DEPARTMENT OF COMMERCE

BUREAU OF STANDARDS

George K. Burgess, Director

NICKEL AND ITS ALLOYS

CIRCULAR OF THE BUREAU OF STANDARDS, No. 100

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NICKEL AND ITS ALLOYS.

ABSTRACT.

In this circular the various physical properties of pure and commercial grades of nickel are described, together with a discussion of the relation of these properties to the composition and treatment of the material. The properties and applications of nickel and its commercially important alloys as Monel metal, nickel steels, ferronickels, copper-nickel and chromium-nickel alloys, and other alloys containing nickel are dealt with. Attention is given to those alloys now finding wide industrial applications by reason of their electrical resistance, heat-resisting, and acid-resisting qualities. An extensive bibliography on nickel and its alloys is included.

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INTRODUCTION.

The bureau is continually in receipt of requests for information concerning the properties, statistics, and manufacture of metals and of alloys coming from other departments of the Government, technical or purchasing agents of manufacturing firms, or from persons engaged in special investigative work in universities and private technical institutes. Such information is rarely to be found in systematic form; usually the sources of such information are difficult of access, and their accuracy not always certain. Often quoted information of this sort is valueless, either for the reason that the data upon which it is based are actually incorrect or that they have not been properly interpreted.

There are, therefore, being issued from time to time in response to these demands 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 material.

The circulars deal primarily with the physical properties of the metal or alloy. All other features, except a few statistics of production and the 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 information regarding these factors by which the properties are affected.

The endeavor, therefore, in the circulars is to reproduce only such data as have passed critical scrutiny and to qualify suitably in the sense outlined above all statements, numerical or otherwise, made relative to the characteristics of the metal. The probable degree of accuracy of data is indicated or implied by the number of significant figures in the values given.

The bureau has received much valuable assistance and information in the preparation of this circular from the International Nickel Co., American Nickel Corporation, British–America Nickel Corporation, the Driver–Harris Co., the Electrical Alloys Co., the Crucible Steel Co. of America, the Hoskins Manufacturing Co., the American Brass Co., the Scovill Manufacturing Co., and others; also, from Dr. P. D. Merica and R. G. Waltenberg, of the International Nickel Co., and Dr. C. T. Hennig of the American Nickel Corporation, for which it wishes to express its grateful appreciation.

HISTORICAL.

1. NICKEL.

Long before the isolation and recognition of the element nickel alloys of a copper-nickel composition were known and used. Representative of such alloys are Bactrian coins of the third century B. C.

The existence of the mineral known as niccolite was first stated in 1694 by Hiarni, who called it copper-nickel, or "false copper," since it possessed a reddish color, yet no copper could be obtained therefrom. It was not until 1751, however, that the metal itself was discovered and isolated by Cronstedt, who recognized it as a new element and metal and in 1754 named it "nickel." Cronstedt's discovery was confirmed in 1755 by Bergmann. Since that time the chemistry of this metal has been continuously unfolded, until to-day a large variety of its alloys and compounds are known.

2. MALLEABLE NICKEL.

In 1804 Richter showed that the metal was malleable, ductile, and possessed a high tensile strength. Fleitmann, in 1879, made an even more malleable nickel by the addition of magnesium.

3. EARLY DAYS OF NICKEL INDUSTRY.

The nickel and cobalt industry was first developed in 1830 at Birmingham, England, by the firm of Henry Merry. Until about 1872 practically the whole of the nickel supply was obtained from arsenical ores containing considerable quantities of cobalt, and up to 1875 the nickel was produced in the form of cubes or rondelles. Henry Merry appears to have been the first maker of an efficient substitute for packfong, a copper-nickel-zinc alloy very long known in China. In about 1830 he, in conjunction with Charles Askin, carried out experiments which led to the development of "Merry's plate" and "Merry's metal blanc." Prior to the introduction of electroplating by Elkington, Merry and his brother patented, in 1836, a process for silver plating on this metal. The production of nickel up to about 1870 amounted to probably not over 200 tons per annum. The introduction of nickel coinage in Germany after the Franco-Prussian War stimulated the nickel industry.

4. ELECTROPLATING.

The first record of nickel being used for producing a bright electrodeposit was made in 1843 by Boettger. Owing to the high price of the metal and the difficulty of obtaining it in a sufficiently pure state, it was not until 1870 that nickel plating was established as an industry.

5. NICKEL STEEL.

At the New York exposition held in 1853 nickel-iron alloys were exhibited, although accounts of the preparation of nickel-iron alloys had been published by Stodart and Faraday as far back as 1820. Later, in 1888, James Riley, in Scotland, began experimenting with a series of nickel steels prepared by Marbeau, who had, during the preceding few years in France, been working on the preparation of these steels by the crucible process. Riley's epoch-making results were published in 1889, first demonstrating the general properties of nickel steels, as well as pointing out their commercial value. This group to-day is the most widely used of all alloy steels.

6. HYDROGENATION OF OILS.

In 1896 Sabatier and Senderens started their classical experiments which showed that nickel has the remarkable property of causing, by its catalytic action, the reduction of unsaturated hydrocarbons and other organic compounds to saturated ones by means of molecular hydrogen. There was thus initiated the process of producing on a commercial basis edible, saturated oils and fats from cheaper unsaturated ones.

7. THE EDISON ACCUMULATOR.

In 1901 Thomas A. Edison developed and patented the nickel storage-battery cell, largely used in place of the lead accumulator in electric vehicles, in lighting systems for houses, trains, and ships, in railway signals, in radio installations, etc.

8. MONEL METAL.

In 1905 the International Nickel Co. first produced this natural alloy by the direct reduction of their ores, without effecting any separation of the copper and nickel contents. This metal possesses physical and chemical properties very similar to those of metallic nickel, which have led to its extended use by the modern manufacturer, especially where strength combined with resistence to chemical corrosion or steam erosion is a requisite.

PART A.—NICKEL.

I. SOURCES, METALLURGY, REFINING.

The ores from which commercial nickel is obtained are of three classes: (1) *Sulphides*, represented by the pyrrhotite-chalcopyrite ores of Sudbury, Canada, and of Norway, and which contain from 3 to 6 per cent of copper plus nickel, with pentlandite as the nickel carrier, the copper-nickel ratio varying from 1 to ⅓; (2) *silicates and oxidized ores*, which are found principally in New Caledonia and contain from 5 to 8 per cent nickel (plus cobalt), with garnierite as the principal nickel carrier; and (3) *arsenical ores*, which are found in Canada and on the Continent (Saxony) and elsewhere. Of these the first two classes only are of much commercial importance, and the first class furnishes by far the greater proportion of the present output of this metal. In addition to the metal produced from these ores, a small amount of nickel is recovered annually from blister copper.

Sulphide ores are first roasted in heaps and in Wedge roasters to reduce the sulphur from about 25 per cent to about 10 per cent. The roasted ore is then smelted in the blast furnace and in reverberatory furnaces to a matte containing approximately 25 per cent copper plus nickel, 45 per cent of iron, and 30 per cent of sulphur. This matte is then blown in basic lined converters to one containing about 80 per cent copper plus nickel, together with 20 per cent of sulphur; that is, so-called "Bessemer matte," the raw material for the refining process.

Although the smelting practice of the companies operating with sulphide ore of the Sudbury type is essentially the same, as well as the product of this operation, viz, Bessemer matte, the refining of this matte to metal and the separation of the nickel from the copper are accomplished by three widely different processes.

1. The Hybinette process, which is in operation in Norway, is essentially an electrolytic one. The matte is roasted to remove the bulk of the sulphur and leached with 10 per cent sulphuric acid, whereby a large proportion of the copper with very little nickel is dissolved out. The residue is melted and cast into anodes, containing about 65 per cent nickel and from 3 to 8 per cent of sulphur, from which, by a combination of electrolysis and cementation of the copper by waste anodes, nickel cathodes and both cement and cathode copper are obtained.

2. In the Mond process, which is operated in England, the Bessemer matte is first roasted and the copper removed in part by leaching with sulphuric acid with the formation of a solution of copper sulphate. The residue, containing nickel oxide with some copper oxide and iron, is reduced at a relatively low temperature to a finely divided metallic powder. This is carefully protected from contact with the air, and carbon monoxide is passed over it at from 50 to 80° C. (122 to 176° F.). At these temperatures nickel-carbonyl vapor is formed and is decomposed by passing it through a tower containing shot nickel heated to about 200° C. (392° F.); a layer of nickel is formed on the shot, and the carbon monoxide is regenerated and returned to the volatilizing towers. The nickel shot is alternately exposed to and withdrawn from the action of this gas, and in this way a series of concentric layers of nickel are built up around the original nucleus, like the coats of an onion. Mond-nickel shot may readily be distinguished by hammering it upon an anvil, when the various coatings will be broken open, revealing its layer structure.

3. The Orford process, which is the oldest process for the separation of copper and nickel, is being operated in this country. The Bessemer matte is melted with salt cake, or niter cake, together with coke, in the blast furnace. The sodium sulphide formed by the reduction of the sodium sulphate by the coke, together with the copper sulphide, forms a matte of low specific gravity. The product of the blast furnace is allowed to cool in pots, in which a separation occurs, the upper portion or "tops" containing the greater part of the copper sulphide, together with the sodium sulphide, the lower portion or "bottoms" containing the greater part of the nickel sulphide. The "tops" and "bottoms" are readily split apart when cold. After several such treatments in the cupola or reverberatory furnace the "tops" are blown in a converter to blister copper. The "bottoms," consisting essentially of nickel sulphide, are roasted and leached until a pure nickel oxide is obtained. This is reduced with charcoal in reverberatory furnaces to metallic nickel at a temperature above its melting point, such that the resulting product may be cast into ingots, or blocks, or poured into water to form shot. Electrolytic nickel is also produced by casting this reduced metal at once into anodes and obtaining pure nickel cathodes from them by electrolysis with an electrolyte of nickel sulphate.

The silicate ores of New Caledonia, which contain no sulphur, are first mixed with sulphur-bearing materials, such as gypsum or pyrites, and smelted in the blast furnace to a matte, which is shipped for refining, which in this case, in the absence of copper, consists merely of roasting the nickel matte to oxide and reducing the oxide with charcoal.

II. COMMERCIAL GRADES: USES AND APPLICATIONS.

1. NICKEL IN VARIOUS FORMS.

Nickel appears on the market in the following forms:

(*a*) Grains, cubes, rondelles, or powder reduced at a relatively low temperature from nickel oxide and not fused in the process of manufacture.

(*b*) Nickel deposited in concentric layers from nickel carbonyl and not fused in the process of manufacture.

(*c*) Nickel deposited electrolytically in the form of cathode sheets.

(*d*) Nickel in the form of blocks or shot made by reducing nickel oxide above the melting point of nickel and casting the resulting molten metal or pouring it into water without deoxidation.

(*e*) Malleable nickel made in the same manner as (*d*), but treated with some deoxidizer before pouring or "teeming" into ingots. This nickel is produced in the usual commercial forms, viz, rods, sheet, strip, wire, tubes, etc.

The greater part of the commercial production of nickel is of class (*d*).

TABLE 1.—Composition of Various Grades of Commercial Nickel.[1]

Name.	Source.	Form.	Constituents (percentages). Ni and Co [2]	Co	Cu	Fe	C	S	Si	Mn	As	Sn and Sb	Insol.	Remarks.
Norway nickel	V. Hybinette	Electro	99.52	0.89	0.06	0.36								
Banco nickel	British America Nickel Corporation.	do	98.70	Up to 1.0	.10	.60	0.002	0.002	None.			No Sb		Typical analysis.
Canadian nickel	D. H. Browne	do	99.80		.01	.12					Trace.	Trace.	0.015	
Orford nickel	International Nickel Co.	do	99.84		.01		.005	.005			0.01	0.01	.003	Analyzed by Orford (1908).
			99.80	.80	.02	.14		Trace.						Analyzed by Orford (1914).
Electrolytic nickel.	Hybinette process	do	98.75		.10	.50		.01						Royal Ontario Nickel Commission.
Do	International Nickel Co.	do	99.80		.05	.15	.00	.00	.00					Approximate analysis of commercial product (Browne and Thompson).
Nickel shot	U. S. Nickel Co.	Shot	99.00–99.50		.05	.50	.10	.03 (max.)	0.05–.20					Typical analysis.
Mond nickel	L. Mond (England).	do	99.36	.06	.03	.39	.11	.002	.11	0.09				
Do	Mond Nickel Co.	do	99.80	None.	None.		.05	.006	None.					Analyzed by Hadfield (1899).
			99.92	None.	.008	.040	.030	None.	.007					Analyzed by Mond (1915).
Do	L. Mond		99.80											Royal Ontario Nickel Commission.
Do			99.89	Nil.	.03	.05	.03	.003						Metal Industry (London), vol. 21, p. 195 (Sept. 1, 1922).
Nickel shot	International Nickel Co.	A shot	98.65	.80	.15	.50	.45	.06	.15		.015	.015		Analyzed by Orford (1914).
		X shot	99.05	.80	.15	.47	.18	.04	.10		.015	.015		Do.
		A shot	98.60			.50	.50	.050						
		X shot	99.08		.10	.46	.05	.024	.05					Royal Ontario Nickel Commission.
		A shot	98.40		.25	.60	.50	.06	.25					Approximate analysis of commercial product (Browne and Thompson).
		X shot	98.90–99.00		.15–.25	.45–.55	.18	.035	.15					Do.

[1] Much of these data were taken from Browne and Thompson (458), Table 1.

[2] The nickel values of some of the samples mentioned by the Royal Ontario Nickel Commission include nickel only, while in other cases (including those reported from other sources) they include nickel plus cobalt.

NOTE.—The figures given in parentheses in footnote 1 and throughout the text relate to the numbered references given in the Bibliography at the end of this circular

TABLE 1.—Composition of Various Grades of Commercial Nickel [1]—Continued.

Name.	Source.	Form.	Constituents (percentages).											Remarks.
			Ni and Co [2]	Co	Cu	Fe	C	S	Si	Mn	As	Sn and Sb	Insol.	
Banco nickel	British America Nickel Corporation.	Shot	99.25 99.64	0.25 .15	0.06 .06	0.50 .23	None. None.	0.014 .014	None. None.					Typical analysis. Do.
Nickel ingots	International Nickel Co.	Ingots	99.09 99.10	.32 .80	.11 .13	.65 .50	0 04 .10	.04 .06	0.01 .10		0.02 .015	0.02 .015		Analyzed by Le Nickel (1905). Analyzed by Orford (1914).
Do	U. S. Nickel Co.	do	99.0– 99.5		.05	.50	.10	.03 (max.)	.05– .20					Typical analysis.
Banco nickel	British America Nickel Corporation.	do	99.25 99.64	.25 .5	.06 .06	.50 .23	None. None.	.014 .014	None. None.					Do. Do.
Metallic nickel	Le Nickel	Brick Cylinder	99.60 99.11				.111 .251	.01 .006	.104 .151					
Malleable nickel	American Nickel Corporation.	Various products.	99.37 99.11		.14 .06	.28 .40	.087 .212	.013 .016		0.08 .17				Typical analysis. Do.
Nickel rod	H. Boker & Co.	Rods	97.58		.18	.38	.19	.012	.13	1.60				
Electromalleable nickel.	International Nickel Co.	do	99.40	.80	.10	.30	.10	.015	.10		Trace.	Trace.		Analyzed by Orford (1914).
Malleable nickel A	do	do	99.00			.55	.15	.025	.10	.15				Typical analysis Orford Works.
Malleable nickel B	do	do	98.75			.50	.15	.025	.20	1.75				Do.
Malleable nickel C	do	do	96.75			.75	.15	.03	.20	1.75				Do.
Nickel tube	H. Boker & Co.	Tube	97.12		.75	.65	.13		.10	1.15				
Nickel castings	International Nickel Co.	Castings	98.95			.50	.16	.035						Do.
Nickel sheet	Fleitmann, Witte & Co.	Sheet	99.37		.12		.019							
Malleable nickel	Krupp (Germany)	Sheet 1 Sheet 2	99.26 99.05		.12 .10	.40 .40	.045 .13	.024 .045	.17 .16	Trace. .13				
Rolled nickel sheet	Baker & Co.	0.001 by 12 in.	97.99	.88	.12	.49				1.32				
French 25 centimes	France	Coin	99.26	1.36	.083	4.05	.042	.05	.07	Trace.	.018	.021		
20-centisimi piece	Italy	do	99.23		.089	.31				.17				
Arthur Krupp nickel.	Berndorf, Austria.	Wire rod	99.20	.54	.10	.40	.07	.01	.02	.22				
Nickel rod	England	1/4-in. wire	99.13	.62	.23	.30	.16	.022	.06	.66				

Electromalleable nickel.	Driver-Harris Co.	0.081-in. wire	98.47			.80	.13	.06	.16	.30				
Gas mantle	Solex Co. (Ltd.)	Wire	98.96			.57				.15				
Malleable nickel	Fleitmann, Witte & Co.	do	98.60	Trace.		1.22				.16				Royal Ontario Nickel Commission.
Nickel cubes	U. S. Nickel Co.	Cubes	99.16		.065	.32	.41							
Do	do	do	99.40											Private communication; impurities about same as that in nickel shot reported above as from same source.
Metallic nickel	Le Nickel	do	99.41				.176	.015	.04					
Nickel cubes		do	99.00		.10	.23	.07	.008	.12					Royal Ontario Nickel Commission.
Do	Wiggins	do	99.25											Do.
Inco rondelles	International Nickel Co.	Rondelle	99.2			.45	.15	.01	.10					Private communication.
French nickel	Le Nickel	do	99.01		.112	.43	.037	.024					0.068	
Grain nickel	American Nickel Works.	Grain	99.17		.13	.51							1.06	
Mond nickel	Ludwick Mond	do	99.57		.014	.133	.23	.003			Trace.	Trace.	.03	
Metallic nickel	Le Nickel	do	99.38				.048	.010	.109	.01				
Do	U. S. Nickel Co.	Various	99.02	.12	.05	.21	.39	.025	.21		Trace.			
Pure nickel	Kalmus & Harper		99.29	Nil.		.48	Nil.	.025	.042					Royal Ontario Nickel Commission.
Nickel	New Caledonia		98.00		.50	1.60			.13					Do.
Do	do		98.23			.98			.30					Do.
Do	Basse and Selve		97.87	1.45	.10	.45	Trace.	.05	.19					Do.
Do	Deloro Mining		98.00	1.60	.05	.75								Do.

[1] See footnote 1, page 9.
[2] See footnote 2, page 9.

Table 1 gives the chemical composition of a number of samples of commercial nickel, including those of foreign manufacture, and also typical analyses of commercial nickel made in this country. Inasmuch as many analysts usually include cobalt together with nickel in their reports of analysis, it appears desirable here to call attention to and emphasize the need of reporting nickel separately from cobalt or at least stating that the determination includes both nickel and cobalt.

Besides the commercial forms of nickel described above, the metal is on the market in the form of anodes for the metal-plating industry. These cast anodes are quite variable in composition and contain from about 90 to 98 per cent nickel (and cobalt), together with iron, copper, carbon, silicon, manganese, and tin. A typical analysis of American commercial nickel anodes may be as follows:

	Per cent.		Per cent.
Nickel (and cobalt)	97.4	Copper	0.25
Carbon	1.2	Silicon	.20
Iron	1.0		

Tin is oftentimes found present, even to the extent of about 0.5 per cent.

The International Nickel Co. has described certain grades and gives the following average analyses of these materials:

"A" shot nickel, a high-carbon nickel used by manufacturers of anodes for nickel plating, containing approximately:

	Per cent.		Per cent.
Nickel	[1] 98.40	Copper	0.25
Carbon	.50	Silicon	.25
Iron	.60	Sulphur	.06

"X" shot nickel, a purer material used by the manufacturers of crucible nickel steel and of nickel silver, containing approximately:

	Per cent.		Per cent.
Nickel	99.00	Copper	0.15
Carbon	.18	Silicon	.15
Iron	.45	Sulphur	.035

Ingot or block nickel is almost identical in composition with "X" shot. It is sold in 25 and 50 pound blocks or ingots and is used in the manufacture of open-hearth and electric steel.

"F" shot nickel, a special product possessing a low melting point (1,250 to 1,285° C., 2,282 to 2,345° F.) and containing about 5 per cent silicon and about 1 per cent carbon. Designed for use in foundries where nickel additions to cast iron are by necessity made in the ladle.

[1] The nickel produced by this company contains about 0.5 per cent cobalt, which is included in the figure given for the nickel content.

Electrolytic nickel in the form of cathodes 24 by 36 inches, weighing about 100 pounds, or in smaller squares for convenience, is used in the manufacture of high-grade nickel silver and cupro-nickel alloys. It contains approximately:

	Per cent.		Per cent.
Nickel	99.80	Copper	0.05
Carbon	.00	Silicon	.00
Iron	.15	Sulphur	.00

Rolled cathode sheets of this material, about 0.02 inch thick, are also produced for making alloys in small quantities.

The British America Nickel Corporation has reported the following concerning their commercial grades of nickel, which are produced by the electrolytic process and sold under the trade name "Banco nickel."

Banco nickel is produced originally as cathodes about 24 by 36 inches and usually from $\frac{1}{16}$ to $\frac{1}{4}$ inch thick, weighing approximately 30 pounds, and with the following typical composition:

	Per cent.		Per cent.
Nickel (including up to 1 per cent Co)	98.70	Carbon	0.002
Iron	.60	Sulphur	.002
Copper	.10	Silicon, phosphorus, antimony	None.

To suit the customer's requirements, the cathodes are cut into standard sizes, packed, and shipped in barrels or bound into bundles. The sizes used are:

	Size.	Thickness of bundle.	Approximate weight of piece.
	Inches.	Inches.	Ounces.
Cut cathodes	2 by 2		1–2
	4 by 4		8
			Pounds.
Bundled cathodes	4 by 12	5	25
	6 by 24	5	50

Banco shot nickel and ingots are furnished in two grades of the following typical compositions:

	99 per cent.	99.5 per cent.
Nickel (including cobalt reported below)	99.25	99.64
Cobalt	.25	.5
Iron	.50	.23
Copper	.06	.06
Carbon	None.	None.
Sulphur	.014	.014
Silicon, phosphorus, antimony	None.	None.

The ingots are made in two standard sizes:

Top (inches).	Bottom (inches).	Thickness.	Weight.
		Inches.	Pounds.
3½ by 14	2 by 10	3	25
5 by 15	2½ by 12	3½	50

The American Nickel Corporation (1a) produces two grades of malleable nickel, known as "Hennig nickel," of the following typical compositions (approximate):

	Low carbon.	High carbon.
	Per cent.	Per cent.
Nickel	99.37	99.11
Iron	.28	.40
Manganese	.08	.17
Copper	.14	.06
Carbon (by combustion)	.087	.212
Sulphur	.013	.016
Phosphorus	.017	.011

The bureau has been advised that this nickel is free from cobalt, for the manufacturers have found it profitable to separate the cobalt as a by-product, since there is a market for it as in the manufacture of magnet and high-speed steels.

The principal commercial application of nickel is in the manufacture of nickel steel, this industry having absorbed fully 75 per cent of the total nickel production during the World War. The normal consumption amounts to probably 65 per cent. Nickel steels are discussed briefly on page 82.

Besides its use in steel it is used quite extensively as an alloying element with nonferrous metals, principally copper. Many of these alloys are discussed in more detail below. About 15 per cent of the production is normally utilized in the manufacture of alloys of nickel, such as cupronickel and especially nickel silver, the former series of alloys having come into prominence during the war. Nickel coinage and the electroplating industries may each absorb from 2 to 5 per cent of the production, the latter requiring the metal both in the metallic form and in the form of nickel salts; the single salts $NiSO_4.7H_2O$ and the double salt $NiSO_4.(NH_4)_2SO_4.6H_2O$.

