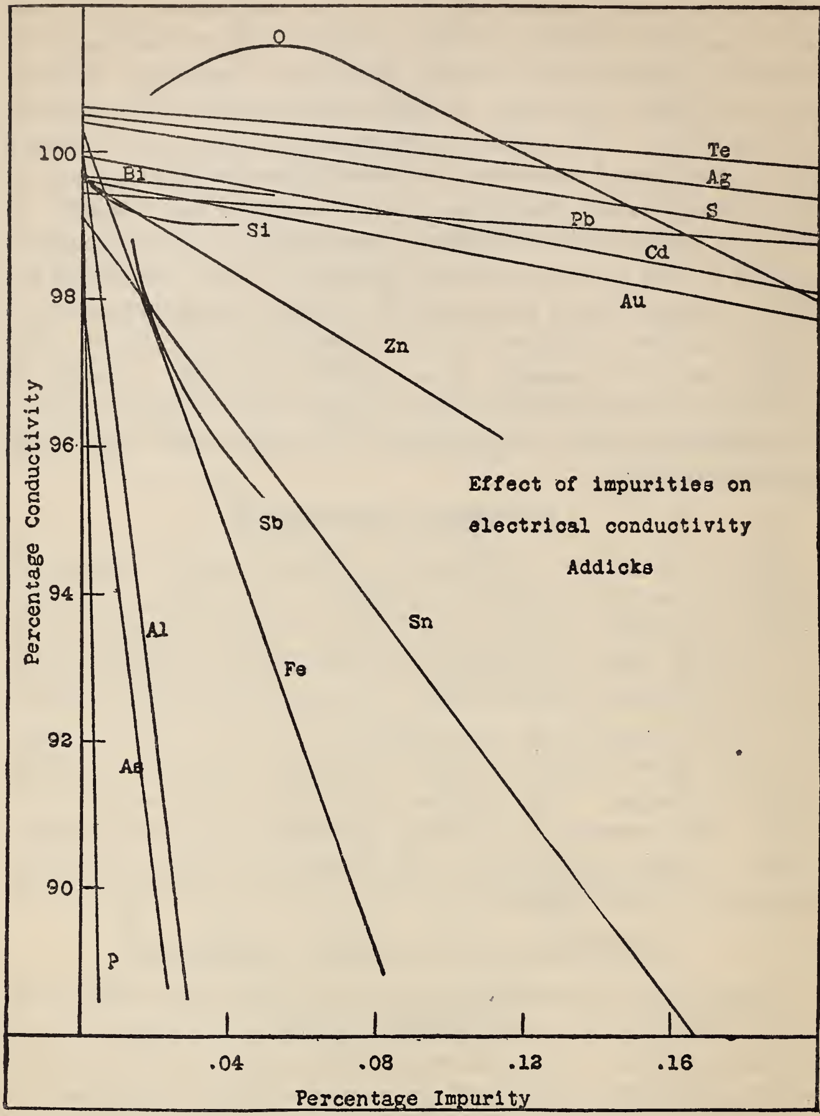

FIG. 24.—*Effect of impurities on the electrical conductivity of copper. Addicks* (243)

In considering the effect of individual elements a knowledge of the equilibrium diagrams of the binary alloys of these elements with copper is really necessary. Reference is made to these in the bibliography. The impurities to be considered may be grouped according to whether moderate amounts of them are soluble as a solid solution in copper, such as manganese, nickel, zinc, tin, aluminum, etc., or whether the impurity is but slightly soluble in the copper, such as bismuth, lead, etc. It is then found, in general, that impurities of the former class harden copper, diminish its ductility, but increase its toughness, and better its rolling and working properties, whereas those of the latter class do not harden the copper, but diminish both the ductility and the toughness and are quite injurious as regards the hot-working properties. The reason for this latter effect is to be found in the presence of the impurity as segregated particles or films of low melting point (300–500° C). The action of arsenic and oxygen is more complex.

ALUMINUM.—The equilibrium of copper-aluminum alloys has been studied by Carpenter and Edwards (196), Curry (197), and Gwyer (198). Copper takes up approximately 9 per cent of aluminum in solid solution.

Some results of Johnson (261), Table 14, indicate the effect of this metal on the mechanical properties of copper.

ANTIMONY.—The constitution of the copper-antimony alloys has been studied by Hiorns (200) and Baikoff (199). From 2 to 3 per cent of antimony as Cu_3Sb are held in solid solution by copper.

Johnson (259) has studied the effect of antimony on the mechanical and working properties of "tough-pitch" copper. His principal results are shown in Table 10, from which he drew the following conclusions:

(1) Antimony up to 0.5 per cent has no detrimental influence on the hot forging qualities of "tough-pitch" copper free from other impurities. It is even possible to forge copper containing 1 per cent antimony if sufficient oxygen be present.

(2) In copper which has been overpoled, antimony tends to mitigate the phenomenon of "spewing" during solidification.

(3) "Tough-pitch" arsenical copper (0.4 per cent arsenic) is slightly hardened for hot rolling by the presence of antimony (0.2 per cent), but otherwise its mechanical properties are slightly improved.

(4) The mechanical properties of "tough-pitch" pure copper after rolling and annealing are but slightly altered by small additions of antimony. The tensile strength is slightly raised (5 per cent) and the elongation lowered (10 per cent). The slight gain in toughness is probably traceable to the greater soundness of the ingot.

(5) With regard to the structural condition of antimony in "tough-pitch" copper, it exists in two forms: (*a*) Partly in solid solution (as Cu_3Sb); (*b*) partly as an insoluble compound with oxygen (slate-colored "oxidules"). Oxygen in excess exists as Cu_2O. The latter, together with the antimony oxidules, form a ternary eutectic with the solid solution.

TABLE 10.—Influence of Antimony on "Tough Pitch" Copper. Johnson (259)[a]

Ingot	Chemical composition			Rods as rolled			Rods as annealed		
	Oxygen	Arsenic	Antimony	Tensile strength	Elongation in 3 inches	Alternations to rupture, Arnold test	Tensile strength	Elongation in 3 inches	Alternations to rupture, Arnold test
	Per cent	Per cent	Per cent	Lbs./in.^{2}	Per cent	Number	Lbs./in.^{2}	Per cent	Number
RR	0.05	....	....	44 400	14.7	118	32 200	51.3	244
A3	.058	....	0.2	43 700	13.0	136	31 900	43.3	210
A2	.054	....	.29	43 600	16.7	116	33 500	46.0	268
AA2	.063	....	.3	43 800	13.0	118	32 800	48.3	258
AA1	.33	....	.49	45 500	6.0	49	34 000	44.7	138
A	.065	0.36	.2	45 200	15.3	119	33 500	48.7	258

[a] Specimens taken from rods rolled at red heat (900° C) from 1¼-inch square ingots: rods rolled in six passes to 11/16 inches, finished a dull-red heat, annealed by raising to a bright-red heat, quenched in pickling bath, and rolled cold to ⅜ inch, and straightened by drawing once through a die. All ingots were tough pitch, with level surface, and they all rolled perfectly. The copper used was the purest electrolytic (Vivian & Sons, Swansea).

All of the ingots listed in the table rolled well hot; ingot *A1*, containing antimony, 0.5 per cent; oxygen, 0.02 per cent (overpoled), was red short and was removed from the rolls at the third pass. Samples of five-eighths inch rods were rolled cold after annealing into strips one-eighth inch thick; rods *RR*, *A*, *A2*, and *AA2* showed no edge cracking; *AA1* showed edge cracking when a thickness of three-sixteenths inch had been reached.

There is much further information of a special nature in this paper and the discussion on it which will interest those desiring more complete information on this subject.

The earlier investigators of this subject were Hampe (253), Hiorns (256), Greaves (252), T. Johnson (264), Lewis (269), and Archbutt (244). Hampe finds that copper with 0.53 per cent antimony can be drawn into wire, and with 1 per cent antimony is red short. Hiorns finds that antimony (0.2 per cent) when added to copper containing lead (0.2 per cent) diminishes the brittleness caused by the lead.

Baucke (246) has determined the effect of antimony on the toughness (S. I. W.) of copper. (See Table 15.)

ARSENIC.—The constitution of the copper-arsenic alloys has been studied by Friedrichs (201) and by Bengough and Hill (202).

A compound (Cu_3As) is formed which is partially soluble in solid copper; the exact limit of solubility has not been determined; it lies probably between 1 and 3 per cent arsenic; that is, copper will take up in solid homogeneous solution that quantity of arsenic as Cu_3As.

Next to oxygen this is probably the most important impurity occurring in copper. Lewis (268) and Bengough and Hill (247) have studied its effect on the mechanical properties of rolled copper; their results are summarized in the following tables.

TABLE 11.—Influence of Arsenic on the Mechanical Properties (Tensile Test) of Rolled Copper. (Lewis, 268)

[Specimens were cast, rolled hot to one-eighth inch diameter and quenched]

Arsenic	Tensile strength	Elastic limit	Elongation in 1 inch	Arsenic	Tensile strength	Elastic limit	Elongation in 1 inch
Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent
0.00	26 800	14 000	25	0.094	36 000	18 000	25
.24	33 800	20 000	27	1.37	37 700	20 000	28
.53	36 800	19 000	29	1.80	35 700	23 000	20
.75	36 600	18 000	21				

TABLE 12.—Influence of Arsenic on the Mechanical Properties of Rolled Copper. (Bengough and Hill, 247) [a]

Chemical analysis [b]				Physical properties				
Copper	Arsenic	Oxygen	Sulphur	Tensile strength [c]	Yield point [c]	Elongation in 2 inches [c]	Reduction of area [c]	Scleroscope [c]
Per cent	Per cent	Per cent	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent	Number
99.055	0.04	....	0.005	34 800	14 000	58	79	11-15
99.733	.26	0.12	.007	35 300	21 000	40	79	11.3
99.344	.75	....	.006	35 100	14 000	57	79	11.0
99.052	.94	.15	.008	37 100	19 300	54	70	10.5
98.055	1.94	.20	.005	37 900	14 000	62	80	10.5

a Specimens prepared from B. E. R. copper and arsenic; alloy poled, cast into 3-inch, ingots, rolled at good red heat with one reheating and finished by drawing cold with one pass of 3/64 inch to 1 inch and tested.

b No trace found of lead, tin, or iron.

c Results are average of two tests.

Bengough and Hill summarize their mechanical tests as follows:

(1) Arsenic in small quantities tends to increase the maximum stress without affecting appreciably the ductility of these alloys.

(2) It increases their resistance to reducing gases at high temperatures.

(3) Alloys with low percentages of arsenic tend to be unhomogeneous, but with increase in the arsenic this ceases to be apparent * * * .

(4) In ordinary oxidizing atmospheres no heat treatment (for three hours or less) short of an approximation to fusion seriously affects the properties of these alloys. The only result of annealing is to render the bars slightly more homogeneous, and to lower the yield point somewhat. This statement, however, does not apply to annealing temperatures in the neighborhood of 1000° C.

(5) Alloys containing less than 1 per cent of arsenic are ruined by the action of reducing gases for three hours at 700° C or above it; in some cases the action is apparent at 600° C. * * *

(6) The yield points of these alloys are somewhat variable and unsatisfactory.

According to these investigators arsenic in amounts up to 1.9 per cent causes, therefore, neither hot nor cold shortness when, as usual, copper oxide is present; that is, in tough-pitch copper. It seems that the presence of oxide affects the influence which arsenic exerts on copper. Roberts-Austen (275) finds that 1 per cent arsenic begins to cause red shortness in oxide free copper. Jolibóis and Thomas (262) state that 0.4 per cent arsenic causes cold shortness in pure copper, whereas 0.4 per cent $x As_2O_3.Cu_2O$ does not.

Baucke has studied the effect of arsenic on the toughness of copper. (See Table 15.)

"Arsenical" copper such as is used commercially for copper which must resist high temperatures, in locomotive fire boxes, etc., contains from 0.1 to 0.4 per cent of arsenic.

Bismuth.—The constitution of the copper-bismuth alloys has been studied by Jeriomin (204), Portevin (203), and others. The amount of bismuth taken up by copper in solid solution is practically zero; it has never been accurately determined.

Johnson (261) has investigated the effect of small amounts of bismuth on the tensile properties, ductility, and malleability of tough-pitch copper. His results are summarized in Table 14. His conclusions are:

> The effect of bismuth on the mechanical properties of "tough" arsenical copper which has been rolled is not serious up to 0.1 per cent, but no commercial arsenical copper could be regarded as fit for working at a red heat, which contained so much bismuth. With 0.02 per cent, although the hot-working properties would be noticeably coarser than if no bismuth were present, the copper would not be ruined. Any crude copper containing over 0.01 per cent bismuth should be regarded with suspicion, since the copper might contain traces of other impurities—e. g., nickel—which, while intensifying the injurious effect of bismuth, would hinder the corrective action of arsenic.

Johnson also concludes that an explanation of the less intense effect of bismuth on the hot-rolling properties of oxygen bearing copper is due to its presence therein as Bi_2O_3 or combination thereof as isolated particles, whereas in overpoled or oxygen free copper the bismuth is present as films of metallic bismuth, which owing to its low melting point destroys the cohesion of the mass at high temperatures.

Other investigators of this subject have been Roberts-Austen (275), Hampe (253), E. A. Lewis (269), and Arnold and Jefferson (245). Roberts-Austen made oxygen free, bismuth bearing copper alloys, which could not be worked at all with more than 0.1 per cent bismuth. Lewis comes to practically the same conclusions as does Johnson regarding allowable bismuth limits and shows that whereas arsenic corrects the ill effects of bismuth, manganese, tin, aluminum, etc., intensify them.

Iron.—The constitution of the alloys of copper with iron has been studied by Ruer and Fick (211), Sahmen (210), and others.

Copper will take up 2 or 3 per cent of iron in solid solution. Within those limits iron hardens copper and diminishes its ductility. No systematic investigation has been made of the effect of iron on the mechanical properties of copper.

Lead.—The constitution of the copper-lead alloys has been studied by Friedrich and Leroux (212), Heycock and Neville (213), and others. The amount of lead which copper will hold in solid solution is very small, probably much less than 0.1 per cent. No systematic study has been made of the effects of lead on the mechanical properties. Its effect on the working properties at high temperatures is dependent on the amount of arsenic or Cu_2O present; 0.1 per cent of lead would render pure copper unworkable, whereas with 0.3 or 0.4 per cent arsenic such a percentage of lead is not out of the question.

Archbutt (244) was able to forge oxide free copper ingots containing 0.05 per cent lead and those containing 0.1 per cent lead and 0.4 per cent arsenic without cracking of the ingots.

Johnson (259) states that the mechanical properties of arsenical copper at ordinary temperatures are but slightly affected by the addition of lead. Rods prepared by him (see Table 10 for method of preparation) containing oxygen – 0.023, arsenic – 0.39, lead – 0.18 per cent, showed the following properties:

	Tensile strength	Elongation in 3 inches	Alternations to rupture, Arnold's test
	Lbs./in.^{2}	Per cent	
As rolled	41 200	17.3	169
As annealed	32 900	53.3	238
Original electrolytic copper:			
As rolled	44 400	14.7	118
As annealed	32 000	51.3	244

The ingot of this leaded copper rolled well (see Table 10 for description of rolling), whereas one containing 0.012 per cent oxygen, 0.38 per cent arsenic, and 0.35 per cent lead smashed at the first pass.

Manganese.—The constitution of the alloys of copper and manganese is discussed by Sahmen (219), Schemtuny, Urasow, Rykowskow (218), and others. Copper and manganese form a continuous series of solid solutions.

Muenker (273) gives results of tests of alloys of copper and manganese (see Table 13), from which it is seen that manganese in small amounts hardens copper and diminishes its ductility.

TABLE 13.—Effect of Small Additions of Manganese, Phosphorus, and Tin on the Mechanical Properties of Copper. Muenker (273) [a]

Composition, per cent	As cold rolled; unannealed			Annealed at 500° C					
				Quenched in water			Slowly cooled		
	Ultimate tensile strength	Elongation in 7.5 cm	Brinell hardness numeral	Ultimate tensile strength	Elongation in 7,5 cm	Brinell hardness numeral	Ultimate tensile strength	Elongation in 7.5 cm	Brinell hardness numeral
	Lbs./in.^{2}	Per cent		Lbs./in.^{2}	Per cent		Lbs./in.^{2}	Per cent	
B. E. R. Copper	52 300	4.24	94	34 100	46.07	74	32 500	46.64	63
Phosphorus: [b]									
0.014	52 900	4.04	96	35 100	45.08	74	32 700	46.54	63
0.042	55 300	3.89	101	35 800	44.10	74	32 800	45.84	65
0.092	57 000	3.43	112	35 900	42.98	74	33 600	44.80	68
0.173	57 800	3.33	118	36 600	41.44	74	34 600	41.70	70
0.399	60 500	3.27	130	37 400	39.81	77	36 300	40.74	74
0.563	66 200	2.46	145	41 200	39.74	84	38 500	40.02	77
1.062	75 900	2.28	160	46 800	38.14	96	41 000	39.87	84
Manganese:									
0.04	52 400	4.14	94	34 200	45.13	77	32 600	45.69	74
0.07	53 300	3.97	96	34 400	44.44	77	33 200	44.72	74
0.12	54 000	3.94	96	34 300	44.22	77	33 900	44.52	74
0.19	54 600	3.94	96	34 600	44.06	77	33 500	44.15	74
0.29	55 400	3.97	99	34 800	43.97	77	34 500	44.43	77
0.40	56 100	4.02	99	35 500	43.98	77	34 700	44.31	77
0.61	56 400	3.99	99	35 800	43.22	81	34 900	44.38	81
0.98	58 400	4.09	106	37 600	42.94	84	36 700	44.41	84
1.34	63 200	3.98	112	40 000	40.59	88	38 500	42.58	84
1.49	64 400	4.12	118	40 700	39.93	94	39 000	40.56	88
Tin:									
0.13	56 300	3.02	106	36 600	43.24	81	35 100	43.97	79
0.24	57 100	3.03	106	37 400	43.01	81	35 900	43.22	81
0.32	60 000	2.91	106	38 600	42.81	81	36 300	43.05	81
0.40	62 300	2.99	118	38 200	42.37	84	36 200	43.08	84
0.53	62 700	3.09	118	38 600	42.24	84	37 000	42.68	84
0.62	63 500	2.95	118	40 100	42.14	90	38 200	42.32	86
0.88	64 800	2.89	125	40 500	41.94	92	38 100	42.10	86
1.15	66 200	2.90	130	40 600	41.75	96	39 300	42.39	88
1.24	67 600	2.84	136	42 800	41.73	96	40 900	42.25	92
1.46	69 600	2.67	145	44 700	40.97	101	41 700	41.35	96

[a] The alloys were made under commercial conditions with B. E. R. copper and additions of phosphor-copper, tin-copper, and mangan-copper. The cast slabs were first hot rolled and then finished cold. Samples were annealed at 500° C and either quenched or slowly cooled. The tensile tests were carried out on strips 3 mm thick, 15 mm wide, of a test length equal to $11.3\sqrt{\text{cross section}}$ or about 75 mm. The Brinell tests were made with a load of 500 kg and a ball of 5 mm diameter.

[b] The phosphorus alloys were otherwise as pure as the original B. E. R. copper; the manganese and tin alloys contained also from 0.012 to 0.020 per cent of phosphorus.

Baucke has studied the effect of manganese on the toughness of copper. (See Table 15.)

NICKEL.—The constitution of the nickel-copper alloys has been studied by Guertler and Tammann (220), Tafel (222), and others. The two metals form a continuous series of solid solutions.

Small additions of nickel harden copper and diminish the ductility slightly, apparently increase its toughness however; see Table 15 (Baucke).

Oxygen.—The constitution of the alloys of copper and oxygen (Cu_2O) shows that oxygen is present in copper as Cu_2O, not dissolved appreciably by the copper (223). There seems to be no published records of test results showing the effect of oxygen on copper free (in the commercial sense) from other impurities. It is, of course, well known that in heating copper it must be brought to pitch in order that it may be cast free from blowholes and possess the best mechanical and "working" properties. If under pitch, the presence of blowholes will cause seams in the metal which may open up in drawing; if underpoled, the excess oxygen may cause cracking during cold rolling, and if the oxygen is in amounts as great as the eutectic composition, it may also be hot short.

Hampe (253) found that Cu_2O had no effect on the strength or malleability of pure copper until 0.45 per cent was reached, when a very slight diminution of tenacity was recorded. Ductility in the cold was not affected until 0.9 per cent was reached. Beyond 0.9 per cent, the quality of the copper suffered more and more as the proportion of Cu_2O was increased.

Johnson has given some results of tests of oxygen bearing arsenical copper. (See Table 14.)

The influence of oxygen on copper is chiefly interesting in conjunction with that of other impurities, notably bismuth, antimony, arsenic, and lead. It diminishes the embrittling effect of bismuth (Johnson) and lead; this is probably due to two facts: (1) That in the presence of oxygen an oxide of either of these metals is formed which melts at a higher temperature than the metal, and (2) that this oxide is distributed as fine globules instead of thin plates as is the metal.

Greaves (252) has studied the effect of oxygen in copper containing arsenic and antimony, considering the cold-rolling and drawing properties, hardness, and microstructure. He cold-rolled strips from 0.35 to 0.02 inch in thickness with intermediate annealing and drew the following conclusions:

As the amount of arsenic increases up to 0.5 per cent the metal may take up more oxygen without suffering deterioration in its capacity for rolling. This quantity of oxygen rises from about 0.05 to 0.2 per cent as the arsenic increases from 0 to 0.2 per cent, then more slowly to about 0.28 per cent as the arsenic rises to 0.5 per cent. * * * When less than 0.3 per cent of O_2 is present, a metal which will roll perfectly is obtained before the arsenic reaches 0.5 per cent.

In a similar way antimony up to 0.4 per cent reduces the cold shortness of pure "dry" copper.

His conclusions, relative to wire-drawing tests, are that the conditions obtaining are entirely similar to those for the rolling of copper.

Baucke, Tables 9 and 15, has given some results on the toughness of cast and forged alloys with varying percentages of oxygen.

PHOSPHORUS.—The equilibrium diagram for alloys of copper and phosphorus has been partly established by Heyn and Bauer (224). Phosphorus in the form of Cu_3P is dissolved in copper to the extent of 0.175 per cent. Phosphorus in these small amounts hardens copper, as can be seen from Table 13 of Muenker's (273) results.

SILICON.—The alloys of silicon and copper have been studied by Rudolfi (226) and Guertler (227).

Copper with small amounts of silicon (0.02 to 0.10 per cent) is used abroad for telephone wire, electric cables, etc. The electrical conductivity is decreased by about 2 per cent by the addition of 0.02 to 0.05 per cent silicon (Guillet).

Apparently in small amounts it does not harden copper appreciably (Vickers, 281); the copper cast with silicon as a deoxidizer is often called silicon bronze, although it contains practically no silicon.

SILVER.—The constitution of the silver-copper alloys has been studied by Heycock and Neville (228), Lepkowski (230), and others. Copper takes up about 3 per cent of silver in solid solution.

Johnson (261) studied the effect of additions of silver to tough-pitch copper, and concludes that up to about 0.2 per cent the tensile strength is increased by about 3 to 5 per cent, the elongation decreased by 10 to 15 per cent, and that "the effect of silver in the proportions ordinarily found * * * is beneficial on the whole as regards mechanical properties, and negligible as regards hot-working properties. (See Table 14.)

SULPHUR.—The constitution of the copper-sulphur alloys has been studied by Heyn and Bauer (231).

The amount of Cu_2S taken up by copper in solid solution is extremely small (less than 0.1 per cent).

Opinion seems to be agreed that as little as 0.1 per cent sulphur in copper renders it hot short (276). No investigation has been made of the effect of sulphur on the mechanical properties at ordinary temperatures.

TIN.—The copper-tin equilibrium diagram has been worked out by Heycock and Neville (233), Sheperd and Blough (234), and others. Copper dissolves about 11 per cent of tin, and within these limits it is hardened by the addition of tin.

Muenker (273) gives results of mechanical tests on copper-tin alloys. (See Table 13.) Baucke finds that tin in small amounts increases the toughness of copper. (See Table 15.) The alloys of tin and copper are called bronzes, and are generally used of compositions from 0 to 25 per cent tin.

Titanium.—The equilibrium of the alloys of titanium and copper has been studied by Bensel (235) and Rossi (236). Copper dis-

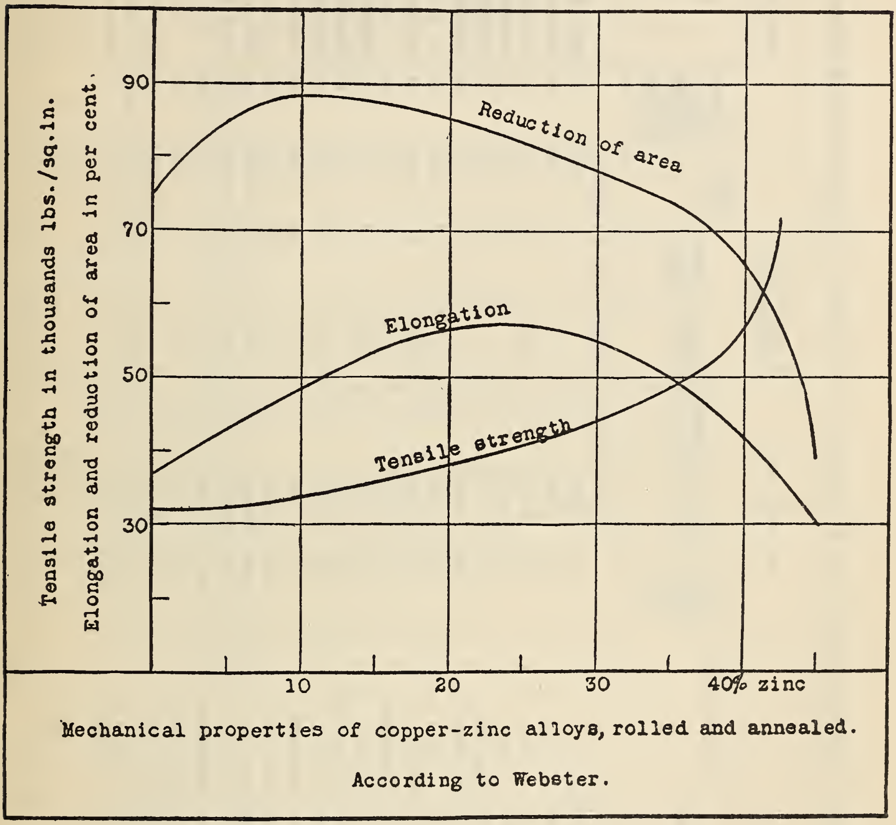

Fig. 25.—*Mechanical properties of rolled and annealed copper zinc alloys.* (*Webster*)

solves up to 0.32 per cent of titanium. In small proportions this metal raises the tensile strength and lowers the ductility.