The bureau has been advised by one of the largest producers of nickel that the nickel of the world, exclusive of that sold as Monel metal, is consumed in the following materials in about these proportions:

	Per cent.		Per cent.
Nickel steel	65	Malleable nickel	5
Nickel anodes	5	Miscellaneous	10
Nickel silver	15		

2. MALLEABLE NICKEL.

Malleable nickel, intended for rolling into sheets or rods or for drawing into wire, is made in various grades, according to the purpose for which it is destined. All malleable nickel is treated before casting into ingots with some deoxidizer, generally magnesium, for the purpose of reducing the nickel oxide present and making the metal suitable for rolling or forging. Manganese is also added both for the purpose of cleaning the metal and as an alloying element. Nickel can not, in general, be rolled or forged without this preliminary treatment with a deoxidizer.

The following grades of malleable nickel ingots are produced for rolling into rods, sheet, strip, and drawing into wire and tubes:

Grade A malleable nickel:	Per cent.	Grade C malleable nickel:	Per cent.
Nickel	98.90–99.00	Nickel	96.50–97.00
Iron	.50	Iron	.50– 1.00
Manganese	.20– .35	Manganese	1.50– 2.00
Copper	.18	Copper	.20
Carbon	.10	Carbon	.20
Silicon	.20	Silicon	.15
Sulphur	.025	Sulphur	.035

Grade D malleable nickel is high manganese nickel having practically the same composition as grade C, except that the manganese content is higher, varying from 3 to 6 per cent. This is used principally for spark-plug wire. Wire of this composition resists the action of high temperatures and combustion gases than the other grades.

The production of malleable nickel, although never large compared to that used in the manufacture of steel, has amounted to about 5 per cent of the total production of nickel and is steadily growing in volume as the properties of the metal in this form become better known. Malleable nickel is produced in all commercial forms, viz, sheet, strip, rods, wire, tubes, pipe, forgings, bolts and nuts, automobile radiators, wire screen and cloth, and wool.

It has hitherto been used principally for subsidiary coinage, and abroad for cooking utensils because of its great resistance to wear and abrasion and to corrosion by foodstuffs. The use of cooking utensils in this country is increasing through the fact that the manufacture of ware sufficiently hard to withstand rough usage has been successfully developed. Miscellaneous household and ornamental stampings and fittings are now made of nickel by reason of its natural pleasing color and finish. Switzerland, France, Austria, Hungary, and Italy use pure nickel coinage.

The resistance to chemical corrosion of nickel has occasioned its wide use for chemical apparatus and equipment in both laboratory and plant. It is used particularly in equipment for operations, such as digestion, evaporation, and transport in connection with dyes and their intermediates, essential oils, and foodstuffs. Malleable nickel castings are quite generally used for heavy equipment of this type. Castings up to 2 tons in weight are made. The bureau has very recently been informed by a manufacturer that the construction of nickel kettles 14 feet in diameter by welding three-fourth inch plates is planned, the kettles to be used as containers for alkalies. Among the uses for nickel tubing are condenser tubes, domestic water heaters, speaking tubes on ships, apparatus for making hydrogen and other gases, etc. Some nickel is used for valve trim.

Quite a little nickel is used in the form of wire, the diameter of the wire being even as small as 0.002 inch. High manganese nickel wire is practically standard for spark-plug points and is also used for suspension wires in electric-light bulbs and in the vacuum-tube amplifier. Nickel is used for these purposes principally because of its resistance to oxidation at high temperatures. For similar reasons nickel is used for pyrometer tubes, for combustion boats employed in the reduction of tungsten and molybdenum oxides, and for blowpipes in glass making.

Nickel castings have been used with much success as rabble shoes by the International Nickel Co. in Edwards calcining furnaces roasting nickel matte. The shoes are exposed to oxidizing and sulphurizing gases at temperatures ranging from 600 to 1,000° C. and to severe mechanical abrasion. They have stood up in this severe service for nine months, whereas cast-iron shoes would last no more than six or eight weeks.

Recent tests have shown that nickel resists remarkably well the action of cyanide and also the conditions attendant to the use of cyanide pots.

3. NICKEL USED IN NONMETALLIC FORM.

Only a relatively small amount of nickel has been used commercially in the nonmetallic form. The chief use in this form is for nickel plating, which is described in more detail on page 48. Aside from this, the two principal commercial applications are in the Edison accumulator or storage cell and in hardening oils by the Sabatier and Senderens process (239).

The Edison cell uses nickel in the form of nickelous hydrate, which, as is well known, is reversibly altered to nickelic hydrate during charge and discharge.

The hydrogenation or hardening of edible oils by the Sabatier and Senderens reaction is accomplished by the use of a catalyzer consisting of finely divided nickel, which is produced usually by the reduction of nickel formate, the form in which nickel is usually sold for this purpose. Much information on this subject may be found in the book by C. Ellis (227).

Nickel oxide is also used in the ceramic industries for the production of under or holding coats of enamel on steel, and also for coloring glazes on pottery.

III. STATISTICS OF PRODUCTION.

Tables 2 to 6 show the exports and imports of nickel and nickel products from and into the United States during recent years according to data of the United States Geological Survey (24a, 25, 26, 34).

TABLE 2.—Nickel Content of Nickel Salts and Metallic Nickel Produced in the United States as a By-Product in the Electrolytic Refining of Copper, 1911–1922.

Year.	Quantity.	Value.	Year.	Quantity.	Value.
	Short tons.			Short tons.	
1911	445	$127,000	1917	402	$331,556
1912	328	93,600	1918	441	401,000
1913	241	79,393	1919 [1]	511	434,485
1914	423	313,000	1920 [1]	365	293,250
1915	822	538,222	1921	111	86,000
1916	918	671,192	1922	208	133,191

[1] Including nickel produced from copper-lead-cobalt-nickel ores mined in Missouri.

TABLE 3.—Nickel Imported for Consumption in the United States, 1913–1922.

Year.	Nickel, nickel ore and matte, nickel oxide, alloys of nickel with copper, etc.		Value of manufactured articles of nickel and nickel sheets and strips.	Total value.
	Quantity.	Value.		
	Pounds.			
1913	47,446,520	$6,562,555	$38,200	$6,600,755
1914	35,098,958	5,000,594	28,224	5,028,818
1915	56,599,381	7,629,686	6,458	7,636,144
1916	72,649,377	9,899,340	25,880	9,925,220
1917	75,526,767	9,617,163	45,248	9,662,411
1918	73,207,147	11,520,775	115,243	11,636,018
1919	36,562,388	8,334,135	90,451	8,424,586
1920	48,492,076	10,657,193	200,464	10,857,657
1921	4,396,119	1,210,317	107,155	1,317,472
1922	14,919,362	3,945,168	110,176	4,055,344

Attention is here called to the fact, as indicated by Tables 2 and 3, that only a very small proportion of the nickel refined or used in the United States is derived from ores mined in this country.

TABLE 4.—Nickel Imported for Consumption in the United States, 1916–1922, by Forms.

Form.	1916		1917	
	Quantity.	Value.	Quantity.	Value.
	Pounds.		Pounds.	
Nickel, alloys, pigs, bars, etc	29,917	$7,869	48	$19
Ore and matte (nickel content)	72,611,492	9,889,122	75,510,400	9,612,400
Nickel oxide	7,968	2,349	15,926	4,744
Nickel sheets and strips	....	4,896	....	....
Nickel, all other manufactures of	....	20,984	....	45,248
Total	72,649,377	9,925,220	75,526,767	9,662,411

Form.	1918		1919	
	Quantity.	Value.	Quantity.	Value.
	Pounds.		Pounds.	
Nickel, alloys, pigs, bars, etc	40	$8	7,258,082	$2,553,431
Ore and matte (nickel content)	79,193,205	11,517,546	29,303,228	5,780,380
Nickel oxide	13,902	3,221	1,078	324
Nickel sheets and strips	8,612	6,881	10,152	4,889
Nickel, all other manufactures of	10,495	108,362	87,527	85,562
Total	73,226,254	11,636,018	36,660,067	8,424,586

Form.	1920		1921		1922	
	Quantity.	Value.	Quantity.	Value.	Quantity.	Value.
	Pounds.		Pounds.		Pounds.	
Nickel, alloys, pigs, bars, etc	6,905,753	$2,193,256	2,324,993	$770,021	11,341,360	$3,438,225
Ore and matte (nickel content)	41,586,108	8,463,872	2,042,178	432,786	3,085,632	396,726
Nickel oxide	215	65	28,948	7,510	492,370	110,217
Nickel sheets and strips	....	....	....	....	....	....
Nickel, all other manufactures of	....	200,464	....	107,155	....	110,176
Total	[1] 48,492,076	10,857,657	[1] 4,396,119	1,317,472	[1] 14,919,362	4,055,344

[1] Does not include data for "nickel, all other manufactures of," which was not reported.

TABLE 5.—Imports of Nickel Ore and Matte into the United States in 1917-1922, by Countries.

Country.	1917			1918			
	Nickel ore and matte.			Nickel ore and matte.			Manufactures.
	Quantity.	Nickel content.	Value.	Quantity.	Nickel content.	Value.	Value.
	Short tons.	Pounds.		Short tons.	Pounds.		
Canada	65,916	73,530,259	$9,138,994	63,835	70,645,034	$10,974,325	$4,441
Australia	2,463	1,980,534	473,406	2,339	2,027,850	433,878	....
Other British Oceania	....	....	....	489	409,023	85,934	....
French Oceania	....	....	....	112	111,207	23,365	....
Chile	....	....	....	1	91	44	....
England	....	....	....	....	....	....	5,517
France	....	....	....	....	....	....	411
Japan	....	....	....	....	....	....	6,671
Switzerland	....	....	....	....	....	....	12,339
Total	68,379	75,510,793	9,612,400	66,776	73,193,205	11,517,546	29,379

Country.	1919				1920			
	Nickel ore and matte.			Manufactures.	Nickel ore and matte.			Manufactures.
	Quantity.	Nickel content.	Value.	Value.	Quantity.	Nickel content.	Value.	Value.
	Short tons.	Pounds.			Short tons.	Pounds.		
Canada	22,760	25,503,767	$4,997,650	$2,580,695	33,182	37,737,459	$7,723,278	$2,179,494
Australia	3,008	3,716,293	760,887	....	....	....	....	....
Austria	....	....	....	....	1,210	1,396,001	361,698	5
Belgium	....	....	....	....	787	857,381	228,242	253
French Oceania	56	83,168	21,843	....	1,389	1,595,267	150,654	....
China	....	....	....	2	....	....	....	109
Denmark	....	....	....	17	....	....	....	39
England	....	....	....	16,246	....	....	....	125,108
France	....	....	....	5,055	....	....	....	3,594
Germany	....	....	....	271	....	....	....	23,083
Japan	....	....	....	13,167	....	....	....	12,666
Netherlands	....	....	....	172	....	....	....	66
Poland and Danzig	....	....	....	....	....	....	....	1,324
Spain	....	....	....	10	....	....	....	....
Sweden	....	....	....	....	....	....	....	2
Switzerland	....	....	....	28,247	....	....	....	49,959
Turkey in Asia	....	....	....	....	....	....	....	308
Total	25,824	29,303,228	5,780,380	2,643,882	36,568	41,586,108	8,463,872	2,396,010

TABLE 5.—Imports of Nickel Ore and Matte into the United States in 1917–1922, by Countries—Continued.

Country.	1921				1922				
	Nickel ore and matte.			Manufactures.	Nickel ore and matte.		Nickel alloys, etc.		Manufactures.
	Quantity.	Nickel content.	Value.	Value.	Nickel content.	Value.	Nickel content.	Value.	Value.
	Short tons.	Pounds.			Pounds.		Pounds.		
Canada	1,576	1,867,279	$390,098	$708,526	2,005,037	$242,001	4,968,847	$1,450,734	$3,216,299
Belgium	112	174,899	42,688	1,925	1,080,595	154,725	...	...	...
Austria	...	...	...	576	...	...	1,442	1,230	1,230
China	...	...	...	...	...	...	...	...	2
Czechslovakia	...	...	...	...	...	...	14	16	343
Denmark	...	...	...	5	...	...	...	...	...
England	...	...	...	75,231	...	...	231,982	70,233	366,710
France	...	...	...	8,175	...	...	2,257	3,519	6,310
Germany	...	...	...	59,330	...	...	20,310	16,719	55,306
Italy	...	...	...	7,165	...	...	85	87	284
Japan	...	...	...	6,562	...	...	122	51	1,766
Netherlands	...	...	...	36	...	...	6	3	433
Scotland	...	...	...	170	...	...	50	30	30
Spain	...	...	...	6	...	...	...	...	...
Sweden	...	...	...	77	...	...	...	...	...
Switzerland	...	...	...	16,222	...	...	173	137	10,329
Total	1,688	2,042,178	432,786	884,006	3,085,632	396,726	5,225,288	1,542,759	3,659,042

TABLE 6.—Quantity and Value of Nickel, Nickel Oxide, and Matte [1] Exported from the United States.

BY YEARS, 1909–1922.

Year.	Quantity.	Value.	Year.	Quantity.	Value.
	Pounds.			Pounds.	
1909	12,048,737	$4,101,976	1916	33,404,011	$12,952,493
1910	15,244,937	4,704,088	1917	21,992,820	8,936,620
1911	25,099,586	8,283,777	1918	17,469,500	6,927,041
1912	25,815,016	8,515,332	1919	3,810,656	1,697,544
1913	29,173,088	9,686,794	1920	1,215,232	574,845
1914	27,595,152	9,455,528	1921	425,851	103,372
1915	26,418,550	10,128,514	1922	9,317,520	1,016,091

EXPORTS FOR YEAR 1922, IN ITEMIZED DETAIL.

[Nickel Alloys and Manufactured Articles are also Included in this Tabulation.]

Material.	Quantity.	Value.
	Pounds.	
Nickel	5,840	$3,022
Nickel oxide and matte	9,311,680	1,013,069
Monel metal and other alloys	913,983	196,702
Manufactures	249,467	179,094
Nickel silver, in bars, rods, or sheets	402,922	121,755

[1] No nickel matte is known to have been exported in the years 1911 to 1922, inclusive.

IV. METALLOGRAPHY.

As far as is known, nickel exists in only one solid modification or phase which is stable at all temperatures up to that of its melting point. It suffers, however, a magnetic transformation, in a manner quite similar to iron, at about 360° C. (680° F.). Below this temperature it is ferromagnetic, above it is only weakly paramagnetic. Values of the temperature of this transformation varying from 320 to 370° C. have been obtained by different investigators working with nickel of different degrees of purity and are shown in Table 7. There is, therefore, some uncertainty attaching to the exact temperature of this transformation, and the value accepted above represents the results of those who worked with the purest material. The magnetic transformation of nickel, as in the case of iron, is accompanied as well by changes in the other physical properties, such as density, resistivity, and thermoelectromotive force, or in their temperature derivatives.

According to Hull (150) the atoms in a nickel crystal are arranged in the face-centered-cube formation, giving rise to the regular crystalline form of this metal.

TABLE 7.—Temperature of the Magnetic Transformation of Nickel.

Reference.	Chemical composition.					Temperature of transformation.
	Cu	Fe	Co	Si	C	
	Per cent.	Per cent.	Per cent.	Per cent.		° C.
Copaux (464)	(1)	(1)	(1)	(1)		340
Guertler and Tammann (691)	Trace.	0.47	1.86			320–325
Curie						340
Pecheux (347)	0.20	Trace.	.15	0		345
	.80	Trace.	Trace.	.20		340
	.40	.60	.10	.15		345
	Trace.	1.50	.50	.10		335
Jänecke (151)						347–356
Werner (156)						352–355
Stark-Tatarczenko (159)						370
Baikow (160a)						360
Honda and Takagi (1157)						370
Hanson and Hanson (720)						[2] 393–348

[1] Cobalt-free nickel melted under hydrogen.
[2] These values were determined from the heating and cooling curves, respectively.

As the magnetic transformation of nickel is not accompanied by any determinable alteration in structure or recrystallization, the microstructure of this material is relatively simple, at least when compared with that of iron and steel. The impurities which are invariably found in commercial nickel are (with the below-mentioned exceptions) soluble in the solid state in the amounts in which they are usually present, namely, iron, copper, manganese, cobalt, and silicon. Nickel oxide, sulphides (of nickel or manganese), and carbon are at times visible as separate constituents in nickel. In addition there may be found in all malleable nickel a small amount of magnesium sulphide in the form of small round particles.

Figure 1 shows the structure of commercial nickel blocks and the appearance of the nickel-nickel oxide eutectic. The effect produced by the presence of nickel oxide upon the malleability of nickel is discussed on page 42. The structure of malleable nickel in the form of hot-rolled rod is shown in Figure 2. The small dark particles scattered throughout the matrix, which is composed of grains of nickel, may possibly be either magnesium or manganese sulphide, in cases where sulphur is present, or refractory oxides. Carbon is usually soluble in nickel to the extent of 0.4 per cent and is, therefore, not ordinarily found in any other form in commercial nickel. Above that percentage, however, it begins to separate out in the form of graphite. Figure 3 shows the appearance of graphite in rolled nickel.

Nickel is subject to a peculiar type of intercrystalline brittleness, which has been well described structurally by Rawdon and Krynitzky (149). When exposed at high temperatures—that is, from 1,000 to 1,200° C.—to the action of oxidizing or sulphurizing gases, the boundaries of the grains at the surface are attacked, either oxidized or sulphurized, and the cohesion between the grains destroyed. These surface layers become quite brittle and will not elongate or flow under subsequent drawing or rolling operations, but there is produced a network of fine cracks on the surface under such treatment. The presence of these cracks indicates a faulty heating operation—that is, either the flame was too oxidizing and "burnt" the metal or it introduced sulphur into it. Figure 4 shows the structure of such "heat-checked" nickel sheet.

Nickel is very resistant in its chemical properties, and for developing the microstructure of nickel for metallographic examination a strongly oxidizing reagent as nitric acid is used, even with a volume concentration of from 50 to 100 per cent acid, although pitting of the etched surface very often results. Somewhat better results may be obtained by using a solution of nitric acid with a volume concentration of from 50 to 75 per cent, made by diluting the concentrated acid with a solution containing 50 per cent glacial acetic acid in water. These acetic acid solutions appear to give more uniform results than the simple aqueous

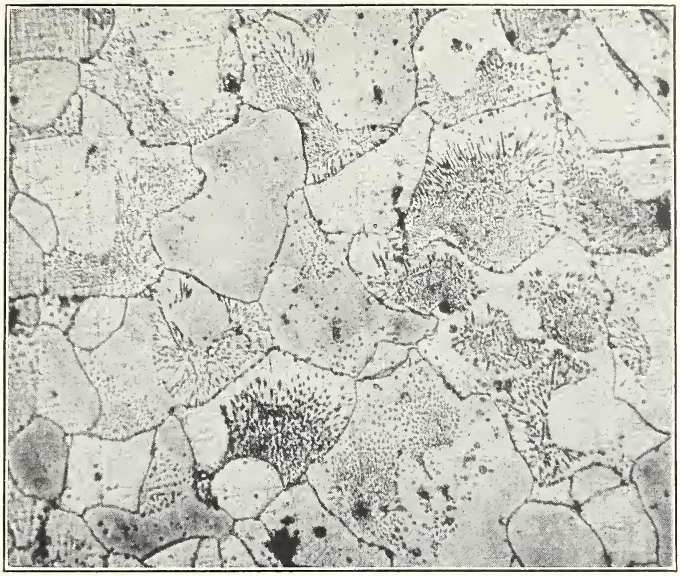

FIG. 1.—*Microstructure of nickel blocks showing nickel—nickel oxide eutectic.* ×100

FIG. 2.—*Microstructure of hot-rolled nickel rod.* ×100

FIG. 3.—*Microstructure of rolled nickel rod containing precipitated graphite in the form of fine particles.* ×100

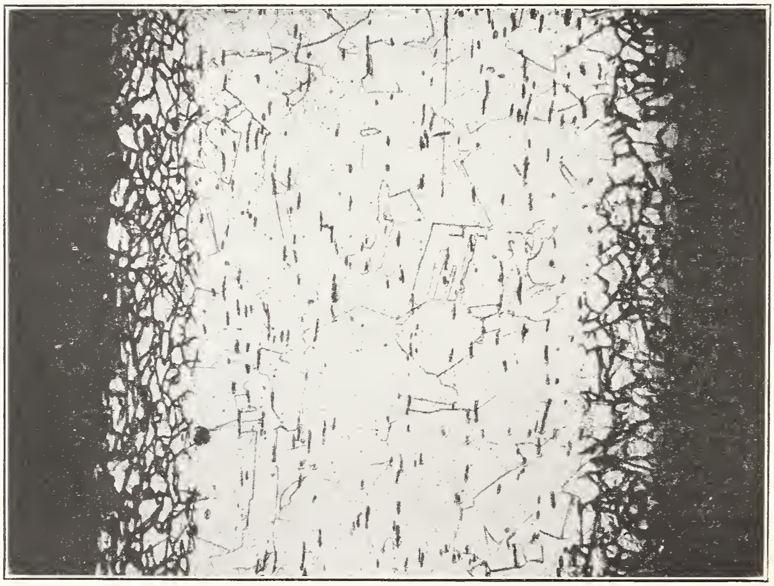

FIG. 4.—*Microstructure of cross section of heat-checked nickel sheet, showing intercrystalline oxidation of surface layers.* ×100

solution of nitric acid in which the metal is readily inclined to assume the passive state.

Rawdon and Lorentz (142) have recently found that etching in concentrated hydrochloric acid develops an excellent and well contrasted etch pattern in nickel, particularly of high purity, with a greater freedom from etching pits than is the case in etching with nitric acid, although a considerably longer time of etching is required. It would appear that one of the principal requirements for the satisfactory etching of nickel is a very slow, uniform action. A solution of ferric chloride acidified with hydrochloric acid produces in a much shorter time results somewhat similar to those obtained with concentrated hydrochloric acid, but oftentimes with an excessive pitting of the specimen. Electrolytic nickel was found to etch with very much more difficulty than the commercial cast metal.

Electrolytic etching is also recommended for nickel, an electrolyte of sulphuric acid and hydrogen peroxide being used:

	Per cent by volume.
Sulphuric acid	22
Hydrogen peroxide solution (3 per cent)	12
Water	66

Another electrolytic-etching method that has very recently been recommended to the bureau as a rapid and very satisfactory one calls for the use of a 5 per cent aqueous solution of a mixture of 75 parts concentrated nitric acid and 25 parts concentrated sulphuric acid (the mixture should be kept cold as the sulphuric acid is being added to the nitric acid). A current density of 0.01 ampere per square centimeter is used. An etching period of four to six seconds should suffice.

V. CHEMICAL PROPERTIES.

Nickel is not an active element chemically. It is not attacked at ordinary temperatures by air, by fresh or sea water, or combinations of the two. Organic acids, such as acetic, oxalic, tartaric, and citric acids attack it appreciably only after long periods of contact. Sulphuric and hydrochloric acids dissolve it slowly; in nitric acid, on the other hand, it is very readily dissolved. Alkalis either in the fused state or in aqueous solution are without effect upon it, and for this reason laboratory fusions with these substances are carried out in crucibles of this metal.

At temperatures around 500° C. nickel becomes slightly oxidized in the air and also decomposes water with the formation of hydrogen. The International Nickel Co. determined, in some exposure tests made at high temperatures for 15 days without any intermittent removal of the scale formed, that ordinary commercial nickel will oxidize in that time to a depth of about 0.001 inch at about 1,000° C. and to a corresponding lesser degree at lower temperatures. Monel metal resists oxidation up to 750° C. (1,382° F.) and is not recommended for temperatures above 800° C. (1,472° F.). Nickel is much superior at these high temperatures.

Hale and Foster (250) have measured the rate of solution of nickel sheet in various solutions at ordinary temperature, and their results expressed in loss of weight per 100 cm^2 are given in Table 8.

TABLE 8.—Corrosion Tests of Nickel.

Specimens immersed in—	Loss of weight, per 100 cm^2, in 7 days (solution renewed daily).	Loss of weight, per 100 cm^2, in 28 days (solution not renewed).
	mg	mg
HNO_3 (*N*/5)	4,200	2,100
HCl (*N*/5)	250	450
H_2SO_4 (*N*/5)	250	400
$MgCl_2$ (*N*/5)	50	100
NaOH (*N*/5)	0	0
$CaCl_2$ (*N*/5)	80	50
NaCl (*N*/5)	0	0
NH_4OH (*N*/5)	0	0
Na_2CO_3 (*N*/5)	0	0

The use of nickel for cooking utensils which is quite extensive in Germany and is growing in this country, although still in its infancy, has inspired numerous investigators to study the question of the solution of the nickel by the liquids used and its absorption by the food, as well as the physiological effect of the amounts thus absorbed (252–256, 262). The results of these investigations have usually been expressed in terms of milligrams of nickel found in 100 g of the food and varied from 0.01 mg to a maximum of 64 mg, the high results being obtained by the use of salt and vinegar, or food containing both. Vuk (253) found losses of from 0.15 to 0.65 mg of nickel per 100 cm^2 of exposed surface after boiling in 5 per cent acetic acid for two and one-half hours. These small amounts of nickel thus absorbed by food from nickel utensils have been regarded as being entirely harmless physiologically.

Sieverts (184) has determined the solubility of hydrogen in nickel and finds that it forms with nickel a homogeneous solid solution. The solubility of hydrogen both in solid and in molten nickel is proportional to the square root of the hydrogen pressure. He found that 100 g of nickel absorb—

0.16 mg of hydrogen at 760 mm pressure, 212° C.
.39 mg of hydrogen at 760 mm pressure, 520° C.
.98 mg of hydrogen at 760 mm pressure, 1,023° C.
1.50 mg of hydrogen at 760 mm pressure, 1,400° C.

and that this amount liberates 1.9 mg of hydrogen upon solidification at 1,452° C. in a hydrogen atmosphere of 760 mm pressure.

Römmler (187a) found that electrolytic nickel at room temperature and atmospheric pressure (740–760 mm Hg) absorbed from 4.3 to 13.6 times its volume of hydrogen. The hydrogen content increases as the acidity of the electrolyte (nickel chloride or sulphate) is decreased and is lowered by a rise in the temperature of the electrolyte.

VI. PHYSICAL PROPERTIES.

1. DENSITY.

The density and specific gravity of nickel varies greatly according to its chemical composition, physical condition, and the mechanical treatment which it has received. Metal which has been reduced by carbon, or carbon monoxide, to a powder or sponge contains numerous voids and may have a density as low as from 7.7 to 8.0, values which have been obtained for powder and rondelles or grain nickel.

Dense nickel, such as electrolytic or malleable nickel, will vary in density from 8.70 to 8.90, averaging about 8.84, which may be taken as quite closely representing most of the commercial material. This corresponds to 552 lbs./ft.^{3}, or 0.319 lb./in.^{3}

2. CHANGE OF STATE.

The melting point of nickel is given by the Bureau of Standards (308) as 1,452° C. (2,646° F.). The element undergoes a magnetic transformation, accompanied possibly by a phase change, at from 340 to 360° C. (see Table 7, Copaux, Pecheux). The transformation point in commercial nickel containing impurities is lower, usually in the region of 320° C. (608° F.) (see Table 7, Guertler and Tammann, Pecheux).

The boiling point of nickel has never been determined.

The heat of transformation is 1.33 cal./gram (at 320–330° C.) according to Wüst (315), and the heat of fusion, 56.1 cal./gram. Dr. W. P. White (313) has recently determined the latent heat of fusion of nickel at 1,450° C. as 73 cal./gram (see end of next section for the chemical composition of the nickel).

3. SPECIFIC HEAT.

Wüst has recently (315) determined the specific heat of nickel (Kahlbaum nickel-analysis not given) from 0 to 1,520° C. (results given in Table 9).

TABLE 9.—Specific Heat of Nickel.

Temperature.		Mean specific heat.	True specific heat.	Temperature.		Mean specific heat.	True specific heat.
		$\frac{q_t-q_0}{t}$	$\frac{dq}{dt}$			$\frac{q_t-q_0}{t}$	$\frac{dq}{dt}$
°C.	°F.	cal./gram/ °C.	cal./gram/ °C.	°C.	°F.	cal./gram/ °C.	cal./gram/ °C.
0	32	....	0.1095	800	1,472	0.1299	0.1295
100	212	0.1147	.1200	1,400	2,552	.1298	.1296
200	392	.1200	.1305	1,451	2,642	.1298	.1296
300	572	.1252	.1409	1,451	2,642	.1684	.1338
320	608	.1263	.1430	1,500	2,732	.1673	.1338
330	626	.1306	.1294	1,520	2,768	.1668	.1338

Jaeger and Dieselhorst (363) determined the true specific heat at 18 and at 100° C. of a sample of nickel containing:

	Per cent.		Per cent.
Co	1.36	Si	0.06
Cu	.15	Mn	1.04
Fe	.44		

They found the following values:

$$\sigma_{18°C}=0.1065 \text{ cal./gram/ °C., and } \sigma_{100°C}=0.1160 \text{ cal./gram/ °C.}$$

Schimpff (317) finds the following values of the mean specific heat of nickel containing 1.5 per cent Co, 0.6 per cent Fe, and 97.9 per cent Ni:

$$\sigma_m \text{ (17 to 100° C.)}=0.1084 \text{ cal./gram/ °C.}$$
$$\sigma_m \text{ (17 to 79° C.)}= .0973 \text{ cal./gram/ °C.}$$
$$\sigma_m \text{ (17 to 190° C.)}= .0830 \text{ cal./gram/ °C.}$$

White (313) obtained the value 0.134 cal./gram/ °C. as the mean specific heat, between 20° C. and its melting point, of nickel containing 99.1 per cent Ni, 0.35 per cent Fe, 0.16 per cent Cu, 0.25 per cent Si, 0.1 per cent C, and 0.03 per cent S.

4. THERMAL EXPANSIVITY.

Guillaume (332) gives the equation for the thermal expansivity between 0 and 40° C. (32 and 104° F.) of five bars of commercial nickel:

$$\frac{\Delta l}{l_0 t} = (a + bt)\ 10^{-6}$$

in which coefficients a and b had the following values:

	a	*b*		*a*	*b*
1	12.66	0.0055	4	12.49	0.0079
2	12.52	.0066	5	12.55	.0054
3	12.49	.0070			

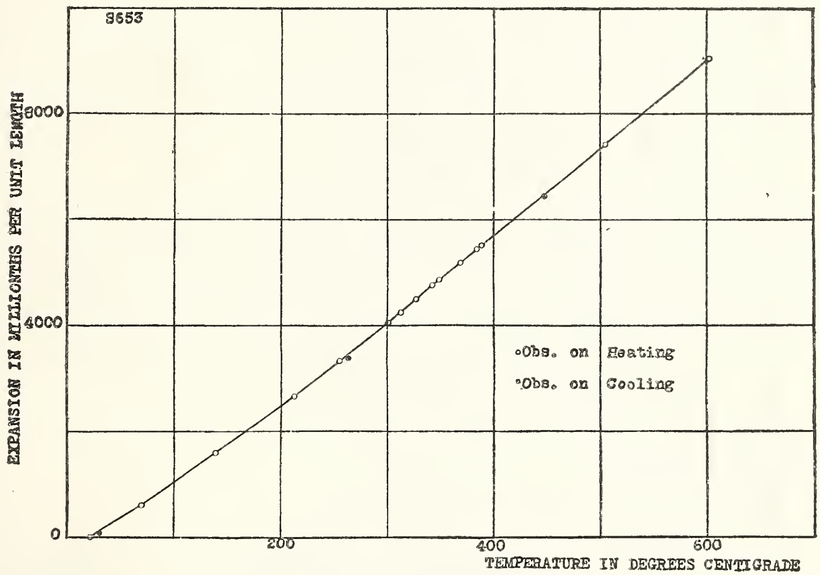

FIG. 5.—*Thermal expansion of commercial nickel* (*Souder and Hidnert*).

The observations from which this "typical expansion curve" was plotted, were made on sample S653, referred to in Table 10.

Souder and Hidnert (323) have recently made a very comprehensive series of determinations of the thermal expansivity of commercially pure nickel over the temperature range—room temperature to about 600° C. Table 10 and Figure 5 are taken from their data, the curve shown in the latter being represented as a typical expansion curve. They found that the nickel samples generally suffered a slight permanent diminution of length after the thermal expansion tests, amounting, in general, to about 0.005 per cent.

TABLE 10.—Average Coefficients of Expansion of Commercial Nickel. (Souder and Hidnert, 323.)

Lab. No.	Material.	Composition in per cent.							Average coefficients of expansion × 10⁶.								
		Ni	Cu	Fe	Mn	C	Si	S	25 to 100° C.	100 to 200° C.	200 to 300° C.	300 to 400° C.	400 to 500° C.	500 to 600° C.	25 to 300° C.	300 to 600° C.	25 to 600° C.
S635	Hot-rolled, 3/8 inch round	99.06	0.12	0.37	0.19	0.12	0.12	0.027	13.2	14.4	15.3	16.8	15.5	16.9	14.4	16.4	15.4
S636	Same; annealed at 870° C. (1,600° F.) for 1 hour								13.3	14.5	15.4	16.4	16.6	16.3	14.5	16.5	15.5
S652	Hot-rolled, 3/8 inch round, low carbon	99.02	.12	.37	.22	.08	.16	.020	12.9	14.5	15.4	16.9	16.5	16.8	14.4	16.7	15.6
S653	Same; annealed at 900° C. (1,650° F.) for 1 hour								13.3	14.5	15.5	16.7	16.3	16.9	14.5	16.6	15.6
S654	Hot-rolled, 3/8 inch round, high carbon	98.76	.17	.38	.18	.22	.26	.020	13.0	14.2	15.7	15.9	15.7	14.4	14.4	15.3	14.9
S655	Same; annealed at 900° C. (1,650° F.) for 1 hour								13.3	14.2	15.6	16.3	16.2	16.3	14.5	16.3	15.4
S637	Hot-rolled, 1/4 inch round	97.05	.15	.44	2.08	.09	.15	.029	13.1	13.5	14.8	17.2	16.6	17.1	13.8	17.0	15.5
S638	Same; annealed at 870° C. (1,600° F.) for 1 hour								13.5	14.3	15.8	16.0	16.6	17.3	14.6	16.6	15.7
S639	Hot-rolled, 1/4 inch round	94.21	.14	.46	4.92	.12	.10	.030	13.2	14.1	15.4	15.9	16.7	17.3	14.3	16.7	15.5
S640	Same; annealed at 870° C. (1,600° F.) for 1 hour								13.3	14.1	15.4	15.9	16.6	17.6	14.3	16.7	15.6

5. THERMAL CONDUCTIVITY.

Determinations of the thermal conductivity of nickel have been made by Lees (338), Jaeger and Deiselhorst (363), and Ingersoll (722). Their results are as follows:

Lees—Electrolytic nickel: analysis not given	$\lambda_{0°}$ C.=0.140 cal./gram/second/° C. $\lambda_{18°}$ C.= .140 cal./gram/second/° C.
Jaeger and Dieselhorst—1.36 Co, 0.44 Fe, 1.04 Mn, 0.15 Cu, 0.06 Si	$\lambda_{18°}$ C.= .142 cal./gram/second/° C. $\lambda_{100°}$ C.= .138 cal./gram/second/° C.
Ingersoll—Electrolytic nickel: less than 0.10 C, about 0.5 Co, about 0.15 Fe, about 0.10 Cu.	$\lambda_{20-100°}$ C.=0.1428 cal./gram/second/° C.

Figure 6 gives results by Lees and by Angell (337) of determinations made on the thermal conductivity of nickel.

Bridgman (336) determined the effect of pressure upon the thermal conductivity of very pure nickel at 30° C. and at pressures up to 12,000 kg/cm.[2] He found that the conductivity decreases with the pressure and obtained the value −0.000012 for the pressure coefficient of thermal conductivity.

6. ELECTRICAL RESISTIVITY.

A number of precise determinations of the electrical resistivity of nickel have been made, but the nickel used was in many cases quite impure, and the values of the resistivity so obtained are much higher than the value for pure nickel. The following table gives several of the values which have been observed:

TABLE 11.—Electrical Resistivity of Nickel.

Reference.	Material.	Electrical resistivity at 0° C.	Temperature coefficient 0 to 100° C.
		microhm-cm	
Fleming (351)	Electrolytic, no analysis given	6.926	0.0061
Copaux (464)	Pure, reduced from oxalate, no analysis	6.4	.0066
Campbell (350)	Purchased in Germany in 1901	8	....
Pecheux (347)	0.20 Cu, 0.15 Co, no C or Si, trace Fe, 0.35 total impurities.	9	.0058
Ruer and Kaneko (645)	Kahlbaum, 0.035 C	7.7	....
Jaeger and Dieselhorst (363)	1.36 Co, 0.44 Fe, 1.04 Mn, 0.15 Cu, 0.06 Si	[1] 11.76	.0044

[1] At 18° C.

The most probable value for the resistivity of pure nickel from the above determinations is the lowest, that of Copaux; with this lowest value is associated also the highest temperature coefficient. The other values are higher, due to the presence of impurities which depress also the value of the temperature coefficient. The most probable value of the latter between 0 and 100° C. is that given by Copaux; that is, 0.0066.

Figure 7 gives the results of several determinations of the electrical resistivity at various temperatures and Figure 8 the results of one series of determinations of the influence of temperature on the temperature coefficient of resistivity, by Somerville (348). At the transformation point the resistivity-temperature curve changes its slope, and there is a marked change in the value of the temperature coefficient.

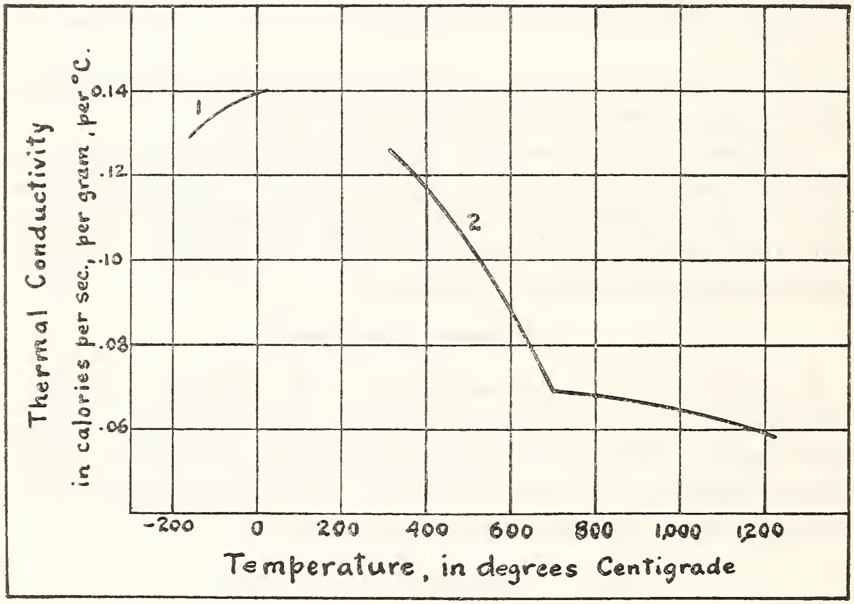

Fig. 6.—*Variation of thermal conductivity of nickel with temperature.*

Curve 1, from determinations of Lees (338) on 99 per cent nickel bar.
Curve 2, from determinations of Angell (337) on nickel rod from Boker, no analysis given.

Results of determinations of the electrical resistivity made at various temperatures by Hunter, Sebast, and Jones (339) on electrolytic nickel, commercial malleable nickel (grades A, C, and D; see p. 15), and Monel metal are given in Figure 9. In Table 52 will be found some resistivity values for pure and commercial grades of nickel as produced by different manufacturers for electrical resistance purposes. Grades of malleable nickel with high manganese content have higher and lower values of resistivity and temperature coefficient, respectively, thus: Grade D nickel (4.5 per cent of manganese) has a resistivity of 20 microhm-cm with a temperature coefficient of 0.0020.

Bridgman (338a, 339a) in an investigation made on the effect of tension and of pressure on the electrical resistivity of very pure nickel at several temperatures between 0 and 100° C. and at 0 to 12,000 kg/cm^2 pressure verified Tomlinson's observation made many years before on much less pure nickel that the resist-

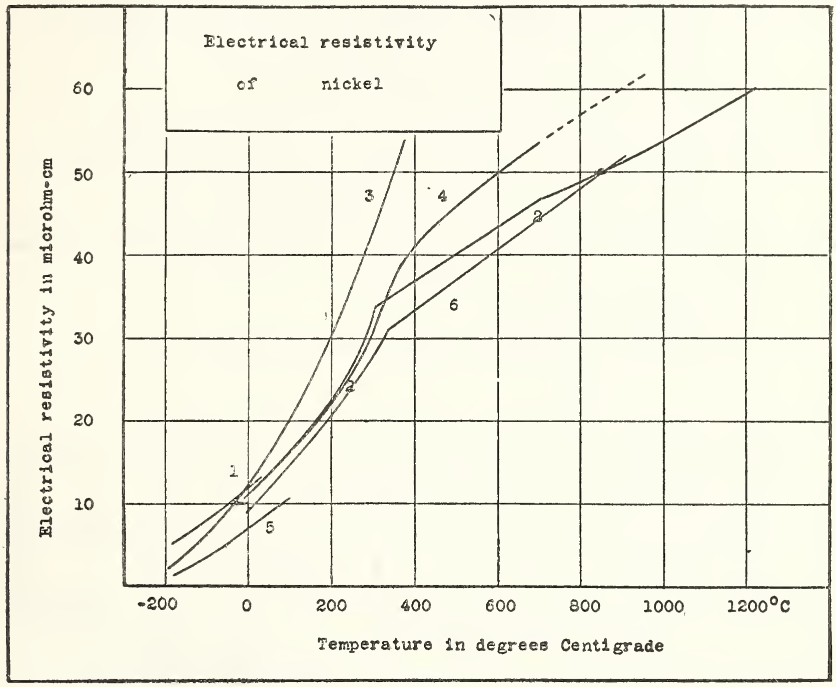

FIG. 7.—*The electrical resistivity of nickel at various temperatures.*

Curve *1*, from determinations of Lees (338) on 99 per cent nickel bar.
Curve *2*, from determinations of Angell (337) on nickel rod from Boker, no analysis given.
Curve *3*, from determinations of Niccolai (349) on Kahlbaum nickel, analysis not given.
Curve *4*, from determinations of Harrison (362) on nickel wire, not otherwise described.
Curve *5*, from determinations of Fleming (351) on electrolytic nickel, annealed in hydrogen and drawn into wire, no analysis given.
Curve *6*, from determinations of Pecheux (347) on nickel of the following composition:

Cu	0.20 per cent
Fe	Trace
Co	0.15 per cent
C+Si	None

Total impurities=0.35.

ance decreases as tension is increased, though not linearly. He made the additional observation that if the nickel wire was subjected to a "seasoning" by a repeated application and removal of a fixed load and then to a cycle of resistance measurements, the plotted resistance measurements took the form of an open

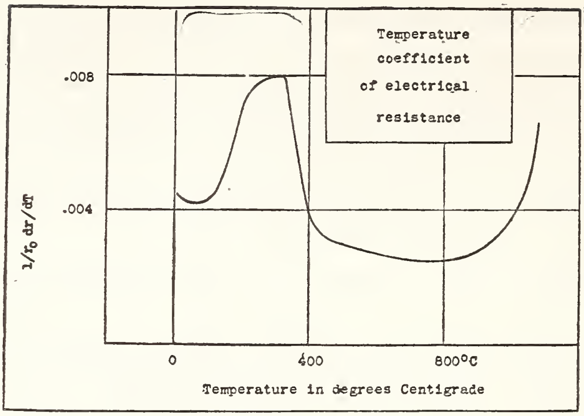

FIG. 8.—*The temperature coefficient of electrical resistance of nickel according to Somer ville (348).*

The coefficient measured is:

$\frac{1}{r_0}\frac{dr}{dt}$, when r_0=the resistivity at $0°$ C.

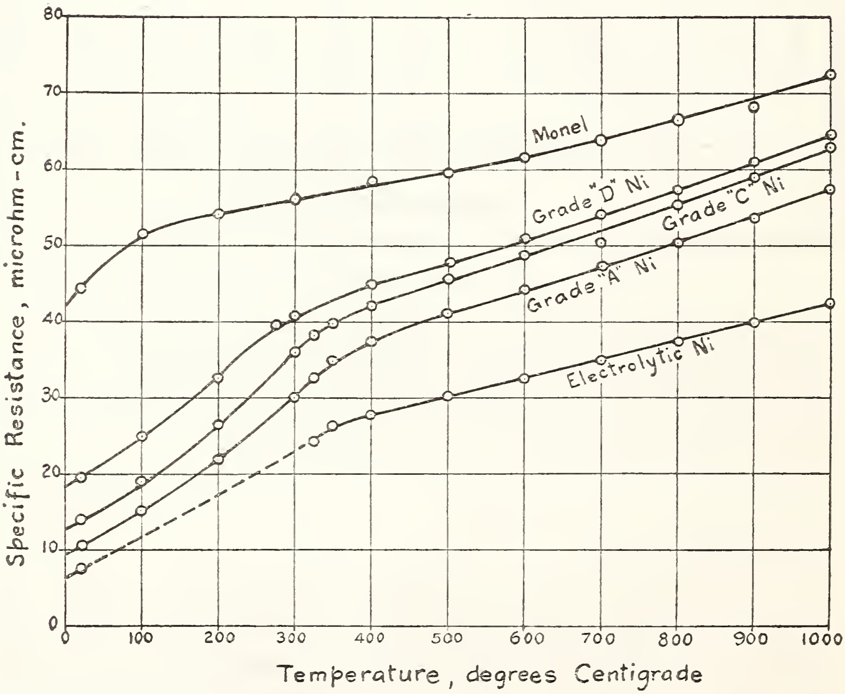

FIG. 9.—*Electrical resistivity of commercial nickel and Monel metal at elevated temperatures.*

Plotted from the results of Hunter, Sebast, and Jones (339).

hysteresis loop and did not follow with decreasing tension those made with increasing tension. The pressure coefficient was found to increase with temperature, though not linearly.

7. THERMOELECTROMOTIVE FORCE.

Figure 10 gives the results of determinations of the thermoelectromotive force of nickel to platinum, lead, copper, and silver.

8. MAGNETIC PROPERTIES.

Nickel is ferromagnetic at ordinary temperatures and up to the temperature of its magnetic transformation, at 340 to 360° C.