Zinc.—The zinc-copper equilibrium diagram has been studed by Roberts-Austen (239), Shepherd (240), Tafel (241), and others.

Zinc is dissolved in copper to the extent of about 35 per cent. It hardens copper and first increases, then diminishes, its ductility. Curves, Fig. 25, by Webster (282) show the mechanical properties of rolled and annealed copper-zinc alloys; that is, the brasses made of pure materials.

TABLE 14.—Effects of Bismuth, Silver, and Aluminum on the Properties of Arsenical "Tough-Pitch" Copper[a]

Mark	Chemical composition			Appearance of ingot	Hot-rolled rods			Rods, cold-rolled and annealed		Cold-bend test	Cold malleability		Order of hot malleability[c]
	Oxygen	Added impurity	Arsenic		Alternations to rupture; Arnold test	Tensile strength	Elongation in 3 inches	Tensile strength	Elongation in 3 inches		Reduction in thickness under hammer	Description[b]	
	Per cent	Per cent	Per cent			Lbs./in.²	Per cent	Lbs./in.²	Per cent	Degrees			
R	0.089	....	Nil	Level	164	33 500	39	....	....	d 180	89	Slight cracks	1
E	.066	....	0.344	.....do	190	35 100	41	....	....	d 180	91	No cracks	2
EE	.060	....	.410	.....do	177	35 300	51	32 300	35	d 180	91	Incipient cracks	2
V1	.052	....	.361	.....do	190	35 300	38	....	....	d 180	91	No cracks	2
V	.132	....	.300	Elevation	122	32 600	34	....	....	e 135	67	Incipient split	2
U	.091	....	.383	Depression	152	35 200	47	....	....	d 180	89	Incipient crack	2
W	.162	....	.427	.....do	160	34 200	45	....	....	d 180	79	.....do	2
F1	.056	0.042 Ag	.300	Level	180	35 300	48	32 700	36	d 180	91	No cracks	2
F	.075	.087 Ag	.363	Depression	161	36 000	33	....	....	d 180	91	.....do	2
FF	.063	.094 Ag	.417	Level	187	35 600	43	34 000	43	d 180	86	Slight crack	2
G	.200	.185 Ag	.373	Depression	170	36 000	39	....	....	e 45	81	Incipient crack	2
GG	.058	.175 Ag	.453	Level	174	37 900	39	34 400	46	d 180	90	No cracks	2
H	.095	.292 Ag	.305	Depression	174	36 400	41	....	....	d 180	88	Incipient crack	3
HH	.048	.292 Ag	.423	Level	180	36 800	47	33 000	37	d 180	83	.....do	3
K1	.079	.052 Bi	.366	?	186	33 800	50	....	....	d 180	89	No cracks	5
KK1	.055	.051 Bi	.420	Level	201	35 200	44	33 800	42	d 180	89	Incipient cracks	5–6
K2	.084	.074 Bi	.464	Depression	172	35 300	40	....	....	d 180	85	.....do	5–6
KK2	.068	.073 Bi	.403	Level	186	35 400	46	32 700	40	d 180	89	.....do	6
K3	.155	.094 Bi	.355	Depression	178	33 800	37	....	....	d 180	79	Slight crack	5
KK3	.084	.097 Bi	.390	Level	178	36 000	48	33 100	33	d 180	83	Incipient crack	7
K4	.127	.122 Bi	.400	Depression	158	35 200	45	....	....	d 180	87	Slight crack	7

KK4	.073	.124 Bi	.468	Level	164	36 200	42	33 200	35	d 180	90	No cracks	8
X	.026	.014 Al	.526	do	199	34 400	44	....	....	d 180	92	Uncracked	2
Z	Nil	.320 Al	.260	Depression	189	35 500	43	....	....	d 180	79	Deep splits	8

[a] Ingots were made of cathode copper, arsenic, and impurity, poled to pitch and cast as 1¼ by 1¼ by 6 inch ingots, rolled at bright red heat in 8 passes to one-half-inch rods and quenched. Some specimens were hammered out flat to one-fourth inch thickness cold, then passed through cold rolls set at one-fourth inch. The specimens were then annealed at dull red heat for one-half hour and quenched in water.

[b] A test piece, 0.75 by 0.375 inch, was placed under hammer and subjected to light blows.

[c] Material falling in classes 1–4 may be rolled at a bright red heat. The point which determines the classifying of metal between 1 and 4 is the comparative susceptibility to cracking during rolling. Class 5 may be regarded as the critical stage between material fit for rolling at a bright red and material unfit for such treatment, material of this class (5) would better be rolled at a slightly lower temperature. Material in a lower class (i. e., 5–8) can be considered unfit for hot rolling.

[d] Unbroken.

[e] Broken.

Baucke finds that zinc in small amounts increases the toughness of copper. (See Table 15.)

TABLE 15.—Effect of Impurities on Specific Impact Work (Frémont Test) of Copper. Baucke (246)[a]

Composition, per cent	Preparation of sample	S. I. W.[b]	Composition, per cent	Preparation of sample	S. I. W.[b]
		Kg-m	Zinc:		Kg-m
Electrolytic copper	Forged hot	14,13	0.68		18 (29–14)
			1.42		29 (31–28)
Bismuth, 0.025	Forged samples	4 (6–2.5)	Aluminum:		
Arsenic:			0.02	Oxygen free	26 (27–24)
0.53	Cold forged, annealed	14 (25–5)	0.02	Cu_2O present	5 (9.5–2)
			Manganese:		
0.61	Hot forged	16 (21–11)	0.03		30 (33–27)
Antimony:			0.53		30 (32–30)
0.37		11 (13–8)	1.09		34 (35–33)
0.56		4 (6–3)	Oxygen:		
Nickel:			0.06		11, 15
0.17	Hot forged	20 (29–15.5)	0.10		10, 12
0.31	do	22 (26.5–21)	0.12		8
1.52		28 (34–24)	0.18		6
Tin:			0.51		9
1.20		28 (29–27)			
1.92		26 (33–24)			

[a] Specimens 10 by 10 mm in section, with 3 mm saw cut; specimens prepared by casting a 6 by 6 by 6 cube and forging hot or cold, followed by annealing to 10 by 10 section. Original electrolytic copper from which samples were prepared analyzed: Copper, 99.884 per cent; lead, 0.008 per cent; iron, 0.018 per cent; and oxygen, 0.080.

[b] Baucke gives S. I. W. in kilos, but it is assumed that he means kilogram-meters.

3. GASES IN COPPER

It is generally held that the solubility of gases in solid copper is quite small; in fact, it is to that fact that the "spewing" upon solidification of overpoled copper is due. The molten copper absorbs gas which is given up upon solidification.

Sieverts (284, 285) has determined the solubilities of H_2 and SO_2 in copper. He finds that 100 g of copper will absorb the following amounts of gas:

TABLE 16.—Absorption of Gas by Copper

Temperature, degrees centigrade	H_2 solubility in manganese per 100 g	SO_2 solubility in manganese per 100 g	Temperature, degrees centigrade	H_2 solubility in manganese per 100 g	SO_2 solubility in manganese per 100 g
1400	1.2		[a] 1084	0.6	
1330		706	[b] 1084	.2	
1220		596	400	.006	
1120		448			

[a] Liquid. [b] Solid.

N_2, CO, and CO_2 are not appreciably soluble in solid copper. He finds that for a constant temperature the solubility is proportional to the square root of the pressure of the gas.

Both silver and gold diminish the solubility of SO_2 in molten copper, the former much more markedly than the latter.

Sieverts (284) concludes that dissolved hydrogen has no appreciable effect on the electrical conductivity of copper up to 870° C, but that SO_2 increases the resistivity (part of this change may have been due to interreaction with the porcelain containing tubes).

X. "DISEASES" OF COPPER

Copper is, relatively speaking, insensitive to variations in conditions and operations of manufacture. After annealing or after forging operations at a bright red heat (900° C) it may be either slowly cooled or quenched in water, the latter method, according to some (see p. 49), conferring even greater ductility and toughness than the slow cooling.

It is possible, however, to overheat and to burn copper. Heyn (289) has shown that maximum toughness (repeated bend test) is obtained by annealing at 500° C, the time of annealing being without effect. Samples of copper which gave six and three-fourths 90-degree bends upon such annealing gave only four, when annealed for 90 minutes at 1050° C.

Baucke (287) has shown that heating to 700° C has practically no effect on the toughness as indicated by the Frémont test; in fact, heating in air or CO_2 at 1055° C for 15 minutes produced only a slight decrease of the S. I. W., from 101 to 77 foot-pounds (15.1 to 11.6 kg-m).

Copper should be worked at about 900° C and not above 1000° C according to Johnson (290). If heated to and worked at temperatures in the neighborhood of the eutectic melting temperature, the copper may be burnt, pits form, and grain boundaries become oxidized.

When copper is heated to 800° C and above in an atmosphere of reducing gases, CO, H, etc., the gases permeate into the copper and reduce the Cu_2O; water is formed, as steam under pressure, and produces fine cracks throughout the copper, which is described as "gassed." Such copper is, of course, weak and brittle. A photomicrograph, Fig. 11, shows such cracks near the brazed seam of a failed copper bend steam pipe. The brazing operation was improperly conducted, a reducing flame having been played on the copper with the result that cracks were formed near the surface, leading later to failure. Baucke (287) has reduced the toughness of copper as shown by the Frémont test from a S. I. W. of 94 to 101 foot-pounds (13 to 14 kg-m) to 14.5 foot-pounds (2 kg-m) by heating the sample for two hours at 800° C in H_2 gas.

Matthews and Thalheimer (191) have carried out the most extensive tests to determine the actual effect of annealing in reducing atmosphere on the strength and ductility of copper. They used coal gas and annealed for 40 minutes strips, 0.064 to 0.067 inch in thickness at 600, 800, and 1000° C.

Their average results are given in the table below.

TABLE 17.—Effect of Annealing in Coal Gas on Mechanical Properties of Copper

[Time of annealing, 40 minutes]

	Tensile strength	Reduction of area	Elongation
	Lbs./in.^{2}	Per cent	Per cent
Electrolytic copper	33 000	46	54
600° C	29 000	....	22
800° C	19 000	12	11
1000° C	21 000	12	11
Mohawk copper	33 000	49	55
600° C	30 000	....	27
800° C	18 000	....	8
1000° C	21 000	15–18	16
Copper range copper	33 000	50	57
600° C	31 000	39	41
800° C	21 000	12	11
1000° C	22 000	16	16

The copper range copper, containing 0.296 per cent arsenic, undoubtedly resists the action of reducing gases better than do the purer varieties. This is also shown by experiments by Bengough and Hill (247).

Corrosion of Copper.—Copper is exposed to corrosion by water, air, steam, etc., in a variety of commercial forms, pipe, steam fittings, roofing, etc., such that the question of the corrosion of copper under such conditions is an important one. Practically no systematic investigation has been made, however, of the rate of corrosion of different samples of copper under these various conditions.

Carpenter (296) exposed sheets of aluminum, copper, iron, and other metals to corrosion on the roof of an office building, in a railway tunnel, and in a smokestack, and observed the rate of corrosion expressed in the decrease of thickness per year. His results follow:

Metal	Corrosion loss		
	On office building	In railway tunnel	In smoke-stack
	Inch	Inch	Inch
Copper (plain)	0.0000	0.004	0.014
Aluminum	.0011	.013	....
Iron	0.001–0.004	.15	.018
Steel	....	.12	.020

The copper samples tested were from 99.53 to 99.76 per cent pure. The corrosion was quite uniform in the case of the copper and is seen to be less than that of the other materials.

Corrosion of copper may be quite uniform, a covering and protecting layer of oxide or green basic carbonate or, in marine atmospheres, of oxychloride being formed. Often, however, the attack is quite local, with formation of pits and furrows. Such pits are mentioned by Corner (297), Merica (299), and others; they are to be attributed to local electrolytic action caused by the presence near the pit of a substance electronegative to the copper. It is probable that copper oxide and even some of the basic oxidation products of copper may serve as such electronegative "poles."

It has been shown also by Rhead (301) that hard copper is more readily corrodible than soft copper, the rate of corrosion of the former having been from 0 to 500 per cent greater than of the latter in his experiments. Eastick (298) also holds that the presence of hard and soft areas in copper are often responsible for local corrosion.

APPENDIXES

Appendix 1.—DEFINITIONS OF PHYSICAL TERMS

THE ARNOLD ALTERNATING STRESS TEST.—The specimen in the form of a round rod 6 by 3/8 inch is fastened rigidly in the stationary die of the machine in a vertical position and submitted to alternating strains back and forth 3/8 inch from either side of the vertical by a slotted arm. Number of alterations (complete) to rupture is given as a measure of toughness of the specimen.

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, $J^1{}_\lambda$, to that of the entering light, $J^0{}_\lambda$; $\frac{J^1{}_\lambda}{J^0{}_\lambda}=e^{-2\pi k}$ when k is the absorption index.