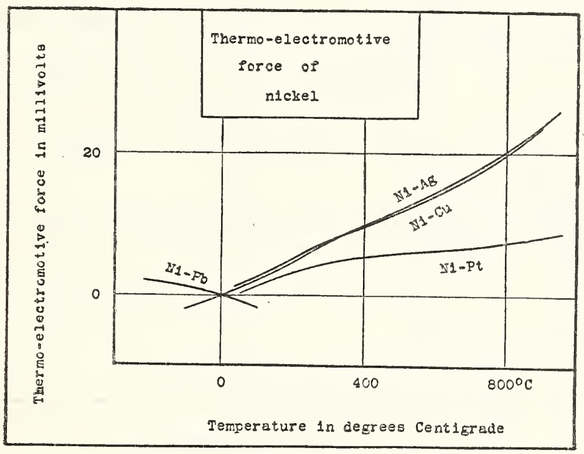

FIG. 10.—*The thermoelectromotive force of nickel to platinum, copper, and silver.*

Ni-Ag, according to determinations of Hevesy and Wolff (402) on nickel wire, no analysis given, furnished by the Vereinigte deutsche Nickel Werke.

Ni-Pt, calculated from the preceding results on the Ni-Ag couple, together with those of Holborn and Day on the Ag-Pt couple.

Ni-Cu, according to determinations of Pecheux (360) on nickel wire of the following compositions: Cu, 0.20; Co, 0.15; Fe, trace; C+Si, none; total impurities, 0.35.

Ni-Pb, according to determinations of Dewar and Fleming (364) on Mond nickel.

The electromotive force developed is such that the current flows at the 0° C. junction from the Ag, the Cu, or the Pt to the Ni, when the EMF is+.

Above this temperature it is paramagnetic and follows Curie's law (373). Figure 11 gives the results of some magnetic tests of nickel; the values for magnetic induction and magnetizing force or "strength of field" are expressed in gausses.

The susceptibility of nickel in any direction is markedly diminished by the application of a tensile stress and augmented by that of compressive stress in that direction (385, 388).

The permeability of nickel increases with temperature up to 300 to 340° C. (Ewing, 391, 393).

9. ELECTROLYTIC SOLUTION POTENTIAL; PASSIVITY.

The true reversible potential of nickel in a normal aqueous nickel-sulphate solution is given by Schoch (404) as −0.48 volt, measured against the normal calomel electrode. Schoch attributes the higher values obtained by other investigators to occluded hydrogen.

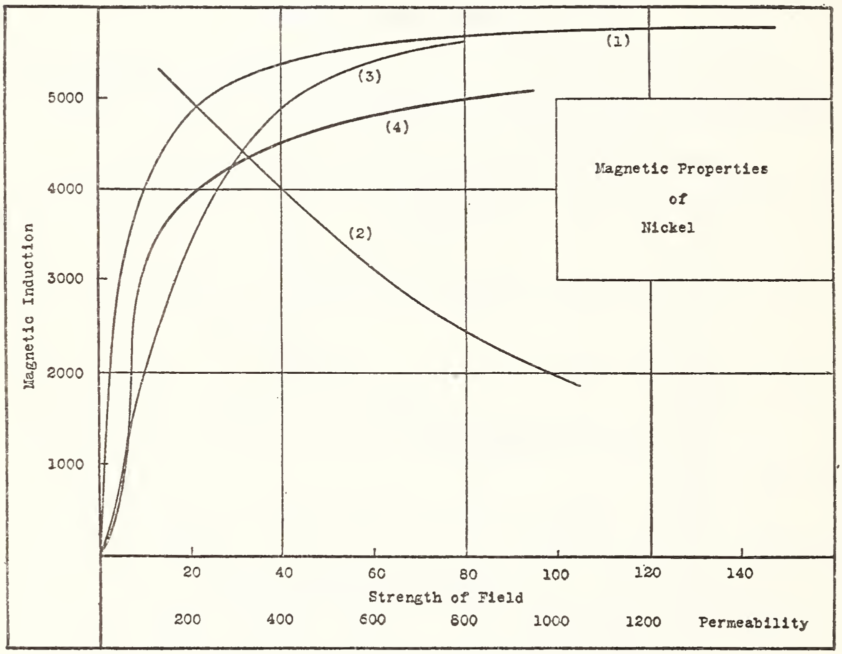

FIG. 11.—*The magnetic properties of nickel.*

Curve *1*, induction curve for malleable nickel (International Nickel Co.) containing: Ni, 98.82 per cent; Fe, 0.46 per cent; C, 0.11 per cent; S, 0.22 per cent; Cu, 0.18 per cent; Mn, 0.27 per cent; Si, 0.13 per cent (Burrows method).

Curve *2*, permeability curve for same material.

Curve *3*, induction curve of nickel, composition unknown. Perkins (395).

Curve *4*, induction curve of nickel, composition unknown. Ewing (393).

Schweitzer (406) gives the value −0.612 volt for the potential of nickel powder in contact with N $NiSO_4$ and −0.596 volt for nickel powder in contact with N $NiCl_2$. Both were measured against the normal calomel electrode.

Measurement has been made by N. Isgarischew (401) of the potential of nickel against a solution of $NiCl_2$ in methyl alcohol. The combination was:

$$Ni/.0277 N NiCl_2/.02698 N KCl/Hg_2Cl_2/Hg.$$

At a temperature of 25° C. the potential difference was 0.247 volt.

Nickel becomes passive (410); that is, it behaves like a noble metal to a greater degree than do other metals of high solution potential. This state may be established by simple immersion in strong oxiding agents like nitric acid or bichromate solutions. The condition of passivity may often be destroyed by slight changes in the chemical environment or by scratching or mechanical shock. Pure nickel as an anode is readily rendered passive in electrolytes containing salts of oxygen acids, especially at high current densities. The presence of impurities in the anodes as well as of chlorides or fluorides in the electrolyte tends to prevent passivity. Coincident with the establishment of passivity there is pronounced drop in the solution potential.

TABLE 12.—Optical Reflectivity of Nickel and Monel Metal.

Wave length of light in microns (μ=0.001 mm).	Hagen and Rubens (443) electrolytically deposited nickel.	Bureau of Standards test report 1920; commercial rolled nickel.	Coblentz (924) commercial rolled Monel metal.
	Per cent.	Per cent.	Per cent.
0.45	59.4	....	56.5
.50	60.8	61.5	57.8
.55	62.6	63.2	59.0
.60	64.9	64.0	60.2
.65	66.6	65.1	61.8
.70	68.8	67.1	63.7
.75	....	68.5	65.6
.80 [1]	69.6	....	67.2
.90	....	....	70.0
.95	....	....	71.1
1.00	72.0	....	72.3
1.05	....	....	73.0
1.10	....	....	73.6
1.20	....	....	74.8
1.40	....	....	77.0
1.50	78.6	....	78.2
1.75	....	....	81.2
2.00	83.5	....	83.8
2.50	....	....	87.0
3.00	88.7	....	83.7
3.50	....	....	89.5
4.00	91.1	....	91.0

[1] Infra-red, where wave length=0.80 μ and over.

10. OPTICAL PROPERTIES.

One of the most important properties of nickel is its ability to take and retain a high polish and to reflect a large percentage of light incident on such a polished surface. This is, for example, one of the properties which make the metal valuable for electroplating. In Table 12 are given the best values of the reflectivity of both nickel and Monel metal.

Meyer (442) gives the following values for the optical constants of nickel:

Reflectivity	$=65.5$ per cent for $\lambda=0.589\ \mu$
Absorption index (K)	$=3.42$ per cent for $\lambda=.589\ \mu$
Refractive index (n)	$=1.58$ per cent for $\lambda=.589\ \mu$

11. COMPRESSIBILITY.

Bridgman (444) in a recent study made on the linear compressibility of annealed samples of commercially pure nickel rod and very pure nickel wire at 30 and 75° C. over a pressure range of 12,000 kg/cm^2, which ranges were considered sufficient to give temperature and pressure coefficients of compressibility, found that the compressibility of nickel decreases with increasing pressure and increases with rising temperature.

The change in volume produced by compression was calculated by means of the following formula:

$$\frac{\Delta V}{V_0} = -(a+bp)p$$

where

V = volume at the pressure in question,
V_0 = volume at atmospheric pressure,
p = pressure applied, in kg/cm^2,
a = value of initial compressibility.

$$b = \frac{\text{value of initial proportional change of compressibility} \times \text{value of initial compressibility } (a)}{2}$$

12. ELASTICITY.

According to determinations of Harrison (431), Grüneisen (434), Schaefer (424), Searle (426), and Guillaume (332), the value of Young's modulus for nickel varies from 21,000 to 23,000 kg/mm^2 (30,000,000 to 33,000,000 lb./in.^{2}).

Koch and Dannecker (418) and Harrison (431) have determined the values of the modulus of torsional elasticity and of Young's modulus, respectively, at higher temperatures. Their values are given in Table 13.

TABLE 13.—Modulus of Elasticity of Nickel.

Temperature. °C.	Temperature. °F.	Modulus of elasticity in torsion.	Young's modulus.	Temperature. °C.	Temperature. °F.	Modulus of elasticity in torsion.	Young's modulus.
		kg/mm²	kg/mm²			kg/mm²	kg/mm²
20	68		22,000	400	752	7,120	
27.5	81.5	7,300		401	754		15,700
96	205		21,300	465	869		11,900
110	230	6,430		600	1,112	6,080	
200	392	6,860		800	1,472	4,940	
222	431.6		20,300	1,000	1,832	3,730	
300	572	7,390		1,200	2,192	2,900	
329	623		17,800	1,300	2,372	2,480	

Poisson's ratio for nickel is 0.33 according to Benton (425).

13. HARDNESS.

In the annealed condition the scleroscope hardness of nickel of low carbon (0.10 per cent) and manganese (0.30 per cent) content will vary from 12 to 15 (universal hammer). The Brinell hardness (500 kg) of the same material varies from 80 to 100; the hardness (3,000 kg) from 100 to 120. The effect of carbon and manganese on the hardness of annealed metal is discussed below. When hardened by cold working, the scleroscope hardness may be raised to 30 to 40, the Brinell hardness (500 kg) to 130 to 160.

14. TENSILE PROPERTIES.

Table 14 gives the values usually obtained for the tensile properties of nickel of low carbon and manganese content in various conditions. (These values refer to malleable nickel A of the International Nickel Co.; for compositions see Table 1, p. 10.)

TABLE 14.—Tensile Properties of Nickel.

Kind of nickel.	Tensile strength.	Yield point.	Elongation in 2 inches.	Reduction in area.
	Lbs./in.²	Lbs./in.²	Per cent.	Per cent.
Hot-rolled rods	70,000- 80,000	20,000- 30,000	40-50	50-70
Sheet: Hard-rolled	90,000-110,000	85,000-105,000	1-2	20-40
Sheet: Annealed	60,000- 75,000	15,000- 25,000	35-45	40-60
Wire: Hard-drawn	90,000-110,000	85,000-105,000		
Wire: Annealed	65,000- 75,000	20,000- 30,000		
Cast nickel (deoxidized)	50,000- 60,000	20,000- 30,000	20-30	

The American Nickel Corporation furnishes the following values obtained for its product, containing at least 99.0 per cent nickel.

Condition.	Tensile strength.	Elastic limit.	Yield point.	Elongation in 2 inches.	Reduction in area.
	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Per cent.	Per cent.
Hot-rolled	85,000	55,000	65,000-70,000	50	70
Cold-rolled	100,000—150,000	80,000	100,000-125,000	10-35	20-65

Sykes (416) has carried out some very valuable tensile tests of relatively pure nickel wire at low and high temperatures from which the following values are chosen as representative. This wire was drawn from 0.095 to 0.025 inch diameter and annealed at 800° C.; it contained 99.8 per cent nickel (including probably 0.5 per cent cobalt) and 0.15 per cent iron. Two rates of loading were used in the tests and are indicated in the table as "slow" and "rapid," the upper jaw being lifted 0.125 inch per minute for the former and 1 inch per minute for the latter.

TABLE 15.—Tensile Properties of Nickel Wire at Various Temperatures (Sykes).

Temperature.		Tensile strength.		Elongation in 2 inches.		Reduction of area.	
°C.	°F.	Slow.	Rapid.	Slow.	Rapid.	Slow.	Rapid.
		Lbs./in.^{2}	Lbs./in.^{2}	Per cent.	Per cent.	Per cent.	Per cent.
−185	−301	....	84,000	....	22.0	....	58
25	77	60,000	62,000	22.0	23.5	75	75
100	212	56,000	57,000	20.3	20.3	73	71
200	392	50,000	51,000	15.5	18.7	68	75
300	572	50,000	51,000	17.5	14.0	75	79
400	752	43,000	47,000	17.3	19.5	75	80
500	932	34,000	36,000	19.5	20.0	75	75
600	1,112	25,000	29,000	15.5	19.5	65	60
700	1,292	17,000	21,000	15.5	14.0	60	60
800	1,472	13,000	17,000	15.5	15.5	45	48
900	1,652	9,000	11,000	15.5	20.0	39	48
1,000	1,832	7,000	9,000	26.5	19.0	48	43

The International Nickel Co. has communicated the following results of their tensile tests at higher temperatures of nickel and Monel metal (their regular grade of rod nickel A and of hot-rolled rod Monel B).

TABLE 16.—Tensile Properties at Various Temperatures of Rolled Nickel and Monel Metal and of 20 Per Cent Cupronickel (International Nickel Co.).

Temperature.		Tensile strength.			Yield point.		Elongation in 2 inches.			Reduction in area.	
°C.	°F.	Rolled nickel.	Rolled Monel.	Cupro-nickel.	Rolled nickel.	Rolled Monel.	Rolled nickel.	Rolled Monel.	Cupro-nickel.	Rolled nickel.	Rolled Monel.
		Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
21	70	81,000	90,000	63,000	24,000	45,000	51	46	28	70	69
93	200	82,000	86,000	61,000	24,000	38,000	51	45	27	68	68
204	400	84,000	84,000	58,000	24,000	34,000	52	44	26	68	66
316	600	83,000	82,000	51,000	23,000	32,000	51	42	24	68	64
427	800	83,000	78,000	41,000	21,000	30,000	50	38	22	66	62
538	1,000	58,000	60,000	30,000	19,000	28,000	50	29	17	75	31
649	1,200	45,000	45,000	18,000	17,000	24,000	48	13	14	76	15
760	1,400	30,000	22,000	6,000	13,000	15,000	50	8	23	78	10
871	1,600	17,000	15,000	5,000	....	....	33	14	27	32	15
982	1,800	11,000	8,000	....	....	....	36	18	....	40	25
1,093	2,000	8,000	5,000	....	....	....	70	22	....	99	29

VII. EFFECT OF IMPURITIES ON THE PROPERTIES OF NICKEL.

With reference to the effect which they exert upon the physical properties of nickel the ordinary impurities fall naturally into two classes; that is, those which are soluble in the solid state in nickel and those which are not. Those of the former class act, in general, only to increase the hardness and strength of the metal and, of course, to diminish its electrical conductivity. Those of the latter class affect chiefly the hot but also the cold working properties of the metal.

1. CARBON.

Carbon is hardly to be looked upon as an impurity in nickel any more than it is to be so regarded in steel. It is an element which is never absent in the metal, and its presence is necessary, in the present state of the art, for the production of malleable nickel on a commercial scale. The American Nickel Corporation has, however, informed the bureau that it has been successful in making nickel containing only 0.005 per cent carbon and which can be satisfactorily rolled. This nickel was made for the United States Navy in connection with its experiments on materials used for gun liners.

The nickel-carbon equilibrium diagram has received some attention at the hands of investigators, but there are still many gaps in our knowledge of the constitution of this binary system. Ruff and Borman (624) determined that with increasing carbon content the melting point of pure nickel is progressively lowered from 1,452 to 1,311° C., at which temperature nickel forms a eutectic with 2.2 per cent carbon in the form of graphite. The liquidus temperature then rises again with increasing carbon content, and at 2,100° C. the metal absorbs 6.42 per cent carbon, the melt apparently being in the form of a carbide, Ni_3C, which is, however, rapidly decomposed at lower temperatures with the formation of graphite. The equilibrium below the eutectic temperature has never been satisfactorily worked out. Ruff and Borman state from the results of their investigations that the solubility of graphite in nickel in the solid state is not greater than 0.5 per cent at the eutectic temperature (1,311° C.), but they give no information regarding the solubility at lower temperatures. This solubility undoubtedly diminishes with lowering temperature. Tests made at this bureau showed that the carbon remaining in solid solution at room temperature in samples obtained in the sand-cast and chill-cast condition from nickel having a total carbon content of about 2 per cent and subjected to various heat treatments amounted to less than 0.1 per cent after annealing. Despite the lack of exact knowledge regarding the equilibrium at lower temperatures, it is known that the presence of carbon introduces no transformation such as that which occurs in steel and with which might be associated the possibility of altering profoundly the physical properties of the alloys by means of suitable heat treatment.

Within the limits in which carbon is usually found in nickel it occurs in solid solution and merely increases the hardness and strength of the metal. It increases the ease of hot-working operations by making the metal tougher at these temperatures and less susceptible to edge cracking. On the other hand, it increases the difficulties of cold working both because with increased carbon the metal is initially harder and also because it hardens more rapidly with progressive cold work. The effect of carbon in increasing the hardness of nickel is illustrated in Table 17.

TABLE 17.—Effect of Carbon on the Hardness and Tensile Strength of Nickel.

Chemical composition.					Tensile properties.				Hardness.		Remarks.
C	Mn	Si	S	Fe	Yield point.	Tensile strength.	Elongation in 2 inches.	Reduction of area.	Brinell 3,000 kg.	Scleroscope.	
Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Lbs./in.^{2}	Lbs./in.^{2}	Per ct.	Per ct.			
0.08	....	0.04	0.026	0.63	22,000	69,000	46	50	103	10	Hot-rolled.
.26	0.48	.13	.016	.56	34,000	93,000	40	35	132	17	Do.
.06	.21	.33	....	.59	....	....	....	....	97	10	Annealed.
.19	.26	.33	....	.68	....	....	....	....	131	15	Do.

When the percentage of carbon exceeds 0.4 per cent, the separation of graphite may take place, a change accompanied by a loss of malleability. Free graphite should not be present in good-quality malleable nickel. The statement that carbon is harmful to malleable nickel and that its presence should be avoided is correct only when the carbon is in the form of graphite.

2. MANGANESE.

Manganese is generally absent from nonmalleable nickel but is added intentionally to malleable metal both because of its effect on its ultimate properties and because of its usefulness in decreasing manufacturing difficulties. It renders the metal less tender just after freezing, and thus aids in the production of ingots free from "pulls" and hot cracks. It also increases the fluidity of the molten nickel, and thus renders easier the production of ingots with good surface.

The advantages of its presence as far as ease of manufacturing is concerned are obtained with small additions. Added in larger amounts it increases the resistance of nickel to oxidation and renders it less susceptible to the action of sulphur in the fuels used in hot rolling. The C and D grades of nickel containing from 1.50 to 6 per cent manganese are for these reasons largely used for the spark points of motor ignition systems.

The equilibrium of the system manganese-nickel has been studied by Zemczuzny, Urasow, and Rykowskoff (763), who find that the two metals are soluble in all proportions both in the solid and in the liquid state. This agrees with our rather meager knowledge of the properties of high manganese-nickel alloys. These may be rolled readily with a manganese content up to 10 per cent and probably beyond, although the 50 per cent alloy is known to be quite brittle. Within these limits the addition of manganese mildly increases the hardness and strength of nickel without materially decreasing the ductility. The addition of manganese, however, does decrease the electrical conductivity of nickel markedly (1266); thus the resistivity of nickel, drawn and annealed, was increased from 12.43 microhm-cm to 28.0 and 51.2 microhm-cm with the addition of 10 and of 20 per cent, respectively, of manganese. Table 18 shows the effect of manganese on the tensile properties and resistivity of hot-rolled nickel rod.

TABLE 18.—Effect of Manganese on the Tensile Properties and Electrical Resistivity of Hot-Rolled Nickel Rod.

No.	Chemical composition.					Tensile properties.					Electrical resistivity.
	C	Mn	Fe	Si	S	Proportional limit.	Yield point.	Tensile strength.	Elongation in 2 inches.	Reduction of area.	
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent.	Per cent.	Microhm-cm
1	0.06	3.00	0.62	0.22	0.018	20,000	23,500	74,100	51	60	14.5
2	.06	3.58	.62	.23	.018	22,500	23,700	74,400	50	62	....
3	.06	4.40	.73	.27	.021	25,000	27,500	75,500	43	63	17.9
4	.06	5.06	.72	.28	.020	22,500	26,800	77,500	48	62	19.2
5	.07	6.78	.89	.34	.020	31,000	30,500	82,000	50	66	23.6
6	.08	6.84	.91	.35	.020	31,500	31,200	81,300	36	50	24.6
7	.10	9.18	.95	.42	.021	32,000	32,900	84,100	48	62	29.3
8	.10	9.24	.94	.41	.020	31,000	32,800	83,800	48	64	29.7

3. NICKEL OXIDE (NiO).

This compound is not usually present in malleable nickel, but does occur in shot and in blocks. Its presence was believed to be responsible for the complete lack of malleability in these forms of the metal, although some recent work carried out at this bureau has, on the contrary, shown that nickel may contain nickel oxide in amounts up to the eutectic composition and still be malleable either hot or cold.

No published results of a systematic study of the equilibrium of nickel and nickel oxide appear in the literature. The only work on this subject reported so far is that of Ruer and Kaneko (645), who state that the presence of NiO in molten nickel depresses the melting point by about 10° C. and give a micrograph showing the eutectic structure of it in nickel. Figure 1 shows the appearance of this nickel oxide—nickel eutectic in nickel blocks. Recent work at this bureau indicates that the eutectic composition is about 1.1 per cent NiO, and that the melting point of the eutectic is 1,438° C. (14° below the melting point of pure nickel). The melting point of nickel oxide was found to be 1,660° C.

4. SULPHUR.

Recent work conducted at this bureau has shown that sulphur may occur in nickel in three different forms. (*a*) Sulphur in nickel not treated with manganese or magnesium occurs as nickel sulphide, Ni_3S_2. Bornemann (790, 791) investigated the equilibrium of the nickel-sulphur system and reported that a compound, Ni_3S_2, is formed which is soluble in molten nickel and forms with it a eutectic containing 21.5 per cent sulphur at 644° C. upon solidifying. He also stated that the solubility of Ni_3S_2 in nickel in the solid state at the eutectic temperature is about 0.5 per cent and rapidly approaches zero at lower temperatures. The results obtained at this bureau, however, show that the nickel sulphide is apparently insoluble in molten nickel and that only a small percentage of nickel sulphide forms a eutectic with nickel at about 625° C. It was also found that nickel sulphide possesses a well-defined transformation point at 526° C. on heating and at about 500° C. on cooling. Microscopic examination shows the nickel sulphide as in the form of films distributed along the crystal boundaries, and also as particles in the body of the grain (see fig. 12 *a*). (*b*) If manganese is present, the sulphur occurs as a manganese sulphide, MnS, which forms a eutectic with nickel at about 3 per cent sulphur. The melting point of this eutectic is 1,325° C. Figure 12 *b* shows isolated particles of manganese sulphide distributed along the grain boundaries in a sample of commercially pure nickel containing about 0.5 per cent manganese and 0.025 per cent sulphur. Several of these particles are surrounded by dark-colored rings produced by the etching. (*c*) Nickel which has been treated with magnesium contains a magnesium sulphide, MgS, which is practically insoluble in nickel, and is shown in Figure 12 *c* as darkened round particles distributed in the body of the grain. As magnesium is generally added in the production of malleable nickel, it is in this form that sulphur usually occurs. It is believed that nickel properly treated with magnesium may contain as much as 0.05 per cent sulphur without seriously affecting its ductility, although the presence of 0.01 per cent of sulphur as either sulphide of nickel or of manganese makes the metal hot-short.

5. IRON.

This element is always present in commercial nickel, due both to imperfect removal of the iron originally present in the ores and to the wear and solution of tools used in the roasting and refining furnaces. The amount present is usually less than 1 per cent and has no appreciable effect upon the properties of the metal. The system nickel-iron has been investigated by Guertler and Tammann (749), Ruer and Schüz (741, 748), and others who find that the metals form an uninterrupted series of solid solutions, with certain interesting anomalies described below. (Sec. X, 4, p. 79.)

6. COBALT.

This element in amounts up to 1 per cent and averaging about 0.5 per cent in American nickel is invariably found in nickel and is usually included in the figure given for the nickel content. It is soluble in the nickel in all proportions, both in the liquid and in the solid state, and in these amounts does not exert any appreciable effect upon the properties of nickel except possibly the electrical resistivity.

7. SILICON.

According to Guertler and Tammann (787) this element forms a compound, Ni_3Si, with nickel which is soluble in molten nickel but upon solidifying forms with it a eutectic containing 10.6 per cent silicon at 1,153° C. The solubility of this compound in the solid state in nickel is equivalent to 6 per cent of silicon at the eutectic temperature, decreasing to 2.5 per cent at 660° C. and approaching lower values as the temperature decreases. Silicon is always present in furnace-refined nickel, generally in amounts under 0.25 per cent, which have comparatively little effect. In larger amounts the hardness of the metal is increased and its ductility decreased, and with the increasing amounts the malleability, both hot and cold, is diminished and finally destroyed completely. This occurs at from 3 to 5 per cent of silicon.

VIII. TECHNOLOGY.

1. CASTING.

Nickel is cast from the furnace into open molds to produce blocks for remelting and for anodes, into ingot molds after deoxidation with manganese and magnesium for the production of malleable nickel, and into sand molds for nickel castings. It is also poured directly into water to form nickel shot and spatter.

Nickel for remelting is not "deoxidized," but it is necessary to degasify and "deoxidize" all nickel intended for malleable ingots or castings. The pig metal may be melted in crucibles or in an electric arc or an open-hearth type furnace, care being taken to adjust the carbon content between 0.10 and 0.30 per cent. This is known by nickel refiners as "bringing it to pitch" and is accomplished, depending on the carbon content of the charged metal and the atmosphere of the furnace, by addition of charcoal or by oxidation either with nickel oxide or with an oxidizing furnace atmosphere.

When at the proper pouring temperature, from 1,540 to 1,650° C. (2,800 to 3,000° F.), it is poured into a ladle and deoxidized with manganese and magnesium. If melted in a crucible, it is, of course, deoxidized directly in the crucible. It is better practice, when possible, to deoxidize in the furnace; e. g., when using an electric arc type of furnace. Manganese may be added as metallic manganese or as ferromanganese in amounts from 0.25 to 2 per cent; the standard addition of magnesium is 1.5 ounces to 100 pounds of metal. The magnesium must be plunged with tongs underneath the surface of the metal.

Besides the process of deoxidation, which is absolutely essential, the production of malleable nickel ingots requires no operations different from those followed, for instance, in the steel industry. Deoxidized nickel solidifies without blowholes but with a pronounced pipe, which renders the use of proper risers or hot-tops and properly designed molds necessary.

The molding of nickel castings follows the practice used for steel castings, usually with an allowance of one-fourth inch to the foot for shrinkage. Molds are preferably baked, but must be at least skin dried. Ample gates and risers must be provided to insure proper feeding of the mold.

Ordinary commercial platers' anodes are melted with a higher carbon content than malleable nickel and may be poured at a much lower temperature. They do not require deoxidation treatment of any kind, and are consequently much easier to handle in the foundry than is low-carbon metal.

2. ROLLING, FORGING, ANNEALING.

In the hot-working of nickel both the temperature and the condition of the heating flame should be subject to careful control. In rolling the temperature for preheating should be from 1,100 to 1,200° C. (2,000 to 2,200° F.), and ingots should not be subjected to temperatures much in excess of this, as they become somewhat hot-short at higher temperature. Below this temperature the metal may be too hard to roll satisfactory. The flame used for heating should be as nearly neutral as possible, and a low-sulphur fuel (oil) is essential for successful heating.

For hot-rolling bars and rods of the usual cross sections the same designs of rolls as are used for steel may be and are employed with success. Pure nickel and nickel alloys of high nickel content are very easily "guide marked" when hot.

The above remarks apply also to the forging of nickel. Nickel is much more successfully forged under the hammer than under a press; in fact, the metal has a pronounced tendency to crack under the slow action of the press, which may be due to the fact that the surface cools more readily than under the quick blows and short contact of the hammer.

The process of drawing nickel tubes, either seamless or welded, on a commercial basis has, according to Prentiss (465a), been successfully developed by the American Nickel Corporation. The

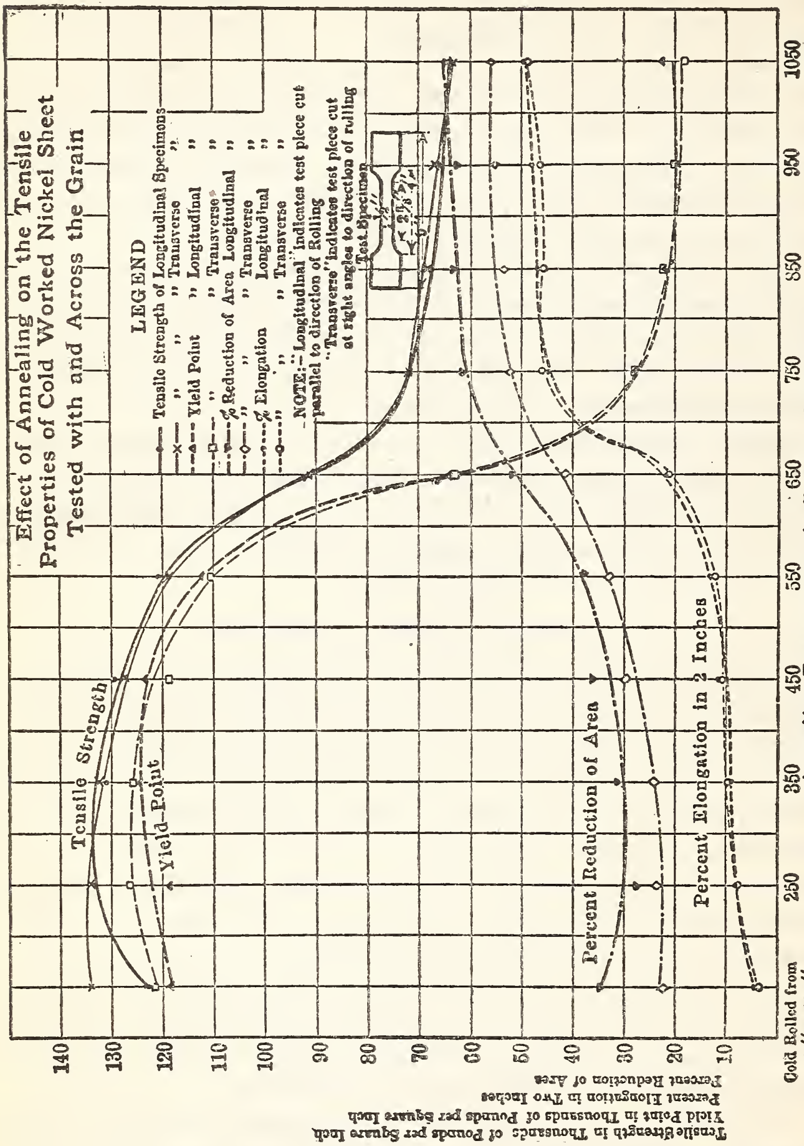

FIG. 13.—*The annealing of nickel (Price and Davidson, 148); its effect upon the tensile properties.*

same piercing, drawing, and heating equipment is used for nickel as for steel, brass, and copper. Nickel is pierced as easily as steel or copper, though with a greater consumption of power because of

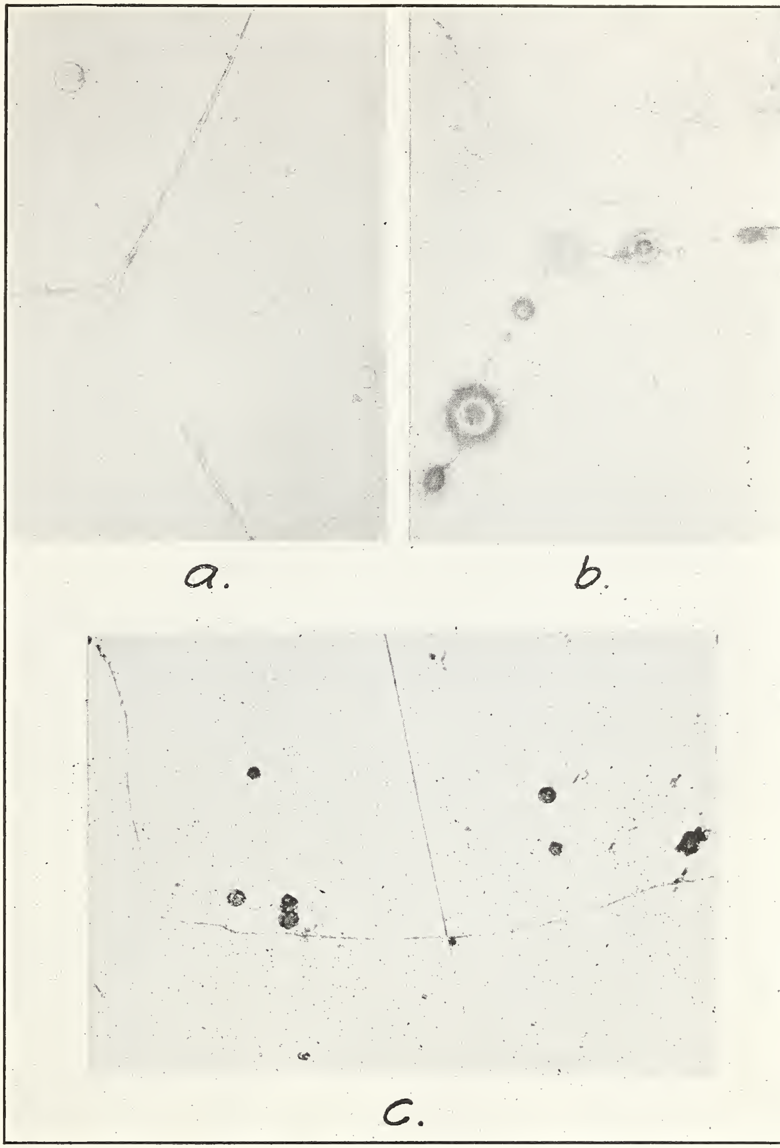

FIG. 12.—*Three types of sulphides found in commercial nickel.* × 500.

(*a*) Nickel sulphide. Sample of nickel taken from furnace during tapping

(*b*) Manganese sulphide. Sample of nickel taken after metallic manganese had been added to melt in ladle (7 ounces to 100 pounds).

(*c*) Magnesium sulphide. Sample of nickel taken after the manganese had been added in the same manner as in (*b*) and final deoxidation had been made by adding magnesium (1.5 ounces to 100 pounds).

Analysis of commercial nickel: Ni, 99.2 per cent; Fe, 0.34 per cent; C, 0.13 per cent; Si, 0.17 per cent; Mn, about 0.5 per cent; S, 0.025 per cent.

Etched with acetic-nitric acid mixture (30 parts glacial acetic acid, 30 parts concentrated nitric acid, and 40 parts water, by volume).

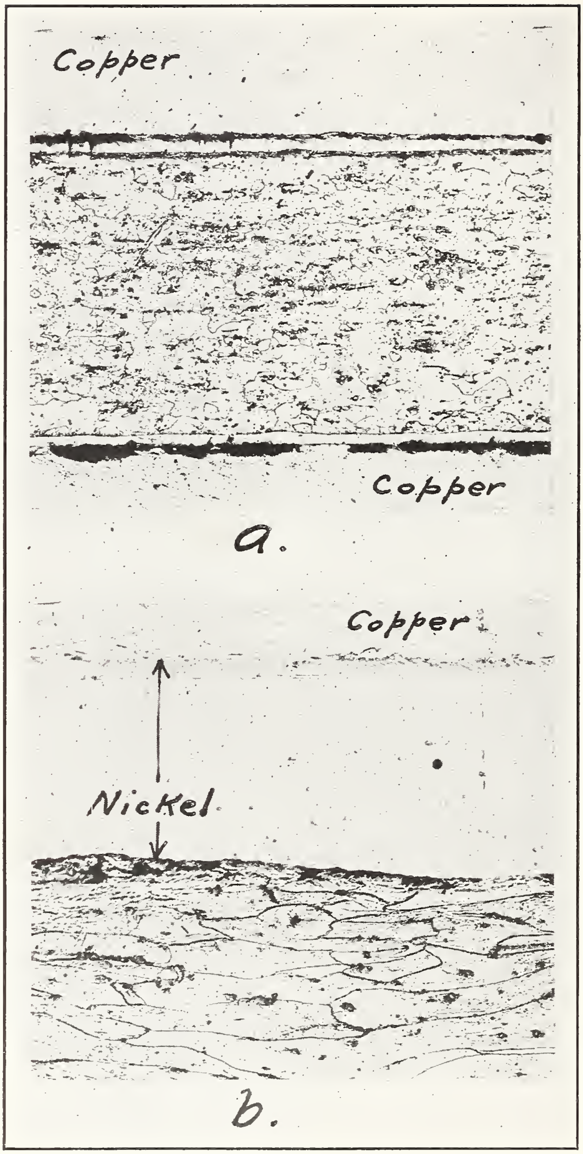

Fig. 14.—*Nickel-coated Armco iron.* × 100.

(*a*) Armco iron sheet coated on both sides. The thickness of each nickel coat measures about 5 per cent of that of coated sheet.

(*b*) Armco iron sheet coated on one side. The thickness of the nickel coat measures about 20 per cent of that of coated sheet.

The specimens were electroplated with copper before being prepared for microscopic examination.

Etched with 5 per cent alcoholic picric acid.

its higher tensile strength. With nickel, a smaller degree of reduction between each drawing operation is effected, and hence a greater number of drawing operations are required to reach the same total reduction. In the annealing between drawing operations the same temperature range is used as for the rolling operations stated above.

In order to soften nickel which has been worked cold, it must be heated to from 700 to 900° C. (1,292 to 1,652° F.) and allowed to remain in the furnace until thoroughly heated throughout. It may be cooled rapidly or slowly, as desired, as there is no alteration in the properties of the metal produced by cooling after annealing. For the commercial annealing of nickel, which has only been lightly cold-worked, a temperature of 900° C. should be used, as this will insure a more thorough and homogeneous anneal than might be accomplished at lower temperatures.

Price and Davidson (148) have studied the annealing of commercially pure nickel (grade A) and their results are shown in Figure 13. The annealing range for the metal is from 600 to 800° C. (1,112 to 1,472° F.); commercially the metal is usually annealed at 900° C.

Whenever possible the metal should be close-annealed in tight boxes to prevent the formation of surface oxide. Any oxide formed may be reduced by the creation of a reducing atmosphere in the box, either by the presence of a small amount of charcoal or by the admission of some reducing gas. When annealing is done in this manner, no pickling is required, and on account of the difficulty and expense pickling should only be adopted as a last resort.

If necessary, pickling may be accomplished by the use of sulphuric acid with some oxidizing agent, such as ferric sulphate or chromic acid, at a temperature around 60 to 70° C. (140 to 158° F.), but it is a slow and tedious process.

3. WELDING AND SOLDERING.

Nickel can not be smith-welded owing to the formation of a coating of nickel oxide which can not be fluxed and which prevents the adherence of the two surfaces to be welded. On the other hand, under conditions where a reducing atmosphere may be maintained the metal may be very satisfactorily welded, as by the use of the oxyacetylene torch, the metallic arc welding process, or by electrical resistance welding. It is by the latter

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method that nickel wire is welded to iron lead wire to form tips or points for spark plugs. Nickel tubing is welded by electrical resistance, and a speed of 69 feet per minute has been attained. Inasmuch as the acetylene or arc welding of nickel follows closely that for Monel metal described below, reference is made here to those paragraphs on page 64 describing the latter.

Nickel may be soldered and brazed by the ordinary methods; it should be tinned before soldering, as is done with iron.

Under suitable reducing conditions nickel may be plastically welded to steel, and an interesting process, invented by Doctor Fleitman about 40 years ago, for producing nickel-coated steel sheets is based upon this possibility. A steel sheet bar, about three-fourths inch thick, is cleaned and pickled and placed between two thinner plates of clean nickel. Around the whole is wrapped thin steel sheet, which protects the nickel against oxidation and is dissolved off by later pickling. The compound sheet bar is heated in a reducing atmosphere and then rolled and cross-rolled into a solid, compound sheet. Usually the nickel coating so produced is thicker and more durable than electrolytically deposited metal. Figure 14 shows the nickel coating on Armco iron sheets coated with nickel in the manner as indicated above, specimens of which were kindly furnished by Dr. C. T. Hennig, of the American Nickel Corporation. Microscopic examination showed that the union between the steel body and nickel coat was excellent. Conversely, nickel has been used as a base on which platinum is plated or coated by welding. The platinum-coated nickel has been prepared in the form of wire or sheet, which has been suggested as a substitute for platinum where resistance to corrosion is desired.

4. ELECTRODEPOSITION.

Aside from electrolytic refining, the principal application of nickel deposition is in the electroplating of steel, brass, zinc, and numerous alloys. The chief purpose of the nickelplating is to improve the appearance of the finished articles. The average thickness of commercial nickelplating on any article is rarely over 0.0003 inch (0.00076 cm) and is frequently less than 0.0001 inch (0.00025 cm). Even these thin coatings exert considerable protection against the atmospheric corrosion of brass but not of iron and steel. If the nickelplating is initially porous, or is rendered so by abrasion, the corrosion of the exposed iron or steel may be slightly accelerated by the presence of the nickel, which is electro-positive to the iron (that is, has a lower solution pressure than the iron). In order to secure protection against corrosion, it is, therefore, necessary to produce nearly impervious nickel deposits. This requires thorough cleaning of the steel preparatory to plating. The frequent practice of copperplating prior to nickelplating may actually reduce the protection against corrosion if the steel becomes exposed. If, however, it produces a better surface, and thus renders the nickel coating more nearly impervious, the use of the copperplating may be beneficial. Recently some progress has been made in increasing the protective value of the nickel by the preliminary application of zinc or cadmium coatings.

In electrotyping, nickel may be deposited directly upon the wax or lead mold, producing a true nickel electrotype; or it may be deposited upon the face of a finished copper plate, making a nickel-plated electrotype. Stereotype plates are also sometimes nickel-plated. The function of the nickel upon electrotypes is to produce a harder surface, which is also more resistant than copper to the chemical action of colored inks that may be employed.

Owing to the passivity of nickel, the pure metal can not be used successfully for anodes in solutions containing only sulphates. Hence, it has been customary to add to nickel anodes appreciable amounts of iron and carbon, and sometimes tin, which accelerate anode corrosion, probably through the formation of local couples. Incidentally, they lower the fusing point, and thereby facilitate the casting of the anodes. Formerly most nickel anodes contained only 88 to 90 per cent of nickel. In recent years, however, anodes with 95–97 per cent nickel are more commonly used (see p. 12). This development has been rendered possible by the use of solutions containing chlorides, which increase the anode corrosion.

The relation between the composition and structure of nickel anodes and their behavior in electrodeposition has never been exhaustively studied. Recent patents indicate that it may be possible to improve the corrosion of the anodes by suitable heat treatment.

Although a large number of formulas for nickelplating solutions have been proposed, the nickel content of almost all commercial baths is furnished by nickel sulphate. This may be present as the "single salt," $NiSO_4.7H_2O$ (or frequently with $6H_2O$), or as the "double salt," nickel-ammonium sulphate $NiSO_4.(NH_4)_2SO_4.6H_2O$. In the latter the ammonium sulphate increases the conductivity. The same effect may be produced by the addition of magnesium sulphate or sodium sulphate, which may be used in higher concentrations than ammonium sulphate. The content of the latter is limited by the low solubility of the nickel-ammonium sulphate. All of these sulphates also decrease appreciably the nickel ion concentration, which effect may be advantageous. Chlorides, such as NaCl, NH_4Cl, and $NiCl_2$, are added principally to increase anode corrosion, though they also improve the conductivity. Fluorides, such as NaF or NiF_2, improve the anode corrosion, and in the presence of boric acid increase the "buffer action," and thus regulate the hydrogen ion concentration.

The acidity of nickel-depositing solutions may have an important effect upon their operation. Colorimetric methods of measuring the pH or hydrogen ion concentration have been applied by Thompson (489), who found that the optimum pH for electroplating lies between 5.4 and 6.0. The function of the boric acid, as shown by Hammond (528), is to regulate the acidity by its buffer action.

Salts of organic acids, such as tartrates and citrates, are occasionally added to nickel baths, especially for nickelplating on zinc and zinc alloys. The exact function of these salts is not known, but they probably serve (1) to regulate the pH, (2) to dissolve basic compounds of nickel or iron, and (3) to reduce the rate of chemical deposition of nickel by more negative metals, such as zinc.

The effect of impurities in nickel deposition has been studied by Thompson and Thomas (488). They found that, of the impurities likely to be present, copper is most harmful and zinc somewhat less so. They proposed a specification for nickel salts, with a maximum of 0.02 per cent copper, 0.05 per cent Zn, and 0.10 per cent Fe. The proposed limit for iron in the salts was based principally upon the amounts of iron likely to be present in high-grade nickel anodes. In a later paper Thompson (485) has reviewed the literature upon the effects or iron and has shown that they depend, in part, upon the state of oxidation of the iron in the solution and upon the pH of the latter. Under favorable conditions fairly large amounts of iron are not necessarily detrimental and may even improve the appearance and hardness of the deposit. Under different conditions, especially if basic compounds of iron are included in the deposit, an injurious effect may be produced upon the color and structure.

In general, nickelplating has been conducted at room temperatures, but Watts (525) has shown that in solutions with high nickel content and containing chlorides and boric acid very high current densities can be applied if the solutions are used at elevated temperatures.

The following formulas illustrate the various types of nickel baths in commercial use. It is not implied, however, that these formulas will always be satisfactory, much less that they are the best for a given class of work:

	g/l	oz./gal.
1. Nickel electrotyping:		
Nickel ammonium sulphate	45	6
Nickel sulphate	15	2
Sodium chloride	7.5	1
2. Nickelplating—double-salt solution:		
Nickel ammonium sulphate	75	10
Ammonium chloride	22.5	3
Boric acid	15	2
3. Nickelplating—single-salt solution:		
Nickel sulphate	120	16
Ammonium chloride	22.5	3
Boric acid	15	2
4. Nickelplating—fluoride solution:		
Nickel sulphate	280	37
Sodium fluoride	8	1
Boric acid	30	4
5. Nickelplating (Watts)—for high-current density or in hot solutions:		
Nickel sulphate	240	32
Nickel chloride	15	2
Boric acid	30	4
6. Nickelplating on zinc (Hammond):		
Nickel sulphate	240	32
Nickel chloride	15	2
Boric acid	30	4
Sodium citrate	175	23

PART B.—ALLOYS OF NICKEL.