(A variety of usage prevails regarding the definition of this term; this is used by 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 kinds of 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, $R=\rho\frac{l}{s}$ 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), the ohm 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 ∂ in the equation

$$R=\partial\frac{l^2}{m}$$

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, or ratio of the per cent conductivity is calculated in practice by dividing the resistivity of the international annealed copper standard at 20° C by the resistivity of the sample at 20° C. (See p. 21 for value of international standard.)

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 α_{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. Therefore the temperature coefficient at 20° C, for example, is

$$\alpha_{t_0} = \frac{R_t - R_{20}}{R_{20}\ (t - 20)}$$

Boiling Point.—The boiling point of a liquid is the temperature at which it boils, or better the temperature at which its vapor pressure is equal to 760 mm of mercury.

Brinell Test.—An indentation is made by pressure on a polished surface of the material, using a hardened steel ball. There are several ways of expressing the hardness:

The commonest definition of the Brinell hardness is the pressure in kilograms per unit area (square millimeter) necessary to produce spherical indentation.

(Hardness numeral............H. N.)

$$H.\ N. = \frac{\text{Pressure}}{\text{area of spherical indentation}} = \frac{P}{\pi t D}$$

$$\text{where } t = \frac{D}{2} - \sqrt{\frac{D^2}{4} - \frac{d^2}{4}}$$

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 a solution potential, which is a measure of the free energy change of the chemical reaction which is possible at the surface of the metal and liquid. In particular, if the chemical reaction consists in the solution of the metal forming ions, the emf is given by the formula.

$$E = \frac{RT}{nF}\ ln\ \frac{P}{p}$$

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 emf of an electrolytic cell of the following type: Metal solution normal hydrogen electrode is often called the single emf (E_h) for the metal in the solution; that is, arbitrarily assuming the emf of the normal hydrogen electrode to be zero.

Emissivity (E or E_λ).—The coefficient of emissivity, E_λ, for any material represents the ratio, $\frac{J_\lambda^1}{J_\lambda}$, of the intensity of radiation of some particular wave length or color, J_λ^1, 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 of "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 microns (0.001 mm)
E_λ=relative emissivity of substance for wave length, λ

Fusion, Heat of.—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 a constant temperature.

Magnetic Properties.—The usual magnetic characteristics of a substance are given either by the permeability μ or the susceptibility K. Permeability is the ratio of the magnetic induction (in maxwells per square centimeter) to the magnetizing force (in gilberts per centimeter). This is indicated by the relation

$$\mu=\frac{B}{H}$$

Susceptibility is given, in corresponding units, by

$$K=\frac{\mu-1}{4\pi}$$

For all materials except iron and a few other magnetic metals, μ is very nearly unity and K is only a few millionths. When K is positive in sign the substance is diamagnetic. The susceptibility as thus defined is sometimes called volume susceptibility and indicated by K_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 K_m.

Melting Point.—The melting or fusing point of a substance is the temperature at which it fuses, or, more accurately, the temperature at which the solid and the liquid metal are in equilibrium with each other at atmospheric pressure.

The Peltier Effect (π).—When, at the junction of two metals, current flows from one to the other heat is, in general, absorbed or liberated; 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 on to 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 steel.

Specific Heat (σ).—The true specific heat of a substance is $\frac{\partial u}{\partial t}$, when u is the total internal energy of unit mass of the substance. The mean specific heat is defined as

$$\frac{q}{t_1-t_2} \text{ per unit mass}$$

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

$$\sigma=A+Bt+(Ct^2 \quad . \quad . \quad .).$$

TENSILE TEST.—The quantities determined in the tensile 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* (A. S. T. M.) 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.

The *elastic limit* (A. S. T. M.) is the greatest load per unit of original cross section which does not produce a permanent set.

The *proportional limit* (A. S. T. M.) 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 this original length.

The *percentage reduction of area* is the ratio of the decrease of cross section at the "neck" or most reduced section at rupture to the original section.

(See also Elasticity.)

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). Its *temperature coefficient* is expressed as

$$\alpha_{t_0}=\frac{\lambda_t-\lambda_{t_0}}{\lambda_{t_0}(t-t_0)}$$

THERMAL EXPANSION.—If l_t is any linear dimension of a solid at any temperature, $\frac{1}{l}\frac{dl}{dt}$ is the linear thermal expansivity of that solid at that temperature in the direction of l. It is not, in general, proportional to the temperature except approximately over small temperature intervals, but may be expressed in the following manner:

$$\frac{1}{l}\frac{dl}{dt}=a+bt+ct^2+ \quad . \quad . \quad .$$

For small temperature intervals a mean coefficient (α) is often determined; that is,

$$\alpha_{t_0}=\frac{l_t-l_{t_0}}{l_{t_0}(t-t_0)} \text{ or } \frac{\Delta l}{l_0}=at+bt^2+ \quad . \quad . \quad .$$

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 of the temperature of, and of 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:

$$\left.\begin{aligned}\pi&=\frac{T}{J}\frac{dE}{dt}\\ \sigma_1-\sigma_2&=-\frac{T}{J}\frac{d^2E}{dt^2}\end{aligned}\right\}\text{and expressed in calories per coulomb}\quad J=4.18\frac{\text{dynes}\times 10^6}{\text{calories}}$$

when E is the thermo emf, T the absolute temperature, $\frac{dE}{dt}$ the temperature derivative of E, and $\sigma_1-\sigma_2$ the difference in the Thomson effect of the 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.

$$\frac{dE}{dt}=\text{the thermoelectric power;}$$

it is at any temperature therefore approximately the thermo emf of a couple of which the temperature 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 reversibly liberated or absorbed (other than through ohmic resistance), and an emf or counter emf is produced. The coefficient of the Thomson effect, the amount of heat liberated or absorbed when unit quantity of electricity flows from a point at temperature t to one at a temperature $t+dt$

$$=\sigma dt \text{ calories per coulomb}$$

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.

Appendix 2.—TYPICAL SPECIFICATIONS FOR COPPER

STANDARD SPECIFICATIONS[2] FOR ELECTROLYTIC COPPER WIRE BARS, CAKES, SLABS, BILLETS, INGOTS, AND INGOT BARS (SERIAL DESIGNATION: B5–13)

The specifications for this material are issued under the fixed designation B5; the final number indicates the year of original issue, or in the case of revision, the year of last revision. Adopted, 1911; revised, 1913.

1. Marks.—All wire bars, cakes, slabs, and billets shall be stamped with the maker's brand and furnace-charge mark. Ingots and ingot bars shall have a brand stamped or cast in, but need have no furnace-charge mark.

2. Lots.—The refiner shall arrange carloads or lots so that as far as possible each shall contain pieces from but one furnace charge, in order to facilitate testing by the user.

3. Quality.—(*a*) *Metal Content.*—The copper in all shapes shall have a purity of at least 99.880 per cent, as determined by electrolytic assay, silver being counted as copper.

(*b*) *Resistivity.*—All wire bars shall have a resistivity not to exceed 0.15535 international ohms per meter-gram at 20° C (annealed); all ingot and ingot bars shall have a resistivity not to exceed 0.15694 international ohms per meter-gram at 20° C (annealed).

Cakes, slabs, and billets shall come under the ingot classification, except when specified for electrical use at time of purchase, in which case wire-bar classification shall apply.

4. Physical Standard.—Wire bars, cakes, slabs, and billets shall be substantially free from shrink holes, cold sets, pits, sloppy edges, concave tops, and similar defects in set or casting. This clause shall not apply to ingots or ingot bars, in which case physical defects are of no consequence.

5. Weights of Individual Pieces.—Five per cent variation in weight or one-fourth inch variation in any dimension from the refiner's published list or purchaser's specified size shall be considered good delivery; provided, however, that wire bars may vary in length 1 per cent from the listed or specified length, and cakes 3 per cent from the listed or specified size in any dimension greater than 8 inches. The weight of ingot and ingot-bar copper shall not exceed that specified by more than 10 per cent, but otherwise its variation is not important.

6. Claims.—Claims shall be made in writing within 30 days of receipt of copper at the customer's mill, and the results of the customer's tests shall accompany such claims. The refiner shall be given one week from date of receipt of complaint to investigate his records, and shall then either agree to replace the defective copper or send a representative to the mill. No claims shall be considered unless made as above stated, and if the copper in question, unused, can not be shown to the refiner's representative.

Claims against quality will be considered as follows: (*a*) Resistivity by furnace charges, ingot lots, or ingot-bar lots; (*b*) metal contents by furnace charges, ingot lots, or ingot-bar lots; (*c*) physical defects by individual pieces; and (*d*) variation in weights or dimensions by individual pieces.

[2] American Society for Testing Materials.

7. Investigation of Claims.—The refiner's representative shall inspect all pieces where physical defects or variation in weight or dimension are claimed. If agreement is not reached, the question of fact shall be submitted to a mutually agreeable umpire, whose decision shall be final.

In a question of metal contents each party shall select a sample of two pieces. These shall be drilled in the presence of both parties, several holes approximately one-half inch in diameter being drilled completely through each piece; scale from set shall be rejected. No lubricant shall be used and drilling shall not be forced sufficiently to cause oxidation of chips. The resulting samples shall be cut up, mixed, and separated into three parts, each of which shall be placed in a sealed package, one for each party and one for the umpire if necessary. Each party shall make an analysis, and if the results do not establish or dismiss the claim to the satisfaction of both parties, the third sample shall be submitted to a mutually agreeable umpire, who shall determine the question of fact, and whose determination shall be final.

In a question of resistivity each party shall select two samples, and in the presence of both parties these shall be rolled hot and drawn cold into wire of 0.080 inch diameter, approximately, which shall be annealed at approximately 500° C. Three samples shall be cut from each coil and the same procedure followed as described in the previous paragraph.

8. Settlement of Claims.—The expenses of the shipper's representative and of the umpire shall be paid by the loser, or divided in proportion to the concession made in case of compromise. In case of rejection being established, the damage shall be limited to payment of freight both ways by the refiner for substitution of an equivalent weight of copper meeting these specifications.

STANDARD SPECIFICATIONS [3] FOR LAKE COPPER WIRE BARS, CAKES, SLABS, BILLETS, INGOTS, AND INGOT BARS (SERIAL DESIGNATION: B4–13)

The specifications for this material are issued under the fixed designation B4; the final number indicates the year of original issue, or, in the case of revision, the year of last revision. Adopted, 1911; revised, 1913.

1. Definition.—In order to be classed as Lake, copper must originate on the northern peninsula of Michigan, U. S. A.

2. Marks.—All wire bars, cakes, slabs, and billets shall be stamped with the maker's brand and furnace charge mark. Ingots and ingot bars shall have a brand stamped or cast in, but need have no furnace charge mark.

3. Lots.—The refiner shall arrange carloads or lots so that as far as possible each shall contain pieces from but one furnace charge, in order to facilitate testing by the user.

4. Resistivity.—(a) *Low Resistance Lake.*—Lake copper offered for electrical purposes, whether fire or electrolytically refined, shall be known as "Low resistance Lake."

Low resistance Lake wire bars shall have a resistivity not to exceed 0.15535 international ohms per meter-gram at 20° C (annealed). All ingots and ingot bars shall have a resistivity not to exceed 0.15694 international ohms per meter-gram at 20° C (annealed).

Cakes, slabs, and billets shall come under the ingot classification, except when specified for electrical use at time of purchase; in which case wire-bar classification shall apply.

(b) *High Resistance Lake.*—Lake copper having a resistivity greater than 0.15694 international ohms per meter-gram at 20° C shall be known as "High resistance Lake."

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[3] American Society for Testing Materials.

5. Metal Content.—(*a*) Low resistance Lake copper shall have a purity of at least 99.880 per cent as determined by electrolytic assay, silver being counted as copper.

(*b*) High resistance Lake copper shall have a purity of at least 99.880 per cent, copper, silver, and arsenic being counted together. The arsenic content of high resistance Lake copper, when required for special purposes, shall be the subject of agreement at time of purchase.

6. Physical Standard.—Wire bars, cakes, slabs, and billets shall be substantially free from shrink holes, cold sets, pits, sloppy edges, concave tops, and similar defects in set or casting. This clause shall not apply to ingots or ingot bars, in which case physical defects are of no consequence.

7. Weights of Individual Pieces.—Five per cent variation in weight or one-fourth inch variation in any dimension from the refiner's published list or purchaser's specified size shall be considered good delivery; provided, however, that wire bars may vary in length 1 per cent from the listed or specified length and cakes 3 per cent from the listed or specified size in any dimension greater than 8 inches. The weight of ingot and ingot-bar copper shall not exceed that specified by more than 10 per cent, but otherwise its variation is not important.

8. Claims.—Claims shall be made in writing within 30 days of receipt of copper at the customer's mill, and the results of the customer's tests shall accompany such claims. The refiner shall be given one week from date of receipt of complaint to investigate his records, and shall then either agree to replace the defective copper or send a representative to the mill. No claims will be considered unless made as above stated and if the copper in question, unused, can not be shown to the refiner's representative.

Claims against quality will be considered as follows: (*a*) Resistivity by furnace charges, ingot lots, or ingot-bar lots; (*b*) metal contents by furnace charges, ingot lots, or ingot-bar lots; (*c*) physical defects by individual pieces; and (*d*) variation in weights or dimensions by individual pieces.

9. Investigation of Claims.—The refiner's representative shall inspect all pieces where physical defects or variation in weight or dimension are claimed. If agreement is not reached, the question of fact shall be submitted to a mutually agreeable umpire, whose decision shall be final.

In a question of metal contents each party shall select a sample of two pieces. These shall be drilled in the presence of both parties, several holes approximately one-half inch in diameter being drilled completely through each piece; scale from set shall be rejected. No lubricant shall be used and drilling shall not be forced sufficiently to cause oxidation of chips. The resulting samples shall be cut up, mixed, and separated into three parts, each of which shall be placed in a sealed package, one for each party and one for the umpire, if necessary. Each party shall make an analysis, and if the results do not establish or dismiss the claim to the satisfaction of both parties the third sample shall be submitted to a mutually agreeable umpire, who shall determine the question of fact, and whose determination shall be final.

In a question of resistivity each party shall select two samples, and in the presence of both parties these shall be rolled hot and drawn cold into wire of 0.080 inch diameter, approximately, which shall be annealed at approximately 500° C. Three samples shall be cut from each coil and the same procedure followed as described in the previous paragraph.

10. Settlement of Claims.—The expenses of the shipper's representative and of the umpire shall be paid by the loser, or divided in proportion to the concession made in case of compromise. In case of rejection being established, the damage shall be limited to payment of freight both ways by the refiner for substitution of an equivalent weight of copper meeting these specifications.

Explanatory Note.—These specifications have been drawn to cover the peculiar trade situation which has classified the large production of copper from this geographical district as a product in a class by itself.

It is realized that a better classification from an academic point of view could be made by method of production or by chemical composition, but the trade does not yet seem ready for such a step.

STANDARD SPECIFICATIONS[4] FOR SOFT OR ANNEALED COPPER WIRE (SERIAL DESIGNATION: B3-15)

The specifications for this material are issued under the fixed designation B3; the final number indicates the year of original issue, or, in the case of revision, the year of last revision. Adopted, 1912; revised, 1913, 1915.

1. Material.—The copper shall be of such quality and purity that when drawn and annealed it shall have the properties and characteristics herein required.

2. Shapes.—These specifications cover untinned drawn and annealed round wire.

3. Finish.—(*a*) The wire must be free from all imperfections not consistent with the best commercial practice.

(*b*) Necessary brazes in soft or annealed wire must be made in accordance with the best commercial practice.

4. Packages.—(*a*) Wire may be shipped in coils or on reels as agreed upon by the purchaser and manufacturer. In Table I there are stated the maximum and minimum weights of wire of the stated sizes which may be shipped in any one package, whether coil, reel, or spool; in the case of wire larger than 0.010 inch in diameter the maximum and minimum package weights are net, and in the case of wire 0.010 inch and less in diameter the maximum package weights are gross and the minimum package weights are net. The table also states the limiting dimensions of the coils, reels, and spools on which wire may be shipped. The length and diameter stated for reels and spools are to be measured overall and are maximum sizes; reels or spools smaller than these may be used, provided the minimum weights called for are carried by the reel or spool. In the table there are also stated the diameters of the draw block on which the final drawing of the wire is to be made when wire is shipped in coils, it being understood that the wire is not to be rewound after final drawing. This provision is made to insure that coils of wire of a given gage, when supplied by different manufacturers, will be of the same general dimensions.

Wire 0.204 inch in diameter and larger may be shipped in larger packages when agreed upon.

(*b*) The wire shall be protected against damage in ordinary handling and shipping.

5. Specific Gravity.—For the purpose of calculating weights, cross sections, etc., the specific gravity of copper shall be taken as 8.89 at 20° C.

6. Dimensions and Permissible Variations.—(*a*) Size shall be expressed as the diameter of the wire in decimal fractions of an inch.

(*b*) Wire shall be accurate in diameter; permissible variations from nominal diameter shall be: For wire 0.010 inch in diameter and larger, 1 per cent over or under; for wire less than 0.010 inch in diameter, 0.1 mil (0.0001 inch) over or under.

(*c*) Each coil shall be gaged at three places, one near each end and one approximately at the middle; from spools, approximately 12 feet shall be reeled off; the wire shall be gaged in six places between the second and twelfth foot from the end. The coils or spools will be rejected if the average of the measurements obtained is not within the limits specified in paragraph (*b*).

7. Physical Tests.—Wire shall be so drawn and annealed that its tensile strength shall not be greater than the value stated in Table II. Tensile tests shall be made upon fair samples, and the elongation shall be determined as the permanent increase

[4] American Society for Testing Materials.

in length, due to the breaking of the wire in tension, measured between bench marks placed upon the wire originally 10 inches apart. The fracture shall be between the bench marks and not closer than 1 inch to either bench mark. If upon testing a sample from any coil, reel, or spool of wire the results are found to be below the stated value in elongation or above the stated value in tensile strength, tests upon two additional samples shall be made, and the average of the three tests shall determine acceptance or rejection of the coil. For wire whose nominal diameter is between listed sizes the requirements shall be those of the next larger size included in the table.

TABLE II

Diameter	Tensile strength	Elongation in 10 inches
	Lbs./in.²	Per cent
0.460 to 0.290 inch	36 000	35
.289 to .103 inch	37 000	30
.102 to .021 inch	38 500	25
.020 to .003 inch	40 000	20

8. Electric Resistivity.—Electric resistivity shall be determined upon fair samples by resistance measurements at a temperature of 20° C (68° F), and it shall not exceed 891.58 pounds per mile-ohm.

9. Inspection.—All testing and inspection shall be made at the place of manufacture. The manufacturer shall afford the inspector representing the purchaser all reasonable facilities to satisfy him that the material conforms to the requirements of these specifications.

Explanatory Notes.—Soft or annealed copper wire is wire which has been drawn by customary operations and annealed, and finished by cleaning when necessary to remove scale or oxide. The wire is so soft and ductile that it is easily marred and even stretched by careless handling in the operations of winding or cabling; hence the necessity for confining specifications and inspection to wire in packages as it leaves the manufacturer and before being put through processes incident to its use by the purchaser.

4. (*a*) Attention is called to the necessity for the purchaser and manufacturer agreeing on the package weights which will be standard under any individual contract. The committee[5] has indicated limitations to standard package weights which in their opinion will provide packages of sufficient size to be desirable and without being so large that the wire is apt to be damaged in handling.

5. The specific gravity of copper was formerly standardized in these specifications at 8.90. The value has been changed to 8.89, since that is the value adopted as standard by the American Institute of Electrical Engineers and the International Electro-Technical Commission.

6. The use of arbitrary gage numbers to express dimensions can not be too strongly condemned. There are many such gages in existence, and confusion is to be expected unless the particular gage to be used is specified. Many of the gages have their dimensions stated in absurd figures, such as 0.090742 inch, when it is not especially easy to measure dimensions in the fourth decimal place by workshop tools. Definite diameters in measurable units are evidently preferable.

8. Electric conductivity was formerly expressed as a percentage on the basis of a determination made by Matthiessen, about 1865, of the electric resistivity of supposedly pure copper. Since that time the methods of refining copper have advanced, so that it is not uncommon to find copper of over 100 per cent conductivity on the Matthiessen basis. There has until recently not been international agreement on the electric resistivity of copper to be considered the standard for the expression of

[5] Committee B-1 on standard specifications for copper wire.

conductivity. While international agreement upon the value 0.15328 ohm per meter-gram at 20° C for the resistivity of copper equal to 100 per cent conductivity was reached by the International Electro-Technical Commission in 1913, it has been deemed preferable to express the requirements in standard specifications in the terms of quantities directly measurable, rather than by reference to some quantity whose standard value is the subject of agreement only. The use of the arbitrary term "conductivity" has no more warrant than the employment of arbitrary gage numbers. Therefore in these specifications the requirements are stated as the maximum rejection limits to the resistivity.

For the convenience of those who are accustomed to express resistivity in any one of the several more or less common units, the following table of equivalents has been prepared, giving the resistivity of copper at 20° C:

891.58 pounds per mile-ohm is equal to—

- 0.15614 ohm per meter-gram.
- 1.7564 microhms per centimeter-cube.
- .69150 microhm per inch.
- 10.565 ohms per mil-foot.

STANDARD SPECIFICATIONS [6] FOR MEDIUM HARD-DRAWN COPPER; WIRE (SERIAL DESIGNATION: B2-15)

The specifications for this material are issued under the fixed designation B2 the final number indicates the year of original issue, or, in the case of revision, the year of last revision. Adopted, 1912; revised, 1913, 1915.

1. Material.—The copper shall be of such quality and purity that when drawn medium hard it shall have the properties and characteristics herein required.

2. Shapes.—These specifications cover medium hard-drawn wire, as hereinafter described.

3. Finish.—(*a*) The wire must be free from all imperfections not consistent with the best commercial practice.

(*b*) Necessary brazes in medium hard-drawn wire must be made in accordance with the best commercial practice, and tests upon a section of wire containing a braze must show at least 95 per cent of the tensile strength of the unbrazed wire. Elongation tests are not to be made upon test sections including brazes.

4. Packages.—(*a*) Packing sizes for round wire shall be agreed upon in the placing of individual orders.

(*b*) The wire shall be protected against damage in ordinary handling and shipping.

5. Specific Gravity.—For the purpose of calculating weights, cross sections, etc., the specific gravity of copper shall be taken as 8.89 at 20° C.

6. Inspection.—All testing and inspection shall be made at the place of manufacture. The manufacturer shall afford the inspector representing the purchaser all reasonable facilities to satisfy him that the material conforms to the requirements of these specifications.

MEDIUM HARD-DRAWN ROUND WIRE.

7. Dimensions and Permissible Variations.—(*a*) The size shall be expressed as the diameter of the wire in decimal fractions of an inch, using not more than three places of decimals; that is, in mils.

(*b*) Wire is expected to be accurate in diameter; permissible variations from nominal diameter shall be: For wire 0.100 inch in diameter and larger, 1 per cent over or under; for wire less than 0.100 inch in diameter, 1 mil over or under.

(*c*) Each coil is to be gaged at three places, one near each end and one approximately at the middle; the coil may be rejected if, two points being within the accepted limits,

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the third point is off gage more than 2 per cent in the case of wire 0.064 inch in diameter and larger or more than 3 per cent in the case of wire less than 0.064 inch in diameter.

8. Physical Tests.—Wire shall be so drawn that its tensile strength shall not be greater than the maximum values and not less than the minimum values stated in Table I, and its elongation shall not be less than the minimum values stated in Table I. Tension tests shall be made upon fair samples, and the elongation of wire larger in diameter than 0.204 inch shall be determined as the permanent increase in length, due to the breaking of the wire in tension, measured between bench marks placed upon the wire originally 10 inches apart. The elongation of wire 0.204 inch in diameter and smaller shall be determined by measurements made between the jaws of the testing machine. The zero length shall be the distance between the jaws when a load equal to 10 per cent of the required ultimate breaking strength shall have been applied, and the final length shall be the distance between the jaws at the time of rupture. The zero length shall be as near 60 inches as possible. The fracture shall be between the bench marks in the case of wire larger than 0.204 inch in diameter and between the jaws in the case of smaller wire, and not closer than 1 inch to either bench mark or jaw. If upon testing a sample from any coil of wire the results are found to be below the values stated in the table, tests upon two additional samples shall be made, and the average of the three tests shall determine acceptance or rejection of the coil. For wire whose nominal diameter is between listed sizes, the requirements shall be those of the next larger size included in the table.

9. Electrical Resistivity.—Electric resistivity shall be determined upon fair samples by resistance measurements at a temperature of 20° C (68° F).

The wire shall not exceed the following limits:

For diameters 0.460 to 0.325 inch, 896.15 pounds per mile-ohm at 20° C.

For diameters 0.324 to 0.040 inch, 905.44 pounds per mile-ohm at 20° C.

TABLE I

Diameter in inches	Tensile strength in pounds per square inch		Elongation in 10 inches	Diameter in inches	Tensile strength in pounds per square inch		Elongation in 10 inches
	Minimum	Maximum			Minimum	Maximum	
			Per cent				Per cent
0.460	42 000	49 000	3.75	0.289	46 000	53 000	2.75
.410	43 000	50 000	3.6	.258	47 000	54 000	2.5
.365	44 000	51 000	3.25	.229	48 000	55 000	2.25
.325	45 000	52 000	3.0				

Diameter in inches	Tensile strength in pounds per square inch		Elongation in 60 inches	Diameter in inches	Tensile strength in pounds per square inch		Elongation in 60 inches
	Minimum	Maximum			Minimum	Maximum	
			Per cent				Per cent
0.204	48 330	55 330	1.25	0.081	51 000	58 000	1.00
.182	48 600	55 660	1.20	.072	51 330	58 330	.98
.162	49 000	56 000	1.15	.064	51 660	58 660	.96
.144	49 330	56 330	1.11	.057	52 000	59 000	.94
.128	49 680	56 660	1.08	.051	52 330	59 330	.92
.114	50 000	57 000	1.06	.045	52 660	59 660	.90
.102	50 330	57 330	1.04	.040	53 000	60 000	.88
.091	50 660	57 660	1.02				

EXPLANATORY NOTES

Definition.—Medium hard-drawn wire is essentially and necessarily a special product, because when wire has once started on its course through the drawing operations, it can only finish as a hard-drawn wire to be used as such or to be annealed and become annealed wire. Medium hard-drawn wire is annealed wire drawn to a slightly smaller diameter.

5. The specific gravity of copper was formerly standardized in these specifications at 8.90. The value has been changed to 8.89, since that is the value adopted as standard by the American Institute of Electrical Engineers and the International Electro-Technical Commission.