IX. EQUILIBRIUM OF BINARY ALLOYS OF NICKEL.

The constitution of most of the important binary alloy series with nickel has been investigated fairly completely, and the principal results of these investigations are given in Tables 19, 20, 21, and 22. It is observed that nickel has a strong tendency to form solid solutions with other metals, either of limited compositions or in all proportions. It is, structurally speaking, perhaps mainly for this reason that the metal forms a constituent of so many commercially useful ferrous and nonferrous alloys.

TABLE 19.—Binary Alloys of Nickel Having Limited Miscibility in the Liquid State.

Nickel and—	Lowest melting alloy.		Solubility in solid state at melting point of lowest melting alloy.	
	Melting point.	Composition.	(x) in nickel.	Nickel in (x).
	°C.	Per cent Ni.	Per cent (x).	Per cent Ni.
Lead (Voss, 756a; Portevin, 757)	326	97–0	3	0.07
Silver (Pretenko, 789)	961	96–0	4	0.4
Thallium (Voss, 794a)	320	97–0	3	0

TABLE 20.—Binary Alloys of Nickel in Which the Two Metals Form a Simple Eutectiferous Series.

Nickel with—	Eutectic.		Solubility at eutectic temperature.	
	Temperature.	Composition.	Gold in nickel.	Nickel in gold.
	° C.	Per cent Ni.	Per cent Au.	Per cent Ni.
Gold (Levin, 704)	950	27	±16	±6

TABLE 21.—Binary Alloys of Nickel in Which the Two Metals are Soluble in All Proportions in the Solid State.

Nickel and—	Melting point of alloying metal (nickel=1,452°).	Minimum melting point of binary alloy.	Composition at minimum melting point of binary alloy.
	° C.	° C.	Per cent Ni.
Chromium (Voss, 615)	1,615	1,290	40
Cobalt (Guertler and Tammann, 649)	1,480		
Copper[1] (Guertler and Tammann, 691)	1,083	....	....
Iron[1] (Guertler and Tammann, 749; Ruer and Schuz, 741)	1,530	1,425	70
Manganese (Zemczuzny, Urasow, and Rykovskoff, 763)	1,230	1,000	44
Palladium (Heinrich, 777)	1,549	....	....

[1] Attention should be called to the fact that the nickel-iron alloy series is not completely miscible at lower temperatures (see Sec. X, 4), and that a similar question has arisen regarding the nickel-copper alloy series.

TABLE 22.—Binary Alloys of Nickel in Which the Two Metals Form One or More Compounds.

Nickel and—(x).	Compounds formed.	Nickel rich alloys.				(x) rich alloys.			
		Compound.	Solubility of compound in nickel at eutectic temperature.	Eutectic. Temperature.	Eutectic. Composition.	Compound.	Solubility of compound in (x) at eutectic temperature.	Eutectic. Temperature.	Eutectic. Composition.
			Per ct. (x).	°C.	Per ct. (x).		Per ct. Ni.	°C.	Per ct. Ni.
Aluminum	NiAl; $NiAl_2$; $NiAl_3$.	NiAl	14	1,370	13	$NiAl_3$	(?)0	630	6
Antimony	$SbNi_3$; Sb_2Ni_5; SbNi	Sb_2Ni_5	7.5	1,100	35	SbNi	0	612	4
Arsenic	Ni_2As; Ni_5As_2; Ni_3As_2; NiAs	Ni_5As_2	5.5	898	28				
Bismuth	NiBi; $NiBi_3$	NiBi	0	[1] 655		$NiBi_3$	0	272	0
Boron									
Cadmium	$NiCd_4$					$NiCd_4$	0	321	0
Carbon	Ni_3C(?)								
Magnesium	Ni_2Mg; $NiMg_2$	Ni_2Mg	1	1,082	12	$NiMg_2$	7	512	32
Molybdenum	MoNi	MoNi	33	1,300	50				
Phosphorus	Ni_3P; Ni_5P_2; Ni_2P	Ni_5P_2	0	880	12				
Selenium									
Silicon	Ni_3Si, Ni_2Si, Ni_3Si_2, NiSi	Ni_3Si	6	1,153	10.6				
Sulphur	Ni_3S_2; NiS	Ni_3S_2	0.5	644	23				
Tellurium									
Tin	Ni_4Sn; Ni_3Sn; Ni_3Sn_2	Ni_3Sn	15	1,135	33	Ni_3Sn_2	0	229	(?)1
Zinc	NiZn; $NiZn_3$	NiZn	35	[1] 1,035		$NiZn_3$	0	419	0

[1] Peritectic.

X. COMMERCIAL ALLOYS.

1. MONEL METAL.

This alloy was introduced by the International Nickel Co. about 1905 and named after its then president, Ambrose Monell. It is a natural alloy produced directly from Canadian Bessemer matte by roasting and reducing with charcoal and has the following average composition:

	Per cent.
Nickel	67
Copper	28
Other metals (iron, manganese, silicon)	5

(There is made in England under the trade name "Corronil" an alloy resembling very closely Monel metal.)

Several grades of this metal are produced for different purposes, of which the following typical analyses are given:

TABLE 23.—Typical Analyses of Monel Metal.

Material.	Constituents.				
	C	Mn	Fe	Si	S
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Rolled Monel metal sheet (grade A)	0.11	0.15	1.76	0.18	0.026
Rolled Monel metal rods (grade B)	.26	1.78	2.00	.20	.035
Monel metal wire (grade B)	.12	1.66	2.10	.13	.025
Monel metal castings	.18	.25	1.90	1.06	.03

It will be noted that the wire is made with low carbon content in order that it may be readily cold-drawn, whereas hot-rolled rods are produced with somewhat more carbon in order to increase the ease of their hot-rolling.

The practice in producing castings and malleable ingots of this alloy follows very closely that of the production of malleable nickel and nickel castings which has already been described. After bringing to pitch in the furnace—that is, adjusting the carbon and oxide content—it is deoxidized with manganese, or ferromanganese, and magnesium, the latter being used in the same proportions as for nickel and poured into ingot molds or sand castings. Unless so deoxidized it is, generally speaking, not malleable and can not be rolled or forged.

Recent determinations made by the Bureau of Standards (862a) of the oxygen and hydrogen content and of the microstructure of 50-pound blocks cast during a regular heat show that, if the deoxidation of Monel metal is carried out entirely or in part in the furnace, the resulting metal is free from oxygen and porosity, but if the deoxidation is carried out in the ladle, the metal contains oxygen and appears porous.

The ingots so produced may be rolled or forged at from 1,040 to 1,150° C. (1,900 to 2,100° F.) by using the same precautions as in the case of nickel against oxidation and absorption of sulphur during heating. Rods are produced by hot-rolling or forging; from these bright, cold-drawn rods are also produced by close annealing and cold drawing. Wire is drawn from hot-rolled, close-annealed wire rod about one-fourth to three-eighths inch in diameter. Annealing of hot-rolled Monel metal preparatory to cold rolling or drawing is carried out at 820 to 900° C. (1,508 to 1,652° F.), preferably in charcoal boxes to prevent scaling, and

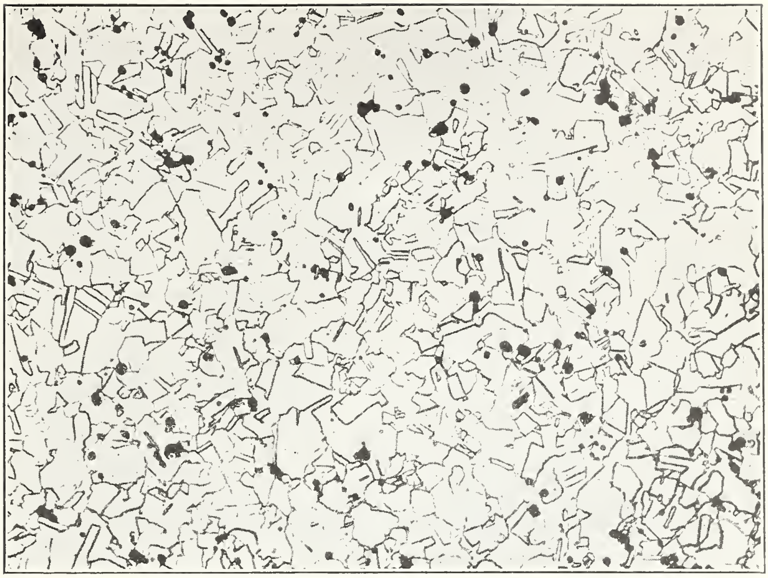

Fig. 15.—*Microstructure of rolled Monel metal rod.* ×100

Fig. 16.—*Microstructure of cold-drawn and annealed Monel metal rod.* ×150

FIG. 17.—*Microstructure of cast Monel metal.* ×100

for at least one hour to secure uniform annealing. The material should not be removed from the annealing box until the cooling has proceeded below about 250° C. (482° F.). Light scaling may, however, be removed by pickling with sulphuric acid and ferric sulphate, as in the case of nickel, but it is a slow and rather unsatisfactory process. The annealing range for cold-worked Monel metal is from 600 to 900° C. (1,112 to 1,652° F.), depending on the amount of previous cold-working.

This metal is on the market in the usual commercial forms [2]—pig, sheet, shot, strip, bars, hot-rolled and cold-drawn rods, wire, and tube (welded only)—as well as in many fabricated forms, such as wire screen and cloth, bolts and nuts, nails, tacks, rivets, cable, chain, balls, and in the form of forgings and castings.

(*a*) METALLOGRAPHY.

The elements entering into the composition of Monel metal form with each other a continuous series of solid solutions. Consequently, the structure of the annealed or rolled metal is quite simple and similar to that of nickel, consisting of grains of solid solution with small particles, probably of magnesium sulphide, embedded therein. This structure is illustrated in Figure 15; the typical structure of cold-drawn and annealed rods of Monel metal is illustrated in Figure 16. The structure of cast Monel metal is, however, quite different from that of cast nickel and is that characteristic of solid solutions; it has the cored or dendrictic structure illustrated in Figure 17. The darker portions are richer in copper than the light areas due to the selective nature of the solidification. This heterogeneity of concentration is relieved by annealing and by the processes incident to hot forging or rolling.

For etching Monel metal, either in the cast or worked condition, the etching reagents recommended by Rawdon and Lorentz (142) for nickel may be used (p. 23). The nitric acid-glacial acetic acid mixture does not give quite as satisfactory results as the ferric chloride solution acidified with hydrochloric acid, though it is considerably quicker in action.

Monel metal exhibits the same phenomenon, as does nickel, of intercrystalline brittleness produced by exposure at rolling temperature to the action of oxidizing or sulphurizing gases (see p. 22).

The discussion above (p. 39) on the effect of impurities on the properties of nickel applies with almost equal force to Monel metal.

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[2] Booklets by the Monel Metal Products Co. and by the International Nickel Co. describe the properties and uses of this alloy

Carbon, as in the case of nickel, hardens the metal and renders it easier to roll and forge hot but more difficult to roll cold. The separation of graphite begins at a somewhat lower carbon content than for nickel, namely, at about 0.35 per cent C.

(b) PHYSICAL PROPERTIES.

DENSITY.—The density of Monel metal varies from 8.70 to 8.85 but may be taken as 8.80 (0.318 lb./in.^{3}).

CHANGE OF STATE.—The melting range of Monel metal varies from 1,300 to 1,350° C. (2,370 to 2,460° F.), chiefly according to its carbon content. For the magnetic transformation point of Monel metal the value 95° C. (203° F.) determined by Burrows (917) with the aid of an electromagnet has been verified by the results of Hunter, Sebast, and Jones (339), who obtained the value 93° C. (199° F.) by means of electrical resistance measurements.

SPECIFIC HEAT.—The specific heat of Monel metal, according to recent determinations by White (919), is 0.128 cal./gram/°C. between 20 and 1,270° C.; he found its latent heat of fusion to be 68 cal./gram.

THERMAL EXPANSIVITY.—The mean coefficient of thermal expansion of Monel metal between 25 and 100° C. is 0.000014, while that between 25 and 600° C. is 0.000016. Table 24 gives the latest data, obtained by Souder and Hidnert (323). The typical expansion curve of Monel metal plotted by them is very similar to that of commercial nickel (shown in fig. 5, p. 27).

THERMAL CONDUCTIVITY.—The thermal conductivity of Monel metal is 0.06 cal./cm^3/sec./°C., or about one-fifteenth that of copper.

ELECTRICAL RESISTIVITY.—The producers of Monel wire state that the average resistivity of drawn Monel metal is 42.5 microhm – cm or 256 ohm-mil-foot, with a temperature coefficient of resistivity at 20° C. of 0.0019 per °C. (0.0011 per °F.). Hunter, Sebast, and Jones (339) have studied the resistivity of Monel metal at higher temperatures (see fig. 9, p. 33).

MAGNETIC PROPERTIES.—Monel metal is slightly magnetic (at temperatures below its transformation point), and its permeability varies markedly with composition and mechanical and heat treatment. Table 25 gives values of magnetic induction obtained by Burrows (917) on an annealed rod of Monel metal containing 66.1 per cent nickel, 28.8 per cent copper, 2.68 per cent iron, 1.91 per cent manganese, 0.22 per cent carbon. and 0.29 per cent silicon.

TABLE 24.—Average Coefficients of Expansion of Monel Metal. (Souder and Hidnert, 323.)

Lab. No.	Material.	Composition in per cent.								Average coefficients of expansion × 10^6.								
		Ni	Cu	Fe	Mn	C	Si	S	Pb	25 to 100° C.	100 to 200° C.	200 to 300° C.	300 to 400° C.	400 to 500° C.	500 to 600° C.	25 to 300° C.	300 to 600° C.	25 to 600° C.
S648	Leaded Monel, cast ⅜ inch square	60.05	32.46	2.21	2.00	0.15	0.87	0.035	2.22	13.9	15.0	15.8	16.8	17.7	20.6	15.0	18.4	16.7
S649	Same; annealed 900° C. (1,650° F.) for 1 hour									14.3	15.0	15.7	16.7	18.1	18.3	15.1	17.7	16.5
S663	Cast nonleaded Monel, ⅜ inch square	66.18	28.42	2.37	2.10	.18	.70	.038	....	13.7	15.1	15.7	16.6	17.7	18.5	15.0	17.6	16.4
S664	Same; annealed at 900° C. (1,650° F.) and slowly cooled									13.9	15.0	15.7	16.6	17.8	18.7	15.0	17.7	16.4
S641	Hot-rolled Monel wire rod, ¼ inch round	66.58	29.57	1.79	1.78	.15	.09	.030	....	14.2	14.9	15.5	16.7	17.0	18.1	14.9	17.3	16.1
S688	Same; annealed 870° C. (1,600° F.) for 1 hour									14.3	15.3	15.8	16.5	17.4	17.7	15.2	17.2	16.2
S650[1]	Hot-rolled Monel metal, ⅜ inch rod, high carbon	67.32	28.73	1.74	1.66	[2].31	.19	.035	....	14.5	15.1	15.9	16.4	17.1	16.2	15.2	16.6	15.9
S651	Same; annealed 900° C. (1,650° F.) for 1 hour									14.3	15.0	15.8	16.5	17.4	17.7	15.1	17.2	16.2
S661	Hot-rolled Monel ⅛ inch sheet, ⅜ inch wide	68.87	29.03	1.60	.18	.13	.15	.027	....	14.2	14.7	15.6	16.4	17.6	17.9	14.9	17.3	16.2
S662	Same; annealed 870° C. (1,600° F.) for 1 hour									14.0	15.0	15.9	16.4	17.3	18.1	15.1	17.3	16.2

[1] The coefficients given for this sample are the average values obtained on two duplicate samples.
[2] Graphitic carbon=0.15.

TABLE 25.—Magnetic Induction of a Monel Metal Rod.

Magnetizing force.	Magnetic induction.	Magnetizing force.	Magnetic induction.	Magnetizing force.	Magnetic induction.
Gausses.	Gausses.	Gausses.	Gausses.	Gausses.	Gausses.
1	413	10	1,203	75	1,300
2	699	20	1,244	100	1,317
4	989	50	1,282	150	1,346

For a magnetizing force of 50 gausses values of the magnetic induction may vary from 500 to 2,000 gausses, depending on the treatment received.

Optical Properties.—The optical properties of Monel metal are not very different from those of nickel. Table 12 gives values of the optical reflectivity of commercial rolled Monel metal as determined by Coblentz (924).

Elasticity.—The modulus of elasticity (Young's modulus) of Monel metal is 25,000,000 to 26,000,000 lbs./in.^{2}; the torsional modulus is 9,500,000 lbs./in.^{2}

Hardness.—The hardness of Monel metal varies with the form and condition of the metal, as may be seen in Table 26.

TABLE 26.—Hardness of Monel Metal Products.

Materials.	Scleroscope hardness (universal hammer).	Brinell hardness (10 mm ball).	
		500 kg	3,000 kg.
Hot-rolled Monel metal rods	20–30	100–130	145–170
Cold-drawn Monel metal rods	....	150–170	180–200
Cast Monel metal	15–25	100–120	....
Annealed Monel metal	15–25	100–120	....
Cold-rolled Monel metal sheets	40–50	180–200	....

Tensile Properties.—The tensile properties of Monel metal also vary with the condition and form of the metal. Table 27 gives the average tensile properties and hardness of hot-rolled rods according to control tests made by the International Nickel Co. in 1916 and in 1919–20.

TABLE 27.—Average Tensile Properties and Hardness of Hot-Rolled Monel Metal. (Merica, Waltenberg, and McCabe, 913.)

Group sizes of hot-rolled rods.	Average tensile properties.				Average Brinell hardness 1919–20.		Average Shore hardness, S.	Some ratios of mechanical properties.					Some products or quality factors.			
	Proportional limit, P. L., lbs./in.²	Yield point, Y. P., lbs./in.²	Tensile strength, T., lbs./in.²	Elongation in 2 inches, e, per cent.	500 kg, B_{500}	3000 kg, B_{3000}		$\frac{P.L.}{Y.P.}$	$\frac{Y.P.}{T}$	$\frac{T}{B_{3000}}\times 0.1$	$\frac{P.L.}{S}\times 0.01$	$\frac{B_{3000}}{B_{500}}$	$T\ e\times 10^{-5}$	$Y\ e\times 10^{-5}$	$\frac{Y.P.+T}{2}e\times 10^{-5}$	$\frac{Y.P.}{T}e$
ROUNDS AND SQUARES.																
Up to 1 in. in diameter:																
1916	......	63, 100	94, 600	40	.....	.....	.....	.....	0. 67	.....	.....	.....	38	25	32	27
1919–20	39, 700	51, 300	91, 500	46	113	144	22	0. 86	.56	64	18	1. 27	42	23	33	25
$1\frac{1}{16}$ to $1\frac{11}{16}$ in.:																
1916	......	62, 000	93, 100	39	.....	.....	.....	.....	.67	.....	.....	.....	36	24	30	26
1919–20	47, 700	59, 600	93, 200	37	130	162	23	.80	.64	58	21	1. 24	34	22	28	24
$1\frac{3}{4}$ to $2\frac{7}{16}$ in.:																
1916	......	50, 100	87, 700	42	.....	.....	.....	.....	.57	.....	.....	.....	37	21	29	24
1919–20	40, 200	51, 900	90, 300	42	127	161	23	.80	.57	57	18	1. 26	38	22	30	24
$2\frac{1}{2}$ to $3\frac{1}{2}$ in.:																
1916	......	43, 800	85, 300	44	.....	.....	.....	.....	.51	.....	.....	.....	38	19	28	22
1919–20	32, 200	41, 800	88, 900	46	120	147	23	.81	.47	60	14	1. 22	41	19	30	22
Over $3\frac{1}{2}$ in.:																
1916	......	47, 300	84, 800	43	.....	.....	.....	.....	.56	.....	.....	.....	36	20	28	24
1919–20	37, 200	50, 300	88, 400	43	120	152	24	.79	.57	61	16	1. 26	38	22	30	24
HEXAGONS.																
All sizes:																
1916	......	60, 700	87, 800	40	.....	.....	.....	.....	0. 69	.....	.....	.....	35	24	30	28
1919–20	49, 100	60, 600	92, 300	38	133	167	25	0. 81	.66	57	19	1. 25	35	23	29	25
RECTANGLES.																
All sizes:																
1916	......	56, 400	85, 600	42	.....	.....	.....	.....	0. 66	.....	.....	.....	36	24	30	28
1919–20	35, 800	47, 000	89, 800	47	114	144	24	.....	.53	62	15	1. 26	42	22	33	25
Averages 1916								.....	0. 62	.....	.....	....	36	22	29	25
Averages 1919–20								0. 80	.57	58	17	1. 25	38	22	31	24

Table 28 gives the tensile properties of other forms of the metal.

TABLE 28.—Tensile Properties of Monel Metal.

Material.	Average range of tensile properties. Yield point.	Tensile strength.	Elongation in 2 inches.
	Lbs./in.²	Lbs./in.²	Per cent.
Cold-drawn rods	60, 000– 90, 000	80, 000–110, 000	20–30
Sheets, annealed	25, 000– 35, 000	65, 000– 75, 000	35–45
Sheets, hard	90, 000–110, 000	100, 000–120, 000	1– 2
Wire, annealed	25, 000– 35, 000	65, 000– 75, 000	20–30
Wire, hard	90, 000–110, 000	100, 000–120, 000	1– 2
Castings	30, 000– 40, 000	65, 000– 80, 000	25–30

The proportional limit of hot-rolled rods averages from 32,000 to 47,000 lbs./in.^{2}; that for castings from 15,000 to 25,000 lbs./in.^{2} Specifications issued by the United States Navy Department for this alloy in its different forms include information concerning its tensile properties (see pp. 127–131).

Merica, Waltenberg, and McCabe (913) have reported the results of torsion tests of hot-rolled Monel rods. Their results are given in Table 29.

TABLE 29.—Average Torsional Properties of Hot-Rolled and Hot-Hammered Monel Metal Rounds and Hexagons. (Merica, Waltenberg, and McCabe, 913.)

Material.	Proportional limit, P. L.	Yield point, Y. P.	Breaking strength, B. S.	Shear, inch per inch of gauge length.	Modulus of elasticity E_s.	Ratio.				
						$\frac{Y.P._s}{P.L._s}$ (1)	$\frac{P.L._s}{P.L._t}$ (1)	$\frac{Y.P._s}{Y.P._t}$ (1)	$\frac{B.S._s}{B.S._t}$ (1)	$\frac{\text{Shear, in.}}{\text{Elongation.}}$
	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}		Million lbs./in.^{2}					Per cent.
¾ to 1 inch rounds, hot-rolled	25,200	30,000	62,000	2.78	9.24	1.19	0.63	0.66	0.69	0.058
1¼ to 2¼ inch rounds, hot-rolled	29,700	38,600	61,800	2.83	9.64	1.29	.67	.68	.67	.072
2½ to 3½ inch rounds, hot-rolled	20,200	26,700	63,300	2.64	9.62	1.32	.61	.64	.71	.057
3¾ to 6 inch rounds, hot-hammered	24,200	32,200	62,100	2.57	9.75	1.32	.63	.64	.69	.060
¾ to 2 inch hexagons, hot-hammered	24,800	36,000	63,600	1.55	9.47	1.45	.55	.59	.69	.085

[1] The subscript $_s$ denotes "in shear"; the subscript $_t$, "in tension."

Direct shearing tests on hot-rolled Monel metal rods carried out in the engineering laboratory of Lehigh University gave the following average results:

TABLE 30.—Shear Tests of Monel Metal Rods.