7. (*a*) The use of arbitrary gage numbers to express dimensions can not be too strongly condemned. There are many such gages in existence, and confusion is to be expected unless the particular gage to be used is specified. Many of the gages have their dimensions stated in absurd figures, such as 0.090742 inch, when it is not especially easy to measure dimensions in the fourth decimal place by workshop tools. Definite diameters in measurable units are evidently preferable.

8. Medium hard-drawn wire approaches hard-drawn wire in its characteristics, but from the very nature of the product exact uniformity in tensile strength can not be obtained; hence the necessity for establishing a range of tensile strength within which standard medium hard-drawn wire must be expected to be found. In the opinion of the committee,[7] any narrowing or reduction in the range permitted in tensile strength can only result in an unjustifiable increase in the cost of production of the wire.

Many other physical tests than those provided in these specifications are included in existing specifications. The reasons for the omission of some of the more common are given as follows:

Twist Tests.—The wire is sometimes required to permit twisting through a stated number of revolutions before breaking. The results are so easily influenced by temperature, speed of rotation, method of gripping, and other variables not easily defined or controlled, that the test is at least of doubtful value. It is the opinion of the committee that it is impractical to so define the conditions of the test that a twist test can be made definite and reliable; hence there is no warrant for its inclusion in specifications.

Wrap Tests.—Wire is sometimes required to permit tight wrapping about a wire of its own diameter, unwrapping and again rewrapping. It is obvious that the making of a test of this kind with wire that is already hard is exceedingly difficult. Everyone who has tried to break off a piece of tough wire by bending it back and forth between the fingers knows how hard it is to confine the bend to one place, because of the hardening action of the previous bends. Hard wire which has been wrapped around a wire of small diameter is hardened still more and it is almost impossible to straighten the wire, let alone recoil it in the opposite direction. In the opinion of the committee, it is inadvisable to include a test which at best is so indefinite as a wrap test. Furthermore, it is the opinion of the committee that wire which will meet the physical tests included in these specifications will meet any properly made twist or wrap test that would reasonably be required.

The committee has carefully considered the matter of twist and wrap tests in connection with both hard-drawn and medium hard-drawn wire, and it is their final opinion that while there might be some possible reason for requiring that wire shall stand wrapping around a wire of equal diameter, there can be no good reason for including in specifications the requirement that it shall stand unwrapping and rewrapping, because such a test is indefinite and can not be made otherwise. It is almost physically impossible to unwrap and rewrap hard-drawn wire about a wire of its own diameter.

Elastic Limit.—During the tension test on wire, there is seldom to be observed any definite drop of the beam or increase in the rate of elongation, corresponding to

[7] Committee B-1 on standard specifications for copper wire.

the yield point commonly observed in testing steel. The only way in which the elastic limit of hard wire may be determined is by the actual plotting of the elastic curve from extensometer readings. Even such tests are difficult of interpretation, because the wire when available for tests is usually curved, due to its having been put up in a coil. There are little sets observable before the true elastic limit has been reached, owing to the fact that one side of the wire, having been stretched in coiling, is really a little harder than the other, and the pull is, therefore, not even. Considering the difficulty of making the test and the uncertainty of the results obtained, it is the opinion of the committee that it would be inadvisable to include an elastic limit test in these specifications. It is evident that if the designing engineer requires a knowledge of the location of the elastic limit, for purposes of calculation in designing, such data can be obtained by special tests on representative sizes of wire, which will fix the relation of the elastic limit to the ultimate strength for all wire which is properly made.

Tests carefully made by members of the committee show that the elastic limit of medium hard-drawn wire averages 50 per cent of the ultimate tensile strength required in these specifications. This statement of experience is based on the definition of elastic limit as "that point on the elastic curve beyond which the ratio of stress to strain ceases to be constant."

9. Conductivity.—Electric conductivity was formerly expressed as a percentage on the basis of a determination made by Matthiessen about 1865 of the electric resistivity of supposedly pure copper. Since that time the methods of refining copper have advanced, so that it is not uncommon to find copper of over 100 per cent conductivity on the Matthiessen basis. There has until recently not been international agreement on the electric resistivity of copper to be considered the standard for the expression of conductivity. While international agreement upon the value 0.15328 ohms per meter-gram at 20° C for the resistivity was reached by the International Electro-Technical Commission in 1913, it has been deemed preferable to express the requirements in standard specifications in the terms of quantities directly measurable rather than by reference to some quantity whose standard value is the subject of agreement only. The use of the arbitrary term "conductivity" has no more warrant than the employment of arbitrary gage numbers. Therefore, in these specifications the requirements are stated as the maximum rejection limits to the resistivity.

For the convenience of those who are accustomed to express resistivity in any one of the several more or less common units, the following table of equivalents has been prepared, giving the resistivity of copper at 20° C:

896.15 pounds per mile-ohm is equal to—
- 0.15694 ohm per meter-gram,
- 1.7654 microhms per centimeter-cube,
- .69504 microhm per inch-cube,
- 10.619 ohms per mil-foot.

905.44 pounds per mile-ohm is equal to—
- 0.15857 ohm per meter-gram,
- 1.7837 microhms per centimeter-cube,
- .70224 microhm per inch-cube,
- 10.729 ohms per mil-foot.

STANDARD SPECIFICATIONS[8] FOR HARD-DRAWN COPPER WIRE (SERIAL DESIGNATION: B1-15)

The specifications for this material are issued under the fixed designation B1; the final number indicates the year of original issue, or in the case of revision, the year of last revision. Adopted, 1909; revised, 1911, 1913, 1915.

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[8] American Society for Testing Materials.

1. Material.—The material shall be copper of such quality and purity that, when drawn hard, it shall have the properties and characteristics herein required.

2. Shapes.—These specifications cover hard-drawn round wire, grooved trolley wire, and figure-eight trolley wire, as hereinafter described.

3. Finish.—(*a*) The wire, in all shapes, must be free from all imperfections not consistent with the best commercial practice.

(*b*) Necessary brazes in hard-drawn wire must be made in accordance with best commercial practice, and tests upon a section of wire containing a braze must show at least 95 per cent of the tensile strength of the unbrazed wire. Elongation tests are not to be made upon test sections including brazes.

4. Packages.—(*a*) Package sizes for round wire shall be agreed upon in the placing of individual orders; standard packages of grooved trolley wire shall be shipments upon reels holding about 2500 pounds each.

(*b*) The wire shall be protected against damage in ordinary handling and shipping.

5. Specific Gravity.—For the purpose of calculating weights, cross sections, etc., the specific gravity of copper shall be taken as 8.89 at 20° C.

6. Inspection.—All testing and inspection shall be made at the place of manufacture. The manufacturer shall afford the inspector representing the purchaser all reasonable facilities to enable him to satisfy himself that the material conforms to the requirements of these specifications.

HARD-DRAWN ROUND WIRE

7. Dimensions and Permissible Variations.—(*a*) Size shall be expressed as the diameter of the wire in decimal fractions of an inch, using not more than three places of decimals; that is, in mils.

(*b*) Wire is expected to be accurate in diameter; permissible variations from nominal diameter shall be: For wire 0.100 inch in diameter and larger, 1 per cent over or under; for wire less than 0.100 inch in diameter, 1 mil over or under.

(*c*) Each coil is to be gaged at three places, one near each end, and one approximately at the middle; the coil may be rejected if, two points being within the accepted limits, the third point is off gage more than 2 per cent in the case of wire 0.064 inch in diameter and larger, or more than 3 per cent in the case of wire less than 0.064 inch in diameter.

8. Physical Test.—Wire shall be so drawn that its tensile strength and elongation shall be at least equal to the value stated in Table I. Tensile tests shall be made upon fair samples, and the elongation of wire larger in diameter than 0.204 inch shall be determined as the permanent increase in length, due to the breaking of the wire in tension, measured between bench marks placed upon the wire originally 10 inches apart. The elongation of wire 0.204 inch in diameter and smaller shall be determined by measurements made between the jaws of the testing machine. The zero length shall be the distance between the jaws when a load equal to 10 per cent of the required ultimate breaking strength shall have been applied, and the final length shall be the distance between the jaws at the time of rupture. The zero length shall be as near 60 inches as possible. The fracture shall be between the bench marks in the case of wire larger than 0.204 inch in diameter and between the jaws in the case of smaller wire, and not closer than 1 inch to either bench mark or jaw. If upon testing a sample from any coil of wire the results are found to be below the values stated in the table, tests upon two additional samples shall be made, and the average of the three tests shall determine acceptance or rejection of the coil. For wire whose nominal diameter is between listed sizes, the requirements shall be those of the next larger size included in the table.

TABLE I

Diameter in inches	Area, circular mils	Tensile strength in pound per square inch	Elongation in 10 inches	Diameter in inches	Area, circular mils	Tensile strength in pound per square inch	Elongation in 10 inches
			Per cent				Per cent
0.460	211 600	49 000	3.75	0.489	83 520	56 100	2.17
.410	168 100	51 000	3.25	.258	66 565	57 600	1.98
.365	133 225	52 800	2.80	.229	52 440	59 000	1.79
.325	105 625	54 500	2.40				

Diameter in inches	Area, circular mils	Tensile strength in pound per square inch	Elongation in 60 inches	Diameter in inches	Area, circular mils	Tensile strength in pound per square inch	Elongation in 60 inches
			Per cent				Per cent
0.204	41 615	60 100	1.24	0.092	8464	65 400	0.97
.182	33 125	61 200	1.18	.091	8281	65 400	.97
.165	27 225	62 000	1.14	.081	6561	65 700	.95
.162	26 245	62 100	1.14	.080	6400	65 700	.94
.144	20 735	63 000	1.09	.072	5184	65 900	.92
.134	17 956	63 400	1.07	.065	4225	66 200	.91
.128	16 385	63 700	1.06	.064	4096	66 200	.90
.114	12 995	64 300	1.02	.057	3249	66 400	.89
.104	10 815	64 800	1.00	.051	2601	66 600	.87
.102	10 404	64 900	1.00	.045	2025	66 800	.86
				.040	1600	67 000	.85

9. Electric Resistivity.—Electric resistivity shall be determined upon fair samples by resistance measurements at a temperature of 20° C (68° F).

The wire shall not exceed the following limits: For diameters 0.460 to 0.325 inch, 900.77 pounds per mile-ohm at 20° C; for diameters 0.324 to 0.040 inch, 910.15 pounds per mile-ohm at 20° C.

GROOVED TROLLEY WIRE

10. Sections.—Standard sections shall be those known as the "American standard grooved trolley wire sections," the shape and dimensions of which are shown in Fig. 1.

11. Dimensions and Permissible Variations.—(*a*) Size shall be expressed as the area of cross section in circular mils, the standard sizes being as follows:

211 600 circular mils, weighing 3386 pounds per mile,
168 100 circular mils, weighing 2690 pounds per mile,
133 200 circular mils, weighing 2132 pounds per mile.

(*b*) Grooved trolley wire may vary 4 per cent over or under in weight per unit length from standard, as determined from the nominal cross section.

12. Physical Tests.—The physical tests shall be made in the same manner as those upon round wire. The tensile strength of grooved wire shall be at least 95 per cent of that required for round wire of the same sectional area; the elongation shall be the same as that required for round wire of the same sectional area.

13. Electric Resistivity.—The requirements for electric resistivity shall be the same as those for round wire of the same sectional area.

FIGURE-EIGHT TROLLEY WIRE

14. Sections.—Standard sections of figure-eight trolley wire shall be as shown in Fig. 2.

15. Requirements.—The requirements for weight, physical properties, and electric resistivity of figure-eight trolley wire shall be the same as for the same sizes of grooved trolley wire.

EXPLANATORY NOTES

5. The specific gravity of copper was formerly standardized in these specifications at 8.90. The value has been changed to 8.89, since that is the value adopted as standard by the American Institute of Electrical Engineers and the International Electro-Technical Commission.

7. (*a*) The use of arbitrary gage numbers to express dimensions can not be too strongly condemned. There are many such gages in existence, and confusion is to be expected unless the particular gage to be used is specified. Many of the gages have their dimensions stated in absurd figures, such as 0.090742 inch, when it is not especially easy to measure dimensions in the fourth decimal place by workshop tools, Definite diameters in measurable units are evidently preferable.

8. Many other physical tests than those provided in these specifications are included in existing specifications. The reasons for the omission of some of the more common are given as follows:

Twist Tests.—The wire is sometimes required to permit twisting through a stated number of revolutions before breaking. The results are so easily influenced by temperature, speed of rotation, method of gripping, and other variables not easily defined or controlled that the test is at least of doubtful value. It is the opinion of the committee [9] that it is impracticable to so define the conditions of the test that a twist test can be made definite and reliable; hence there is no warrant for its inclusion in specifications.

Wrap Tests.—Wire is sometimes required to permit tight wrapping about a wire of its own diameter, unwrapping and again rewrapping. It is obvious that the making of a test of this kind with wire that is already hard drawn is exceedingly difficult. Everyone who has tried to break off a piece of tough wire by bending it back and forth between the fingers knows how hard it is to confine the bend to one place, because of the hardening action of the previous bends. Hard wire which has been wrapped around a wire of small diameter is hardened still more and it is almost impossible to straighten the wire, let alone recoil it in the opposite direction. In the opinion of the committee, it is inadequate to include a test which at best is so indefinite as a wrap test. Furthermore, it is the opinion of the committee that wire which will meet the physical tests included in these specifications will meet any properly made twist or wrap test that would reasonably be required.

Since the adoption of the standard specifications for hard-drawn copper wire, proposed in 1909, the committee has very carefully considered the matter of twist and wrap tests, and it is their final opinion that while there might be some possible reason for requiring that wire shall stand wrapping around a wire of equal diameter, there can be no good reason for including in specifications the requirement that it shall stand unwrapping and rewrapping, because such a test is indefinite and can not be made otherwise. It is almost physically impossible to unwrap and rewrap hard-drawn wire about a wire of its own diameter. With respect to twist tests, the committee has nothing to add to the statement already on record condemning this character of test.

Elastic Limit.—During the tension test on wire there is seldom to be observed any definite drop of the beam or increase in the rate of elongation, corresponding to the yield point commonly observed in testing steel. The only way in which the elastic limit of hard wire may be determined is by the actual plotting of the elastic curve from the extensometer readings. Even such tests are difficult of interpretation, because the wire when available for tests is usually curved, due to its having been put in a coil. There are little sets observable before the true elastic limit has been reached, owing to the fact that one side of the wire, having been stretched in coiling

[9] Committee B–1 on standard specifications for copper wire.

is really a little harder than the other side, and the pull is, therefore, not even. Considering the difficulty of making the test and the uncertainty of the results obtained, it is the opinion of the committee that it would be inadvisable to include an elastic limit test in these specifications. It is evident that if the designing engineer requires a knowledge of the location of the elastic limit for purposes of calculation in designing, such data can be obtained by special tests on representative sizes of wire, which will fix the relaxation of the elastic limit to the ultimate strength for all wire which is properly made.

Tests carefully made by members of the committee show that the elastic limit of hard-drawn copper wire from sizes 0.460 to 0.325 inch, inclusive, averages 55 per cent of the ultimate tensile strength required in these specifications, with a minimum value of 50 per cent; for sizes 0.324 to 0.040 inch, inclusive, it averages 60 per cent of the ultimate tensile strength required in these specifications, with a minimum value of 55 per cent. This statement of experience is based on the definition of elastic limit as "that point on the elastic curve beyond which the ratio of stress to strain ceases to be constant."

9. Conductivity.—Electric conductivity was formerly expressed as a percentage on the basis of a determination made by Matthiessen about 1865 of the electric resistivity of supposedly pure copper. Since that time the methods of refining copper have advanced, so that it is not uncommon to find copper of over 100 per cent conductivity on the Matthiessen basis. There has until recently not been international agreement on the electrical resistivity of copper to be considered the standard for the expression of conductivity. While international agreement upon the value 0.15328 ohm per meter-gram at 20° C for the resistivity of copper equal to 100 per cent conductivity was reached by the International Electro-Technical Commission in 1913, it has been deemed preferable to express the requirements in standard specifications in the terms of quantities directly measureable, rather than by reference to some quantity whose standard value is the subject of agreement only. The use of the arbitrary term "conductivity" has no more warrant than the employment of arbitrary gage numbers. Therefore, in these specifications the requirements are stated as the maximum rejection limits to the resistivity.

For the convenience of those who are accustomed to express resistivity in any of the several more or less common units, the following table of equivalents has been prepared, giving the resistivity of copper at 20° C:

900.77 pounds per mile-ohm is equal to—

0.15775 ohm per meter-gram,
1.7745 microhms per centimeter-cube,
.69863 microhm per inch-cube,
10.674 ohms per mil-foot.

910.15 pounds per mile-ohm is equal to—

0.15940 ohm per meter-gram,
1.7930 microhms per centimeter-cube,
.70590 microhm per inch-cube,
10.785 ohms per mil-foot.

10. It is obvious that the simplest designation of irregular shapes of similar outline is by sectional area, and the most commonly used unit among electrical engineers is the circular mil. Therefore, while the sizes of grooved trolley wire regularly used are generally known by B. & S. gage number, corresponding to their sectional area, it has been deemed advisable by the committee to list these sizes, in specifications, by their sectional area expressed in circular mils. The three sizes which are most extensively used commercially are the only ones listed; a fourth size is but little used, and the use is growing less.

11. The only way in which gage variations are easily determinable in irregular shapes is by recourse to weights of standard lengths, and this has been the method adopted in the specifications.

STANDARD SPECIFICATIONS [10] FOR BARE CONCENTRIC-LAY COPPER CABLE, HARD, MEDIUM HARD, OR SOFT (SERIAL DESIGNATION: B8-16)

The specifications for this material are issued under the fixed designation B8; the final number indicates the year of original issue, or in the case of revision, the year of last revision. Adopted, 1916.

I. MANUFACTURE

1. Products Covered.—(*a*) These specifications cover bare concentric-lay cables made from round copper wires laid helically around a central core in one or more layers. The central core shall be made of wire having the same quality and temper as the concentric layers, unless otherwise especially provided for in separate specifications governing the individual case.

Classes.—(*b*) The purposes for which the several classes of concentric-lay cables are generally used are as follows:

Class A, for bare, weatherproof, slow-burning, and slow-burning weatherproof cable for aerial use.

Class B, for various insulated cable, such as rubber, paper, varnished cloth, etc.

Class C, for cable where greater flexibility is required than in class B.

2. Requirements of Wires.—The copper wires entering into the construction of standard concentric-lay cable shall, before stranding, meet all the requirements of that one of the standard specifications of the American Society for Testing Materials for hard-drawn, medium hard-drawn, or soft or annealed copper wire (serial designations: B1, B2, or B3), which applies.

3. Brazes.—Brazes may be made in the wire when finished and ready for cabling. Such brazes shall be made in accordance with the best commercial practice. No brazes in cable made from hard, or medium hard drawn copper wire may be closer together than 50 feet.

4. Pitch and Lay.—The pitch of standard cable shall not be less than 12 nor more than 16 diameters of the cable, and the lay may be right or left handed, unless one direction of lay is specified by the purchaser.

II. PHYSICAL PROPERTIES AND TESTS

5. Testing.—Tests for the physical and electrical properties of the wires composing the cables may be made before, but not after, stranding. Experience indicates that the tensile strength of concentric-lay copper cable of standard pitch is at least 90 per cent of the total strength required of the wires forming the cable.

6. Weights and Area.—For the purpose of calculating weights, cross sections, etc., the specific gravity of copper shall be taken as 8.89 at 20° C. The resistance and mass of a stranded conductor are greater than in a solid conductor of the same cross-sectional area, depending on the lay, that is, the pitch of the twist of the wires. Two per cent shall be taken as the standard increment of resistance and of mass. In cases where the lay is definitely known, the increment shall be calculated and not assumed.

7. Variation in Area.—The area of cross section of the completed cable shall not be more than 2 per cent below the area specified, as determined by weight.

8. Construction.—The area of cross section, number and diameter of wires, in standard cable classes A, B, and C, shall be specified in Table I.

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[10] American Society for Testing Materials.

III. PACKING AND SHIPPING

9. Packing and Shipping.—(*a*) Package sizes for cable shall be agreed upon in the placing of individual orders.

(*b*) The cable shall be protected against damage in ordinary handling and transportation.

IV. INSPECTION

10. Inspection.—(*a*) All testing and inspection, both of individual wires entering into the construction of the cable, and of the completed cable, shall be made at the place of manufacture. Tests on individual wires shall be made on samples before cabling, and not on wires removed from the completed cable.

(*b*) The manufacturer shall afford the inspector representing the purchaser all reasonable facilities to satisfy him that the material conforms to the requirements of these specifications.

V. DEFINITION OF TERMS

11. Concentric-Lay Cable.—A single conductor cable composed of a central core surrounded by one or more layers of helically laid wires.

12. Lay.—The lay of a cable is the length expressed in inches for each complete turn of the wire around the axis, measured along its axis.

13. Direction of Lay.—The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

EXPLANATORY NOTES

1. Classes of Cable.—These specifications have been drawn to cover cables made from hard-drawn, medium hard-drawn, and soft copper wire, since the manufacturing of cables from the various classes of wire is similar, and the physical properties of the cable depend upon, and are usually expressed in, terms of those of the class of wire employed.

2. Physical Properties.—The accurate testing of cable for its physical properties is practically impossible in commercial laboratories. In order to do this, it is necessary to use long lengths and hold the samples in such a way that the wires shall all be in equal tension. Otherwise the strength will be considerably below the actual strength of the cable. A much more accurate idea of the quality of the cable may be obtained by testing the individual wires before cabling than by attempting tests of the physical properties of the finished cable.

Wires unlaid from cable will manifestly have different physical and electrical properties from those of the wire when prepared for cabling, on account of the deformation brought about by laying and again straightening for test.

3. Stranding Table.—The stranding table covers present practice. Class A covers the usual bare and weatherproof construction. Class B is the same as adopted by the Standards Committee of the American Institute of Electrical Engineers, and is given in the Bureau of Standards Circular No. 31, Table XII.

In class C the figures are those of the Bureau of Standards Circular No. 31, Table XII, with additions to cover well-established practice. There is need for a table to cover extra-flexible stranding from soft wire, but there are differences of opinion in regard to what should become standard practice. The Standards Committee of the American Institute of Electrical Engineers have this matter under consideration, and it has seemed best not to attempt to include figures for extra-flexible stranding in this specification. The stranding table will necessarily be the subject of revision which will be undertaken in cooperation with the Standards Committee of the American Institute of Electrical Engineers.

TABLE I

Area of cross section	Approximate A. W. G. or B. & S. gage sizes	Class A[a]		Class B		Class C	
		Wires	Diameter of wires	Wires	Diameter of wires	Wires	Diameter of wires
Cir. mils			Mils		Mils		Mils
2 000 000	....	91	148.2	127	125.5	169	108.8
1 900 000	....	91	144.5	127	122.3	169	106.0
1 800 000	....	91	140.6	127	119.1	169	103.2
1 700 000	....	91	136.6	127	115.7	169	100.3
1 600 000	....	91	132.6	127	112.2	169	97.3
1 500 000	....	61	156.8	91	128.4	127	108.7
1 400 000	....	61	151.5	91	124.0	127	105.0
1 300 000	....	61	146.0	91	119.5	127	101.2
1 250 000	....	61	143.2	91	117.2	127	99.2
1 200 000	....	61	140.3	91	114.8	127	97.2
1 100 000	....	61	134.3	91	109.9	127	93.1
1 000 000	....	61	128.0	61	128.0	91	104.8
950 000	....	61	124.8	61	124.8	91	102.2
900 000	....	61	131.5	61	121.5	91	99.4
850 000	....	61	118.0	61	118.0	91	96.6
800 000	....	61	114.5	61	114.5	91	93.8
750 000	....	61	110.9	61	110.9	91	90.8
700 000	....	61	107.1	61	107.1	91	87.7
650 000	....	61	103.2	61	103.2	91	84.5
600 000	....	37	127.3	61	99.2	91	81.2
550 000	....	37	121.9	61	95.0	91	77.7
500 000	....	37	116.2	37	116.2	61	90.5
450 000	....	37	110.3	37	110.3	61	85.9
400 000	....	19	145.1	37	104.0	61	81.0
350 000	....	19	135.7	37	97.3	61	75.7
300 000	....	19	125.7	37	90.0	61	70.1
250 000	....	19	114.7	37	82.2	61	64.0
212 000	4/0	7–19	173.9–105.5	19	105.5	37–61	75.6–58.9
168 000	3/0	7–19	155.0– 94.0	19	94.0	37–61	67.3–52.5
133 000	2/0	7	138.0	19	83.7	37	60.0
106 000	1/0	7	122.8	19	74.5	37	53.4
83 750	1	7	100.3	19	66.4	37	47.6
66 400	2	7	97.4	7	97.4	19	59.1
52 600	3	7	86.7	7	86.7	19	52.6
41 700	4	7	77.2	7	77.2	19	46.9
33 100	5	7	68.8	7	68.8	19	41.7
26 300	6	7	61.2	7	61.2	19	37.2
20 800	7	7	54.5	7	54.5	19	33.1
16 500	8	7	48.6	7	48.6	19	29.5

[a] Class A cable, sizes 4/0 and 3/0, is usually 7-strand when bare and 19-strand when weatherproof, etc.

NAVY DEPARTMENT SPECIFICATIONS (46C5, JAN. 2, 1915; SUPERSEDING 46 C1a AND 46 C4a, AUG. 1, 1913) INGOT COPPER

1. GENERAL INSTRUCTIONS.—General instructions or specifications issued shall form a part of these specifications.

2. GRADES.—There shall be two grades of ingot copper conforming to the requirements stated below.

3. CHEMICAL REQUIREMENTS.—The chemical requirements shall be as follows:

Grade	Cu., min.	Bi., max.	Sb., max.	As., max.	S., max.	Material
No. 1	99.90	None	None	0.0025	0.0025	Only high-grade Lake copper from ore of the best quality or electrolytic copper from ore of the best quality.
No. 2	99.75	0.01	0.01	.03	.01	Copper for this grade may be refined from the ore or reclaimed from scrap.

NOTE.—Copper to be determined by electrolytic assay, silver being counted as copper. Not less than 5 g shall be taken for analysis.

4. Purpose for which Used.—Grade No. 1 to be used in the manufacture of cartridge cases and high-grade bronzes and brasses. Grade No. 2 for ordinary foundry purposes in compositions of commercial brass (B–c), cast naval brass (N–c), screw pipe fittings (S–E), and commercial rolled brass (B–r), and gun metal, composition G, phosphor bronze, composition P–c, and other compositions in which great strength is required.