Diameter of test bar.	Single shear maximum stress.	Double shear maximum stress.
	Lbs./in.^{2}	Lbs./in.^{2}
1-inch	55,000–61,000	115,000–127,000
¾-inch	45,000–50,000	90,000–103,000

Compression tests of rods and castings give the following results:

Property.	Rods.	Castings.
	Lbs./in.^{2}	Lbs./in.^{2}
Proportional limit	25,000–50,000	15,000–25,000
Yield point	60,000–70,000	20,000–30,000

The resistance to alternating stresses has been studied by Merica, Waltenberg, and McCabe (913), who found that a hot-rolled rod having a proportional limit of 36,000 lbs./in.^{2} withstood approximately 60,000,000 alternations of tension and compression in the rotating beam machine. Apparently the proportional limit of Monel metal may be regarded as an approximate safe limit for fatigue stresses.

The effect of temperature on the tensile properties of Monel metal has been studied by Bregowsky and Spring (420), whose results are given in Table 31. Results obtained by the International Nickel Co. on hot-rolled Monel metal rod are given in Table 16 (p. 39).

TABLE 31.—Tensile Properties of Monel Metal and 30 per cent Nickel Steel at Various Temperatures. (Bregowsky and Spring, 420.)

Temperature.		Rolled Monel metal.				Rolled 30 per cent nickel steel.			
°C.	°F.	Tensile strength.	Elastic limit.	Elongation in 2 inches.	Reduction in area.	Tensile strength.	Elastic limit.	Elongation in 2 inches.	Reduction in area.
		Lbs./in.^{2}	Lbs./in.^{2}	Per cent.	Per cent.	Lbs./in.^{2}	Lbs./in.^{2}	Per cent.	Per cent.
21	70	104,900	78,350	31.3	61.7	94,498	39,850	51.2	59.8
149	300	97,400	58,500	29.7	57.8	97,000	37,100	64.1	65.0
233	451	97,800	58,690	29.7	51.0	84,950	32,250	62.5	65.0
275	527	96,400	58,400	32.8	59.5	83,000	26,200	59.4	66.8
317	603	89,600	57,950	32.8	59.5	69,575	25,650	56.3	72.6
399	750	67,600	42,550	28.1	58.1	45,650	21,100	43.0	59.0
510	950	....	....	....	....	....	....	....	....
555	1,031	47,200	26,800	28.1	60.7	36,350	15,500	37.5	55.7

Webster (935) has studied the effect of cold-rolling on the tensile properties of Monel metal with the following results:

TABLE 32.—Effect of Cold-Rolling on Tensile Properties of Monel Metal.

Material.	Tensile strength.	Elongation in 4 inches.	Reduction of area.
	Lbs./in.^{2}	Per cent.	Per cent.
Annealed Monel	79,000	26	35
Same after 20 per cent reduction	102,000	4	22
Same after 40 per cent reduction	118,000	3	18
Same after 60 per cent reduction	132,000	2	17

Waltenberg (922) has carried out impact tests on hot-rolled Monel metal rod, using both the Izod and the Charpy machines, and reports that it requires from 100 to 200 foot-pounds in the Charpy machine to rupture the standard test piece (10 mm square with a 45° V-notch 2 mm deep, fillet of 0.25 mm radius). It was not possible to rupture the test piece in the Izod machine.

Only 50 to 100 foot-pounds (Charpy machine) are required to break specimens of heat-treated alloy steels.

(c) APPLICATIONS, RESISTANCE TO CORROSION.

The principal properties of this metal which render it of commercial value are the following: Resistance to corrosion, the bright nickel finish which it takes and retains, its strength and hardness, particularly at high temperatures, and its resistance to erosion by water and steam.

Monel metal is not appreciably attacked by dry gaseous or liquid ammonia, dilute or concentrated ammonium hydroxide solutions (intermediate concentrations attack it slightly), fused caustic alkalis or carbonates or their aqueous solutions, fatty and many other organic acids, sea water, solutions of many neutral salts (including sulphates and chlorides), gasoline and other mineral oils, phenol and cresols, photographic chemicals (except silver-bearing solutions), urine, or dry mercury when left in quiet contact with it. (It has been found possible to effect an amalgamation by rubbing briskly the mercury into the Monel metal surface. Mercury will amalgamate with Monel metal in the presence of small amounts of acid and also apparently under the influence of pressure.) It is not affected by dyeing solutions (except diazotizing solutions), bleaching solutions, and alcoholic and other beverages. It resists well the action of sulphuric, dilute phosphoric, hydrocyanic, hydrofluoric, acetic, and citric acids, fused cyanides, ferrous sulphate, and dry chlorine. It is not resistant to the action of hydrochloric or nitric acid, molten lead or zinc, sulphurous acid, ferric chloride, or chromic acid.

Monel metal sheet showed the following losses in weight upon exposure to the action of boiling acetic acid for eight hours.

Strength of acid (per cent).	Loss in weight per 100 cm^2 per hour, in milligrams.
10	1.09
26	1.24
56	1.71
90	1.86

It lost 1.18 mg/100 cm^2 per day during eight months' exposure to cold glacial acetic acid.

Because of its relative incorrodibility it has been used to some extent for roofing material. The roof of the Pennsylvania Terminal in New York, N. Y., is covered with Monel sheet, which material was selected because of its superiority over other roofing materials as demonstrated in a 10-year test. It is for the same reason used for window screens.

Both rods and castings are used to a large extent in the manufacture of pumps; e. g., in pump liners, rods, and valves, for handling sea water, mine waters, and acid and alkaline corrosive solutions.

One of the principal applications of the metal is in the construction of pickling tanks and crates for pickling steel; rods are used for this purpose and have apparently proved superior to any other material. In this connection the results of corrosion tests of Monel metal rod in pickling acid are of interest. The rate of corrosion of hot-rolled Monel metal in 6 per cent air-free sulphuric acid solution at 82° C. (180° F.) is 139.5 mg/100 cm^2 per day and in air-saturated similar solutions 697.5 mg/100 cm^2 per day. Monel metal pickle pins and rods have been removed from service after eight years and found to show practically no evidence of corrosion. Experience has shown that the corrosion of Monel metal in pickling solutions is much more marked when it is subjected to intermittent immersion than when constantly submerged.

On account, also, of its resistance to corrosion it is used in the construction of mining machinery, mine screens, dyeing machinery and equipment, and in the chemical and oil industries for miscellaneous parts exposed to severely corrosive conditions. Monel metal is made up into screen of various types and into filter cloth used in the chemical industry for filtering corrosive liquids.

Monel metal takes and retains a finish almost identical with that of pure nickel and is for this reason much used for small fittings, trimmings, and stampings, for golf-club heads, and for knives.

This property, in conjunction with its resistance to corrosion by substances used in preparation of foods and in washing, have made it valuable for the construction of certain cooking utensils, for kitchen and cafeteria trim, for laundry and dairy machinery, etc.

The resistance of the alloy to steam erosion and its strength at high temperatures, which is apparently higher than that of the steels or bronzes, have caused its extensive application in the production of steam-pressure valves and steam-turbine blading. For these purposes it is well suited also by reason of the fact that its thermal expansivity is approximately equal to that of steel with which it is usually associated in such construction.

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Marine propellers have been cast of Monel metal. In connection with its quite widespread use in naval construction it may be recalled that the steam yacht *Sea Call* was covered with Monel sheathing. In this particular case this metal was unsatisfactory for the reason that the galvanic action between it and the exposed steel bolts of the hull caused accelerated corrosion of the latter. It is obvious that construction which involves Monel metal and steel in galvanic contact when exposed to the action of an electrolyte, such as sea water or other aqueous solutions, must be avoided; the entire construction should be of Monel metal.

Monel metal is remarkably resistant to oxidation at temperatures up to 750° C. (1,382° F.) and is therefore used for electrical resistance and spark-plug wire and other parts exposed to high temperatures. It is, however, not recommended for use above 800° C. (1,472° F.); nickel has been found to be much superior for these higher temperatures.

(*d*) FABRICATION.[3]

MACHINING.—In machining properties Monel metal resembles copper, nonleaded brass, and alloy steels in that a tough chip is produced, necessitating some changes from machining practice with steel and cast iron in order to obtain the best results.

Cutting tools for Monel metal should be made from high-grade, high-speed steel and ground with sharper cutting angles than are used ordinarily on steel. A lathe tool with a 13° clearance, 20° top rake, 9° side slope, or one with a 6° clearance, 8° top rake, and 14° side slope will work well with a $\frac{1}{8}$-inch cut and $\frac{1}{32}$-inch feed at a speed of 50 to 60 linear feet per minute. It is advisable to provide proper lubrication in all Monel metal machining operations, although the metal may be readily machined dry on the lathe.

The same general considerations apply to drilling, milling, tapping, and reaming. The metal is worked quite extensively in automatic machines in the production of screws, bolts, and similar products.

WELDING.—Monel metal may be welded by the oxyacetylene, the metallic or carbon arc welding, or by the resistance welding methods, although certain precautions are advisable in order to produce sound and ductile welds by the two former methods.

[3] The International Nickel Co. will forward on request detailed instruction sheets covering practice in fabricating Monel metal by forging, machining, drawing, stamping, welding, etc.

In using the oxyacetylene process the flame should be slightly reducing and the torch tip one or two sizes larger than for steel of same size. No flux is usually necessary, but the work should be well cleaned from scale and oxide, and care should be taken to use bright, clean welding rod and to avoid oxidizing the weld. The welds should be built up well above the surface and completed in one spot before starting in another; that is, the weld should not be built up in horizontal layers.

Welded nickel and Monel metal tubes are being manufactured from sheet by the oxyacetylene process.

The metallic arc welding of Monel metal follows steel practice, with two important modifications. To secure the best results—that is, a sound and ductile weld—it is desirable to coat the Monel metal welding rod with a powdered deoxidizer; for example, an alloy of the following composition:

	Per cent.
Magnesium	14–16
Manganese	27–33
Silicon	45–50

and to reverse the polarity; that is, make the welding rod positive. Details for producing sound welds by this method are given by Merica and Schoener (964).

Welds made in ¼-inch Monel plate by either the oxyacetylene or metallic arc method will average 45,000 lbs./in.^{2} tensile strength and 90 per cent elongation in 2 inches over the weld. They can be bent 90° before cracking.

The Wilson Welder and Metals Co. (Inc.) have recently put on the market a Monel metal welding rod (their grade No. 12), which they recommend for arc-welding gray cast-iron parts. They state that the coefficient of expansion of this welding metal or filler closely approximates that of gray cast iron, thus reducing the cracking which usually accompanies the welding of cast iron. They claim that they and a large number of users have been uniformly successful in producing a homogeneous and readily machinable weld in gray cast iron.

The resistance welding of Monel metal by the spot or butt method is entirely similar to that of steel. The metal may be welded to copper or steel by this process.

Soldering and Brazing.—The soldering and brazing of Monel metal is carried out in the same manner as for copper; it is best, in soldering, to tin the surfaces before making the joint.

Mechanical Working.—The practice in working Monel metal by drop forging, drawing, spinning, stamping, and polishing is so similar to that of steel that no further comment is necessary. The manufacturers supply detailed instructions regarding these operations.

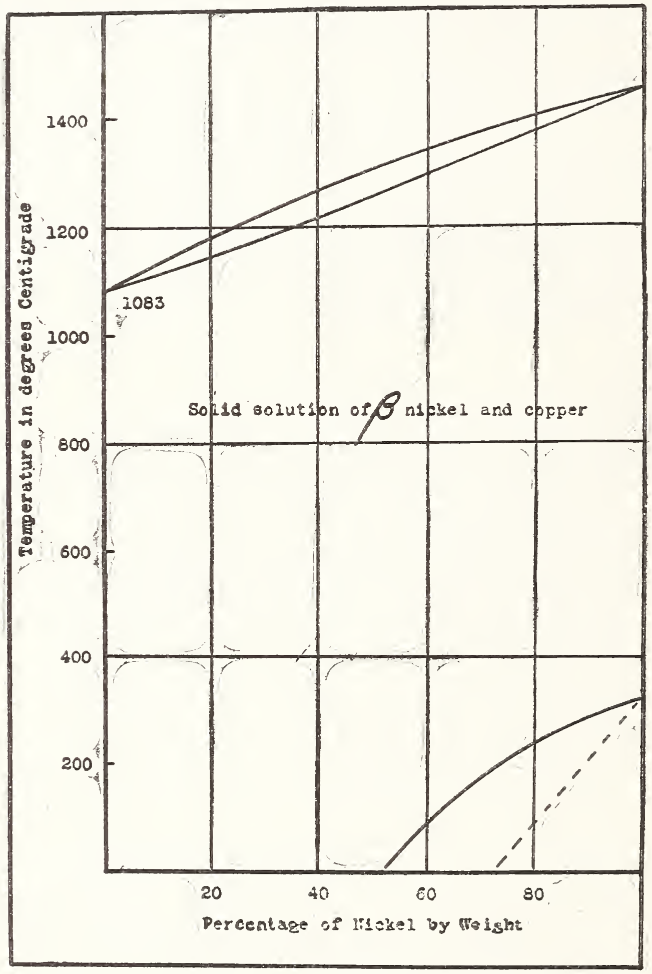

Fig. 18.—*Equilibrium diagram of copper-nickel alloys according to Guertler (595).*

2. COPPER-NICKEL ALLOYS.

These are undoubtedly among the earliest alloys of any sort known to man. Thus Muspratt [4] mentions Bactrian coins containing 77 to 78 per cent copper and 22 to 23 per cent nickel dating from 235 B. C.; this composition is almost identical with

[4] Chemie, 6, p. 1195; 1898.

our present nickel coinage alloy. In spite of their antiquity the pure copper-nickel alloys have not, perhaps, come into the commercial prominence which their unusual properties should give them, although the late World War, with its large requirements of these alloys for bullet jackets and driving bands, has served to stimulate interest in them.

Nickel and copper form solid solutions in all proportions, as may be seen from Figure 18, which gives the equilibrium diagram of this binary series. In conformity with this type of equilibrium the physical properties of the alloys vary continuously with compo-

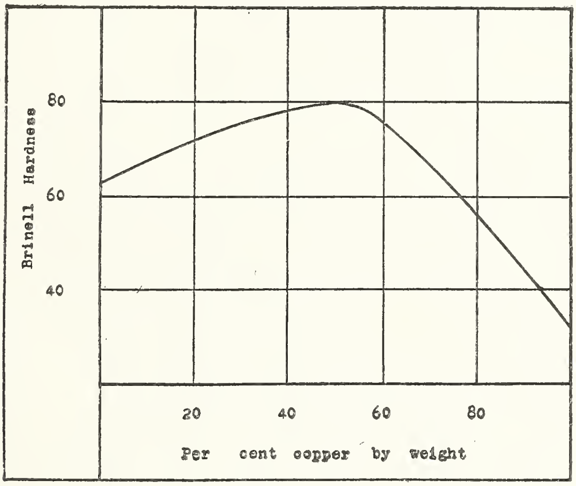

FIG. 19.—*The hardness of copper-nickel alloys according to Kurnakoff and Rapke (674). Rolled and annealed samples; 10 mm ball, 500 kg load.*

sition, maximum and minimum values being encountered within the series. Figures 20 and 21 show the variation of electrical resistivity, its temperature coefficient, and the thermoelectromotive force with composition of copper-nickel alloys.

Throughout the entire range of composition the alloys are ductile and malleable. Their tensile strength and hardness reach a maximum in the neighborhood of 50 per cent of copper; the hardness is shown in Figure 19. Table 33 gives typical values of the tensile properties for commercial compositions of copper-nickel alloys in different forms. In Table 16 there are given some results of tensile tests made by the International Nickel Co. on 20 per cent cupronickel at elevated temperatures.

Baucke (676) has shown that small amounts of nickel increase the toughness of copper as indicated by the notch-bar impact test. He obtains the following results on forged and annealed test bars:

	Specific impact work in kilogram-meters.
Electrolytic copper	14.1
0.17 per cent nickel	20.0
.31 per cent nickel	22.0
1.52 per cent nickel	28.0

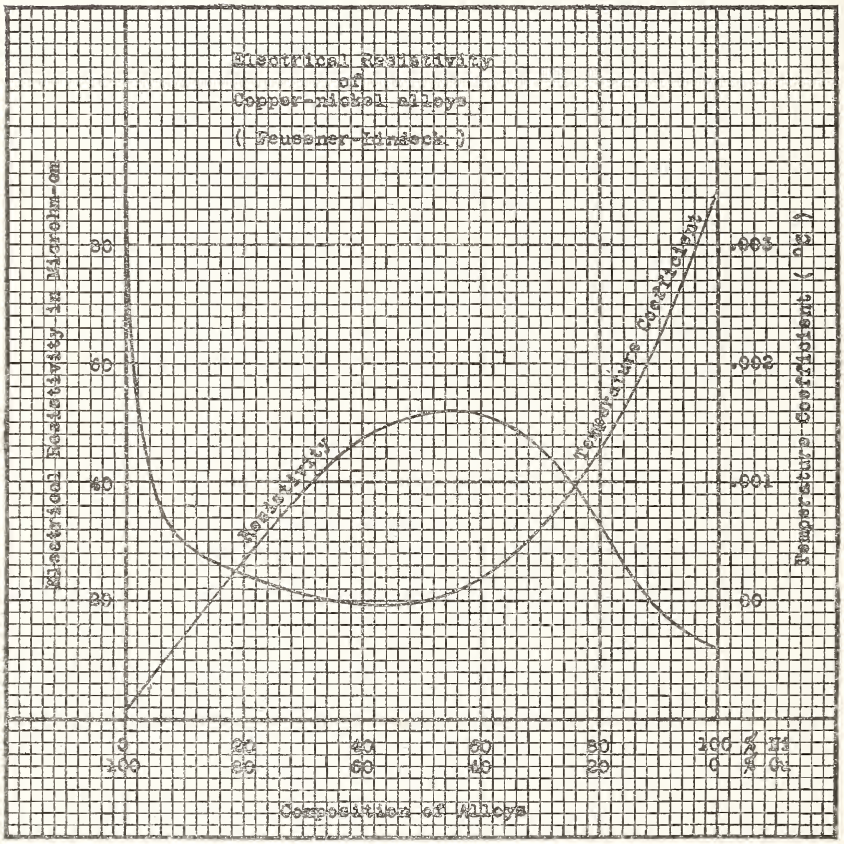

FIG. 20.—*The electrical resistivity of copper-nickel alloys according to Feussner and Lindeck (697).*

Even in small amounts nickel decolorizes copper (and its alpha alloys). Thus bullet-jacket stock containing 15 per cent of nickel is practically white when freshly cut or polished.

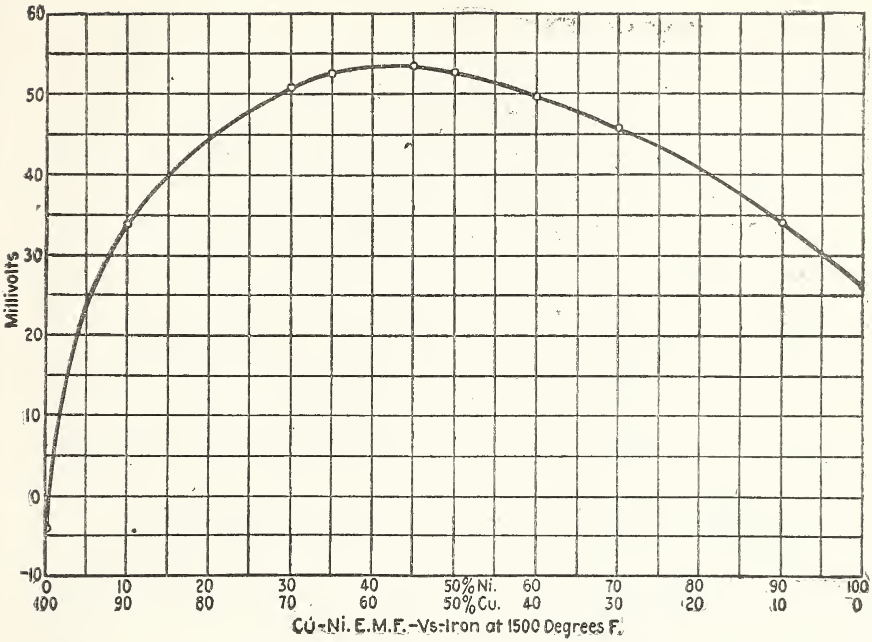

FIG. 21.—*The thermoelectromotive force of copper-nickel alloys toward iron; Bash (1250).*

TABLE 33.—Typical Values of the Mechanical Properties of Commercial Cupronickel Compositions.

Chemical composition.		Form.	Yield point.	Tensile strength.	Elongation.
Ni	Cu				
Per cent.	Per cent.		Lbs./in.²	Lbs./in.²	Per cent.
2	98	Tubes, soft [1]	....	39,200	44
2	98	Tubes, hard [1]	....	63,500	5.5
5	95	Sheet, soft [1]	....	39,200	50
5	95	Sheet, hard [1]	....	67,500	4
20	80	Sheet, soft [1]	....	47,200	35
20	80	Sheet, hard [1]	....	90,000	4
25	75	Sheet, soft [1]	....	60,500	31
2.5	97.50	Driving band [2]	14,340	31,770	69.6
2.5	97.50	Wire (0.08 inch diameter), hard [2]	....	72,150	1.6
10	90	Strip, annealed [2]	....	48,450	[3] 28.4
15	85	Strip, hard [2]	....	71,000	[3] 3
15	85	Strip, annealed [2]	....	47,000	[3] 28
20	80	5/8-inch rod, hard [2]	57,800	61,500	[3] 14.8
20	80	5/8-inch rod, annealed [2]	18,000	47,600	[3] 40
25	75	5/8-inch rod, hard [2]	58,000	64,000	[3] 17
25	75	5/8-inch rod, annealed [2]	21,000	51,600	[3] 39
40	60	1/8-inch rod, annealed [2]	....	69,400	[3] 28

[1] Values quoted by Hiorns (682).
[2] Values supplied by an American manufacturer.
[3] Elongation in 2 inches.

The alloys containing less than 60 per cent of nickel are not perceptibly magnetic, but above that percentage of nickel the magnetism of the alloys may readily be detected with a small magnet. Gans and Fonseca (653) have determined by the magnetic method the transformation points of copper-nickel alloys ranging in nickel content from 35 to 65 per cent.

There are several compositions of copper-nickel alloys now in common commercial use. The most prominent ones are the following: (1) Two and one-half per cent (2.5 per cent of nickel) cupronickel for driving bands of shells. (2) Fifteen per cent cupronickel, used largely for bullet jackets and by the United States Navy for condenser tubes and feed-water heaters, containing from 14 to 16 per cent of nickel. (3) Nickel-bronze, or coinage bronze, used for baser currency and containing 25 per cent of nickel. (4) Copper-nickel, containing 50 per cent of nickel, used for remelting in the manufacture of nickel-copper alloys. (5) Constantan, used as one element in the construction of thermocouple pyrometers and also as electrical-resistance wire, containing 45 per cent of nickel. (See pp. 72 and 97.)

Of these perhaps the most interesting, in view of its large use during the war, is the bullet-jacket composition commonly known as cupronickel. This alloy is generally made by melting copper in crucibles, together with shot or electrolytic nickel, following the practice in melting brass and bronze. The metal has a strong affinity for gases and oxygen and before casting is usually deoxidized with from 0.5 to 1.0 per cent of cupromanganese in order to secure a sound ingot. It may also be readily deoxidized with magnesium. These ingots are cold-rolled to the size required and annealed at about 700° C. Blazey (649a) recently investigated several factors relating to the melting practice for 20 per cent cupronickel and their effects upon the composition and physical properties of the resulting product. The following are some of his conclusions: Continuous remelting of the same metal in ingot form results in a considerable increase in the percentage of iron, sulphur, silicon, and carbon. If the unmelted metal is exposed to furnace gases, the melting down of bulky light scrap produces in the resulting melt a marked decrease in the carbon and silicon content and a smaller one in the iron and manganese content. Heating the melt to temperatures well above its melting point increases the carbon content. All strips made from this alloy may be successfully annealed under proper regulation of temperature and duration of annealing without suffering deterioration; a very rapid deterioration may result by annealing at a high temperature, such as 1,000° C. This deterioration is a function of carbon content, temperature, and duration of anneal and coincides with and is apparently due to the precipitation of graphite. An absence of manganese in the alloy is concomitant with very rapid and severe deterioration.