5. Sampling.—Samples are to be taken as follows: One ingot shall be taken from such location in each lot of 8000 pounds or fraction thereof of an order as to represent as nearly as possible the average quality of the metal. Two 9/16-inch holes shall be drilled from the top to one-fourth inch from the bottom of each ingot. The drillings from the first one-fourth inch shall be discarded and the inspector shall forward for analysis, as directed, not less than 5 ounces of the remaining drillings from each ingot in separate packages for analysis. Drillings from all the samples from an order will be thoroughly mixed and a portion taken therefrom for analysis, unless a question of homogeneity of the metal arises, in which case separate analysis shall be made as may be deemed expedient.

6. Form and Marking.—To be furnished in standard commercial shaped ingots, between 9 and 12 inches in length, with brand name cast or stamped in.

7. Brand.—Bidders will state in their proposals the brand of copper offered.

NAVY DEPARTMENT SPECIFICATIONS (47 C1a, JAN. 2, 1915; SUPERSEDING 47 C1, JUNE 1, 1911)—SHEET COPPER FOR SHEATHING BOTTOMS OF WOODEN CRAFT

1. General.—To be best commercial quality sheet copper containing at least 99 per cent of pure copper, to be free from all defects, blisters, bad edges, and corners; to be smooth on both sides, commercially flat, and reasonably free from waves and buckles.

2. Size, etc.—To be in sheets 14 by 48 inches, hard or soft rolled, as specified in order, and in accordance with the following table, a variation of 7 per cent under gage at edge of sheet, and a variation in weight of 5 per cent above and below being allowed.

Thickness in inches	Ounces per square foot	Weight of sheet 14 by 48 inches		Maximum weight		Minimum weight		Minimum gage
		Pounds	Ounces	Pounds	Ounces	Pounds	Ounces	
0.0189	14	4	1	4	4	3	4	0.0176
.0203	15	4	6	4	10	4	2	.0189
.0216	16	4	10½	4	14	4	7	.0201
.0230	17	4	15½	5	4	4	11	.0214
.0243	18	5	4	5	8	5	0	.0226
.0257	19	5	8½	5	13	5	4	.0239
.0270	20	5	13½	6	2	5	9	.0251
.0297	22	6	6½	6	12	6	1	.0277
.0323	24	7	0	7	6	6	10	.0301
.0352	26	7	9	7	15	7	3	.0328
.0379	28	8	2½	8	9	7	12	.0353
.0406	30	8	12	9	3	8	5	.0378
.0433	32	9	5½	9	13	8	13	.0404

3. Basis of Payment.—Payment will be made on a basis of net weight delivered.

4. Marking.—Sheets to be packed in strong, well-made cases, marked with the name of the material, the size and thickness or weight of the copper per square foot, the total weight contained, and the name of the manufacturer. The weight per square foot marked on cases to be the same as the order calls for, although on account of the weight tolerance the actual weight per square foot may be actually nearer the next gage.

5. Deliveries.—Deliveries shall be marked with the name of the material, the name of the contractor, and the contract or requisition number under which delivery is made.

6. Notes for General Storekeepers.—When ordering sheet copper under these specifications, the thickness in decimals of an inch should be given, as shown in the first column of table in paragraph 2.

NAVY DEPARTMENT SPECIFICATIONS (47 C2a, NOV. 1, 1915; SUPERSEDING 47 C2, AUG. 1, 1913)—COPPER, ROLLED (NONFERROUS METAL C1-r)

[Copper, rolled, bar; copper, rolled, plate and sheet; shapes, copper, rolled]

1. General Instructions.—General specifications for the inspection of material, issued by the Navy Department, in effect at date of opening of bids, shall form part of these specifications.

2. Scrap.—Scrap will not be used in the manufacture except such as may accumulate in the manufacturer's plants from material of the same composition of their own make.

3. Chemical Characteristics.—The material shall contain not less than 99.5 copper.

4. Physical Properties.—Material shall be clean, smooth, of uniform color, quality, and size, and shall be free from all injurious defects. It shall conform to the physical requirements of the tables below:

Rods, Bars, and Shapes

Grade	Tensile strength (minimum)	Elongation in 2 inches (minimum)
	Lbs./in.²	Per cent
Soft	30 000	25
Hard:		
Up to 3/8 inch, inclusive	50 000	10
Over 3/8 to 1 inch, inclusive	45 000	12
Over 1 to 2 inches, inclusive	40 000	15
Over 2 inches	35 000	20

Sheets and Plates [a]

Grade	Tensile strength	Minimum elongation in 2 inches
	Lbs./in.²	Per cent
Soft	30 000–40 000	25
Hard, minimum	35 000	18

[a] Sheets less than 0.072 in thickness need not be test physically.

5. Physical Tests.—From each lot of 500 pounds or less of material of the same size and from the same heat, a heat being one ladle or crucible of metal, test specimens will be taken and subjected to the following tests:

(*a*) Tensile test which must conform to requirements of foregoing tables.

(*b*) Hammer test—Bars to stand hammering hot to a fine point.

(*c*) Bending test—Bars to stand bending cold through 120° C to radius equal to diameter or thickness of test bar.

6. Trimming.—Plates and sheets will be cut to the required dimensions and will be ordered in as narrow widths as can be used.

(*a*) The following will be considered stock lengths for copper sheets when ordered in 10-foot lengths:

40 per cent in weight may be in 8 to 10 foot lengths.
30 per cent in weight may be in 6 to 8 foot lengths.
20 per cent in weight may be in 4 to 6 foot lengths.
10 per cent in weight may be in 2 to 4 foot lengths.

No lengths less than 2 feet will be accepted, and the total weight of all pieces on lengths less than 10 feet must not exceed 40 per cent in any one shipment.

(*b*) Rods and bars, when ordered to any length, will be received in stock lengths, unless it is specifically stated that the lengths are to be exact. Stock lengths will be as follows:

When ordered in 12-foot lengths, no lengths less than 8 feet.
When ordered in 10-foot lengths, no lengths less than 6 feet.
When ordered in 8-foot lengths, no lengths less than 6 feet.
When ordered in 6-foot lengths, no lengths less than 4 feet.

When ordered to the lengths given above, the weight of lengths less than length ordered shall not exceed 40 per cent of any one shipment.

This applies to all rods from one-fourth to 1 inch diameter or thickness, whether round, rectangular, square, or hexagonal. Above 1 inch to and including 2 inches the lengths will be random lengths from 4 to 10 feet. Above 2 inches the lengths are special, but no length will be less than 4 feet.

7. TOLERANCES.—No excess weight will be paid for, and no single piece that weighs more than 5 per cent above the calculated weight will be accepted.

Underweight and Thickness Tolerances.—Width of sheets or plates: 48 inches, or less, 5 per cent; 48 to 60 inches, inclusive, 7 per cent; over 60 inches, 8 per cent.

Material shall not vary throughout its length or width more than the given tolerance.

8. FRACTURE.—The color of the fracture section of test pieces and the grain of the material must be uniform throughout.

9. PURPOSES FOR WHICH USED.—The material is suitable for the following purposes: Copper pipe, shapes, receptacles, and general coppersmith work.

10. NOTE FOR SUPPLY OFFICERS.—Seamless copper tubing and copper pipe, iron-pipe size, should not be purchased under this specification, but under specification for such material.

BRITISH STANDARDS FOR COPPER CONDUCTORS [11]

1. *Resolved,* That a wire 1 m long, weighing 1 g and having a resistance of 0.1539 standard ohm at 60° F (15.6° C) be taken as the engineering standards committee standard for hard-drawn high-conductivity commercial copper. For the purposes of this definition the term hard-drawn copper wire shall apply to copper wire which does not elongate more than 4 per cent on a gage length of 10 inches when broken by tension.

2. *Resolved,* That a wire 1 m long, weighing 1 g and having a resistance of 0.1508 standard ohm at 60° F (15.6° C) be taken as the engineering standards committee standard for annealed high-conductivity commercial copper.

3. *Resolved,* That copper be taken as weighing 555 pounds per cubic foot (8.89 g per cc) at 60° F (15.6° C) which gives a specific gravity of 8.90.

4. *Resolved,* That the average temperature coefficient of 0.00238 per degree F (0.00428 per degree C) be adopted for commercial purposes.

5. *Resolved,* That 2 per cent variation from the adopted standard of resistance be allowed in all conductors.

6. *Resolved,* That 2 per cent variation from the adopted standard of weight be allowed in all conductors.

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[11] Engineering Standards Committee, Report No. 7, March, 1910 (No. 7, revised March, 1910).

7. *Resolved,* That an allowance of 1 per cent increased resistance, as calculated from the diameter, be allowed on all tinned copper conductors between diameters 0.118 inch and 0.028 inch, inclusive.

8. *Resolved,* That for the purpose of calculation of tables, a lay, involving an increase of 2 per cent in each wire, except the center wire, for the total length of the cable be taken as the standard.

9. *Resolved,* That the legal standard wire gage, as fixed by Order in Council, dated August 23, 1883, be adopted as the standard for all wires.

BRITISH STANDARD SPECIFICATIONS FOR COPPER TUBES (SUITABLE FOR SCREWED CONNECTIONS) [12]

1. CLASSIFICATION.—Three classes of tube are dealt with in this specification, viz: Low pressure (Table I), medium pressure (Table II), and high pressure (Table III).

2. CHEMICAL ANALYSIS.—The tubes must contain not less than 99.25 per cent of copper and 0.25 to 0.45 per cent must consist of arsenic.

The manufacturer shall supply an analysis when required to do so.

3. FREEDOM FROM DEFECTS.—The tubes must be clean, smooth, and free from surface defects or longitudinal grooving, internally and externally, and the ends must be clean and square.

4. MECHANICAL TESTS.—The manufacturer shall provide, at his own expense, extra tubes at the rate of 1 per cent of each diameter of tube ordered under the contract, and the representative of the engineer (or of the purchaser) shall select and test such of the tubes as he may think proper to the extent of such percentage. All test pieces shall be annealed before testing, and must comply with the following mechanical tests without further annealing:

5. DRIFTING TEST.—The tubes must stand drifting, as shown in Fig. 1, without showing either crack or flaw, until the diameter of the drifted end measured at least 25 per cent more than the original diameter of the tube.

6. FLATTENING AND DOUBLING OVER TEST.—The tubes must be capable of standing the following test, both cold and at a red heat, without showing either crack or flaw. A piece of the tube shall be flattened down until the interior surfaces of the tube meet as shown in Fig. 2, and then be doubled over on itself; that is, bent through an angle of 180° C, the bend being at right angles to the direction of the length of the tube, as shown in Fig. 3.

7. HYDRAULIC TEST.—All copper tubes shall be tested in accordance with their classification by internal hydraulic pressure as follows:

Classification of tube:	Hydraulic test pressure
Low pressure (Table I)	300 pounds per square inch
Medium pressure (Table II.)	300 pounds per square inch
High pressure (Table III.)	500 pounds per square inch

8. GENERAL DIMENSIONS OF TUBES.—The standard size of any tube shall be designated by the nominal size of bore given in the first column of Tables I, II, and III. All copper tubes purporting to be to British standard specification shall have the inside and outside diameters given in columns 2 and 6, respectively, of these tables, subject only to the tolerances [13] specified in clause 9.

9. TOLERANCES.—The outside diameters of the tubes shall not vary from the standard dimensions by more than the tolerances given in Tables I, II, and III, column 7.

[12] Engineering Standards Committee, Report No. 61, April, 1913. The committee desires to call attention to the fact that this specification is intended to include the technical provisions necessary for the supply of the material herein referred to, but does not purport to include all the necessary provisions of a contract.

[13] The word "Tolerance" is defined as "A difference in dimension prescribed in order to tolerate unavoidable imperfections of workmanship."

No tube shall at any point be thinner than the minimum thickness specified in Tables I, II, and III, column 5.

10. Lengths of Tubes.—The requirements of this specification relate to tubes not exceeding 15 feet in length.

11. Weight of Tubes.—The weight per linear foot for low and medium pressure tubes shall be not less than the values given in column 13 or more than the values given in column 14 (Tables I and II), and for high-pressure tubes not less than the values given in column 17 or more than the values given in column 18 (Table III).

12. Inspection and Additional Tests.—The representative of the engineer (or of the purchaser) shall be at liberty to reject any material that does not conform to the terms of this specification. He will attend to stamp tubes for tests or analyses before delivery.

Should any one of the tubes first selected by the representative of the engineer (or of the purchaser) fail to pass the requirements of the mechanical tests or chemical analysis, two further tubes from the same consignment shall be selected for testing and chemical analysis. Should two out of the above total of three tubes so selected fail as to the requirements of either the mechanical or chemical analysis, the tubes represented by the test specimens shall be liable to rejection.

13. Testing Facilities.—The manufacturer shall supply the material required for testing free of charge, and shall, at his own cost, furnish and prepare the necessary test pieces and supply labor and appliances for such testing as may be carried out on his premises in accordance with this specification. Failing facilities at his own works for making the prescribed tests, the manufacturer shall bear the cost of carrying out the tests elsewhere.

14. British Standard Copper Tubes.—The committee recommend that all copper tubes made in accordance with the requirements of this specification be known as: British standard low-pressure copper tubes (suitable for screwed connections); British standard medium-pressure copper tubes (suitable for screwed connections); British standard high-pressure copper tubes (suitable for screwed connections).

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