A striking property of this composition is its great malleability, as evidenced by the fact that an ingot 1.5 inches thick may be cold-rolled to 0.040 inch, or thinner, without intermediate annealing. Webster (935) has determined the effect of cold reductions upon the tensile properties of cupronickel.

TABLE 34.—Effect of Cold-Rolling Upon the Tensile Properties of Cupronickel.

Reduction in cross section, per cent.	Tensile strength.	Elongation in 4 inches.	Reduction of area.
	Lbs./in.^{2}	Per cent.	Per cent.
Annealed	50,000	28	63
20	60,000	5	58
40	70,000	3	56
60	80,000	2	53

A typical analysis and tensile test of this metal are the following:

Copper (per cent)	85.16
Iron (per cent)	.23
Manganese (per cent)	.11
Carbon (per cent)	.029
Nickel (per cent, by difference)	14.47
Tensile strength after cold-rolling to 0.040 inch and annealing (in pounds per square inch)	46,900
Yield point (in pounds per square inch)	22,300
Elongation in 2 inches (per cent)	35.4

Alloys of this composition are also quite resistant to corrosion and are therefore in wide use as "Benedict metal" for condenser tubes. The following values of the tensile properties are typical for this material in the form of tubes.

TABLE 35.—Tensile Properties of Benedict Metal Tubes.

Outside diameter.	Wall thickness.	Tensile strength.	Elongation in 10 inches.	Remarks.
Inch.	Inch.	Lbs./in.^{2}	Per cent.	
0.517	0.038	43,080	39.0	Annealed.
.516	.036	51,520	8.1	Light drawn.
.750	.047	60,300	[1] 4.2	Medium drawn.
.750	.047	75,800	[1] 2.0	Hard drawn.

[1] In 8 inches.

Bengough (677) has studied the effect of high temperatures on the tensile properties of a 20 per cent copper-nickel alloy.

This metal is subject to a curious type of intercrystalline brittleness, at present insufficiently understood. After annealing it frequently is so brittle that it will bend only a few degrees. Under the microscope it presents the appearance shown in Figure 23, whereas normal annealed cupronickel has a structure shown in Figure 22, consisting of an aggregate of grains of copper-nickel solid solution. The intercrystalline appearance in the embrittled metal is rather similar to that which occurs on "burning" nickel and Monel metal as described above. By some (see Thompson and Barclay, 659) this brittleness is considered as being associated with the precipitation of graphitic carbon, and on this account manufacturers of this metal aim to keep the percentage of total carbon below about 0.04 per cent.

Rawdon and Lorentz (142) have found that either an acidified solution of ferric chloride (10 g $FeCl_3$, 30 cc HCl of sp. gr. 1.19 and 120 cc water) or a nitric acid-acetic acid mixture (50 per cent by volume HNO_3 of sp. gr. 1.42, 25 per cent glacial acetic acid and 25 per cent water) gives good results as an etching reagent for cast and cold-rolled cupronickel. Electrolytic etching in an aqueous citric acid solution may, according to Adcock (652), also be satisfactorily employed on this material.

The cupronickel alloys are found not to be subject to corrosion or season cracking as are the brasses, bronzes, and also the nickel silver alloys.

The composition used for "nickel" coinage—that is, containing 25 per cent of nickel—is a very old one. This material has essentially the color of pure nickel, is hard and resistant to abrasion and corrosion; being softer than pure nickel it is not so difficult to stamp as is the latter. It is manufactured in much the same manner as cupronickel.

The alloy Constantan, containing 55 to 60 per cent copper and which is also sold under a number of trade names (see Table 52), is chiefly used for pyrometer and electrical-resistance wire. It is generally made in an open-hearth furnace and cast into ingots which are first hot-rolled to wire rod and then cold-drawn with intermediate annealing into wire. It may be rolled at the temperatures (1,175 to 1,200° C., 2,147 to 2,192° F.) used for Monel metal and annealed at a slightly lower temperature; that is, 850° C. (1,562° F.). The tensile properties of copper-nickel

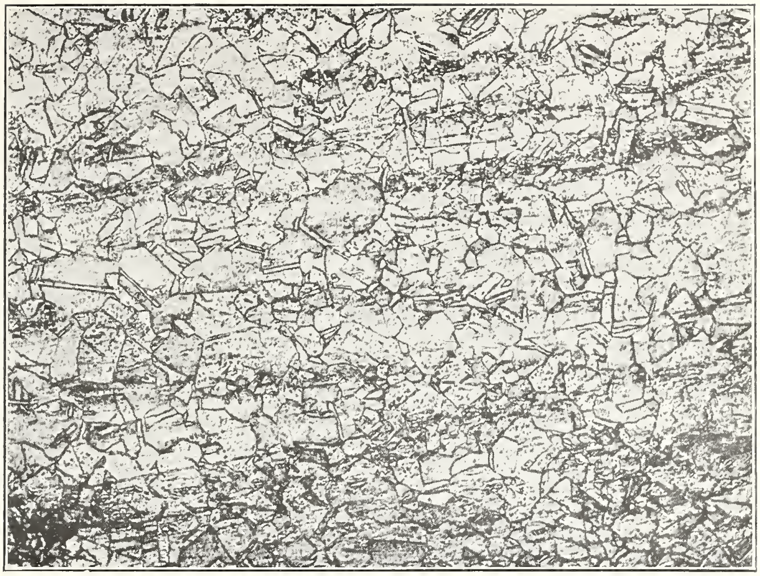

FIG. 22.—*Microstructure of normal annealed cupronickel sheet. Etched with 20 per cent nitric acid, 40 per cent acetic acid, 40 per cent acetone.* ×150

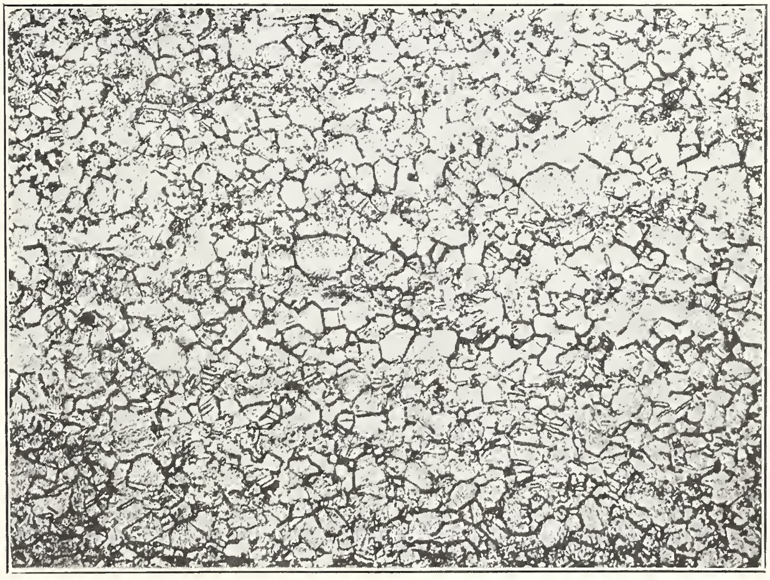

FIG. 23.—*Microstructure of brittle cupronickel sheet showing intercrystalline alteration. Etched in the same manner as Fig. 22.* ×150

alloys containing approximately 45 per cent of nickel will average as follows:

TABLE 36.—Tensile Properties of the 45 per cent Copper-Nickel Alloys.

Tensile property.	¼-inch hot-rolled wire rod.	Annealed wire.	Hard-drawn wire.
Tensile strength (pounds per square inch)	65,000–85,000	60,000–65,000	110,000–140,000
Elongation in 2 inches (per cent)	25–40	....	....

The values of the electrical properties of these compositions are given in Table 52.

3. COPPER-NICKEL-ZINC ALLOYS; NICKEL SILVER (NICKELENE).[5]

This series of alloys is also of very old origin, having been known in China under the name of packfong, or white copper. The most common name for them at one time was German silver, but since the World War the trade has accustomed itself to the term "nickel silver." The compositions of this series of alloys which are in commercial use are quite numerous; they will vary usually within the following limits:

	Per cent.
Copper	52–80
Zinc	10–35
Nickel	5–30

Nickel silver is marketed in several grades, depending chiefly on the nickel content, high-grade alloys containing about 20 per cent and low-grade ones less than 10 per cent. Abroad these are called firsts, seconds, thirds, fifths, etc., but in this country are named according to their nickel content. An idea of the various names which have been given to these alloys may be obtained from Table 37. The very extensive list of alloys compiled by Dr. William Campbell and published in the Proceedings of the American Society for Testing Materials, volume 22, Part I—Committee Reports, page 213 (1922), should be consulted for further information.

[5] The name "nickelene" was suggested a few years ago by the nonferrous nomenclature committee of the American Society for Testing Materials.

TABLE 37.—Names and Compositions of Some Nickel Silvers.

Alloy.	Percentages of chief components.			Percentages of other components.
	Cu	Ni	Zn	
Alfenide	50–70	10–20	5–30	
Alpakka	65.2	13	19.5	Ag 2.
Ambrac	74.5	20	5	Mn 0.5.
Argentan	40–65	15–30	17–32	
Argentan solder	35	8	57	
Argozie	54	14	28	Pb 2. Castings.
Argozoil	54	14	28	Sn 2, Pb 2. Ornamental casting.
Arguzoid	55.78	13.45	23.2	Sn 4.03, Pb 3.54.
Argyrolith	50–70	10–20	5–30	
Bismuth brass	47	31	21	Pb 0.1, Bi 0.1.
Bismuth bronze	53	10	20	Al 1, Sn 15, Bi 1.
Do	45	32.5	21.5	Sn 16, Bi 1.
Carbondale silver	66	18	16	
China silver	50–70	10–20	5–30	
Chromax bronze	66.7	15.2	12.1	Al 3, Cr 3. Can be rolled. Tensile strength 79,000 lbs./in.^{2}; 3 per cent elongation.
Colorado silver	57	25	18	
Craig gold	80	10	10	
Electroplate	50–70	10–20	5–30	
Electrum	51.5	26	22.5	
German silvers:				
Birmingham	....	....	....	(From Hiorns.)
Extra white metal	50	30	20	
White metal	54	24	22	
Arguzoid	48.5	20.5	31	
Best best	50	21	29	
Firsts or bests	56	16	28	
Special firsts	56	17	27	
Seconds	62	14	24	
Thirds	56	12	32	
Special thirds	56.5	11	32.5	
Fourths	55	10	35	
Fifths, for plated goods	57	7	36	
Keene's alloy	75	16	2.25	Fe 1.5, Sn 2.8, Co 2, Al 0.5.
Lutecin	80	16	5	Fe 5, Sn 2, Co 1.
Maillechort [1]	66.2	16.4	13.4	Pb 0.15, Fe 3.2, Sn 0.22. French analysis.
Markus alloy	....	....	....	
Neogen	58	12	27	Sn 2, Al 0.5, Bi 0.5.
Nevada silver	....	....	....	
New silver	....	....	....	
Nickel bronze	60	20	12	Sn 8.
Nickelin	68–55	31–32	0–13	For resistance wire.
Do	74.5	25	....	Fe 0.5.
Nickel Oreide	66–87	5–10	0.10	
Platinoid	54.04	24.77	20.42	Fe 0.5, Mn 0.5.
Do	60	14	24	W 1–2.
Popes Island metal [1]	70	14	15	
Potosi silver	....	....	....	
Ruolz alloys	....	....	....	
Spoon metal	....	....	....	
Silveroid	....	....	....	
Silverite	....	....	....	
Silverine	71–80	16–17	1–8	Fe 1–1.5, Sn 1–2.75, Co 1–2.
Sterlin	68.5	17.88	12.84	Pb 0.76.
Sterline	68	17–18	13–14	Fe 0.5–0.75.
Stuffing-box alloy	61.5	15.5	11	Pb 10, Sn 2. For turbines.
Suhl white copper	40.4	31.6	25.4	Sn 2.6.
Toucas metal	35.7	28.6	7.14	Fe 7.14, Pb 7.14, Sn 7.14, Sb 7.14. Ornamental work.
Tuc Tur	63.02	14.27	22.41	Fe 0.28. Cold-rolled 3/4-inch rod.
Tutenag	45.7	17.3	37	
Tungsten brass	....	....	....	See Wolfram brass.
Victor metal	49.94	15.4	34.27	Fe 0.28, Al 0.11.
Virginia silver	....	....	....	
Weiss Kupfer	....	....	....	
Wessels silver	51–65	19–32	12–17	Ag 2, Fe 0.5.
White copper	....	....	....	
White metal	....	....	....	
White solder	45	10	45	Soldering.
Wolfram brass	60	14	22	W 4.

[1] French generic name for this type of alloy; analysis given is of particular sample and is not necessarily general.

The nickel silvers are largely used as substitutes for silver and as the base metal for plated silverware of all sorts, their suitability for both purposes being due to the fact that their color is very similar to that of silver. They are on the market in the usual commercial forms—sheet, strip, tubes, rods, and wire. They are used in the production of a large number of ornamental and other fittings and stampings for which an attractive finish and resistance to corrosion is desired and also in the form of wire for small springs and for electrical purposes (see p. 98). Their color varies from a nearly white, nickel color with the higher percentages of nickel to a yellowish-white color in the alloys of lower nickel content.

The compositions of nickel silver used for any specific purpose are quite variable; there are given below in Table 38 both typical compositions and ranges of compositions for different classes of service. It will be noted that lead is added when ready machinability is desired (key stock); it is kept out, however, in material which is to be spun or drawn, as it diminishes the ductility of the alloy.

TABLE 38.—Percentage Compositions of Nickel Silver in Commercial Use.

Material.	Nickel.	Copper.	Zinc.	Lead.
Cutlery and knife stock	15–25	55–65	14–20	Fe 0.5–1.5
Key stock	8–18	55–65	15–35	1–2
Jewelers' wire	5–25	53–63	25–32	....
Brazing solder	8–20	35–40	40–55	....
Watchcase metal	10–28	55–65	16–30	0–1
Spoon and fork stock	10–20	57–66	20–30	....
Platers' bars and cores	5–25	56–70	18–24	....
TYPICAL COMPOSITIONS USED IN AMERICAN MANUFACTURED PRODUCTS.				
30 per cent	30	46.67	23.33	....
25 per cent	25	50	25	....
Spoon stock	20	60	20	....
20 per cent	20	53.33	26.67	....
Spoon stock	18	65	17	....
18 per cent	18	72	10	....
Bolster silver	18	65.50	16	0.50
Spring silver	18	54.67	27.33	....
Spinning silver	17.50	67	15.50	....
Spinning silver	16	67	17	....
Bolster silver	16	56	28	....
15 per cent	15	60	25	....
15 per cent	15	56.67	28.33	....
12 per cent	12	58.67	29.33	....
Spinning silver	12	66	22	....
Key stock	12	60	26	2.0
Key stock	12	65	22	1.0
10 per cent	10	62	28	....
10 per cent	10	60	30	....
8 per cent	8	61.33	30.67	....
5 per cent	5	72	23	....
5 per cent	5	63.33	31.67	....

Results of analyses of two typical compositions of nickel silver follow:

TABLE 39.—Typical Compositions of Nickel Silver.

Metal.	No. 1.	No. 2.
	Per cent.	Per cent.
Copper	63.03	63.39
Lead	None.	None.
Iron	.12	.13
Manganese	.037	....
Nickel	16.69	18.37
Zinc	Remainder.	17.98

The alloys are produced by melting copper together with nickel silver scrap in graphite crucibles, adding the nickel and zinc, deoxidizing with from one-fourth to one-half of 1 per cent of cupromanganese and pouring into ingots, which are cold-rolled, with annealing and pickling, into the sheet or strip required, or are drawn into wire. The presence of zinc renders this alloy much easier to cast in a sound condition than cupronickel. Annealing is carried out usually at 700° C. in a muffle furnace to exclude air.

Copper, zinc, and nickel in the proportions used in nickel silvers unite to form a solid solution; these alloys are therefore similar structurally to high and low brass or to copper-nickel alloys and consist of one (alpha) constituent only. They may be etched with ammonium hydroxide and hydrogen peroxide in the manner used for high brass.

An idea of the tensile properties of the copper-nickel-zinc alloys may be obtained from Table 40, which gives some typical values for commercial material.

TABLE 40.—Tensile Properties of Copper-Nickel-Zinc Alloys.

Form.	Tensile strength.	Elongation in 2 inches.	Percentage composition.		
			Nickel.	Copper.	Zinc.
	Lbs./in.^{2}	Per cent.			
Strip, hard	130,000	2	30	47	23
Strip, annealed	73,000	32	30	47	23
Strip, annealed	71,000	38	25	55	20
Strip, hard	94,000	2.5	18	64	18
Strip, annealed	58,000	33	18	64	18
Strip, hard	107,000	2	18	55	27
Strip, annealed	69,000	29	18	55	27
Strip, hard	92,000	4	10	62	28
Strip, annealed	63,000	48	10	62	28

TABLE 41.—Effect of Cold-Rolling and Annealing on the Tensile Properties and Hardness of Nickel Silver. (Price and Davidson 988.)

Alloy.	Chemical composition (percentages).						Properties of cold-rolled strip.[1]						Properties of annealed strip.				
	Cu	Ni	Pb	Fe	Mn	Zn	Yield point.[2]	Tensile strength.	Elongation in 2 inches.	Reduction of area.	Brinell hardness.[3]	Scleroscope hardness.[4]	Yield point.[2]	Tensile strength.	Elongation in 2 inches.	Reduction of area.	Scleroscope hardness.
							1,000 lbs./in.^{2}	1,000 lbs./in.^{2}	Per ct.	Per ct.			1,000 lbs./in.^{2}	1,000 lbs./in.^{2}	Per ct.	Per ct.	
A[5]	64.68	6.73	Trace.	0.194	0.06	Remainder	80–110	80–110	2–6	25–45	140–175	35–50	20–45	50–65	45–65	50–55	11–20
B[5]	65.82	6.17	1.27	.227	.06	do	80–110	80–110	2–7	18–45	155–175	35–50	20–40	50–65	45–55	50–60	12–20
C[6]	65.44	17.83	Trace.	.345	.03	do	85–100	85–100	2–4	25–45	160–175	30–45	25–45	55–65	30–40	40–50	13–20
D[6]	65.60	17.77	1.08	.238	.06	do	85–100	85–100	1–4	20–40	160–175	35–45	25–40	55–65	30–35	45–50	13–19

1 The minimum and maximum values are for reductions of 35 and 75 per cent, respectively.
2 Load producing a permanent set of 0.001 inch in 2 inches.
3 10 mm ball, 500 kg.
4 Universal hammer.
5 The annealed values are for metal annealed at from 500–650° C. (932–1,202° F.) after cold reductions of from 20 to 60 per cent.
6 The annealed values are for metal annealed at from 600–750° C. (1,112–1,382° F.) after cold reductions of from 20 to 60 per cent.

In Table 41 are given in condensed form some data taken from an article by Price and Davidson (988) on the effect of cold-rolling and annealing on nickel silver strip of different compositions. The reader is referred to the original for more detailed data. The material was annealed at temperatures from 350 to 835° C. (662 to 1,535° F.) following reductions in thickness of from 20 to 60 per cent by cold-rolling.

Thompson and Whitehead (980) have recently studied the effect of heat treatment, particularly annealing, upon the mechanical properties of hard-rolled nickel silvers containing 10, 15, and 20 per cent nickel. A striking result of the investigation was the high temperatures at which the alloys can be heated without suffering deterioration, especially when the metal is protected from oxidation by furnace gases. The Erichsen test values were remarkably good, even after annealing at as high as 850° C. The best annealing ranges were determined as follows:

10 per cent Ni alloy .... 725–825° C. (1,335–1,515° F).
15 per cent Ni alloy .... 700–800° C. (1,292–1,472° F.).
20 per cent Ni alloy .... 800° C. (1,472° F.).

The following tensile properties are typical of the best results obtained:

Per cent Ni.	Annealing temperature.	Maximum stress.	Elongation in 2 inches.	Reduction of area.
	°C.	Lbs./in.²	Per cent.	Per cent.
10	825	47,000	67	64
15	800	56,000	49	57
20	800	58,000	45	49

The experimental results showed that, as indicated by the Brinell hardness test, softening occurs to almost a complete degree within the first two hours of annealing; that annealing between 300 to 400° C. (572 to 752° F.) lowers the ductility to a much lower value than that obtained in the hard-rolled state; that quenching from the annealing temperature appears to produce no markedly beneficial effect; and that there is little to choose between annealing for a short time at a high temperature and annealing for a longer time at a low temperature.

The American Brass Co. has informed the bureau that their product "Ambrac" (typical chemical composition 75 per cent Cu, 20 per cent Ni, and 5 per cent Zn) has approximately the following tensile properties:

	Tensile strength.	Elongation.
	Lbs./in.^{2}	Per cent.
Large rods, annealed	50,000	50
Fine wire, hard drawn	145,000	1

They state that "Ambrac" has failed to show any indication of brittleness after being given an extreme amount of cold working as in making fine wire, and also that it shows no tendency to season-cracking when exposed to the weather, salt spray, and to corrosion and mercurous nitrate tests. "Ambrac" is claimed to give satisfaction in service where resistance to corrosion is an important factor, as in paper and laundry machinery, fly screens, etc.

Tuc Tur, an alloy having the typical composition—63 Cu, 15 Ni, and 22 Zn—may have approximately the following mechanical properties:[6]

	As cast.	Cold-rolled rod.	Cold-drawn rod.
Ultimate strength ......lbs./in.^{2}	45,000	82,500	80,500
Yield point ......do	19,000	81,500	77,000
Elongation ......per cent	31	27	15
Reduction of area ......do	32.5	52.5	58

Results of tests made at 700° F. (371° C.) gave the following results: Ultimate strength, 73,700 lbs./in.^{2}; yield point, 73,100 lbs./in.^{2}; elastic limit, 70,200 lbs./in.^{2}; elongation in 2 inches at point of rupture, 12.5 per cent; reduction of area, 41 per cent; modulus of elasticity, 19,900,000 lbs./in.^{2}

4. FERRONICKEL ALLOYS.

The alloys of nickel with iron, including nickel steels, are by far the commercially most important alloys of this metal, and the range of compositions used is a very wide one—from the alloys of low nickel content, the nickel steels, to those containing 30 per cent and more of nickel. These alloys were first discovered in the composition of meteorites and have since not ceased to interest and puzzle investigators because of the unusual properties of the alloys containing from 5 to 40 per cent of nickel.

Binary alloys of all compositions solidify as solid solutions which upon cooling suffer both phase and magnetic transformations of great scientific interest and technical importance. The

[6] These data were obtained from the booklet issued by the Tuc Tur Metal Corporation.

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constitution diagram of the alloys of nickel and iron is given in Figure 24. Without entering upon a detailed discussion of the constitution of these alloys for which further references (1032a, 1099) should be consulted, it is observed that the addition of nickel to iron and steel immediately depresses the temperature of both the A_2 and A_3 transformation and, in addition, increases the temperature difference of lag between Ac_2 and Ar_2; that is, the tem-

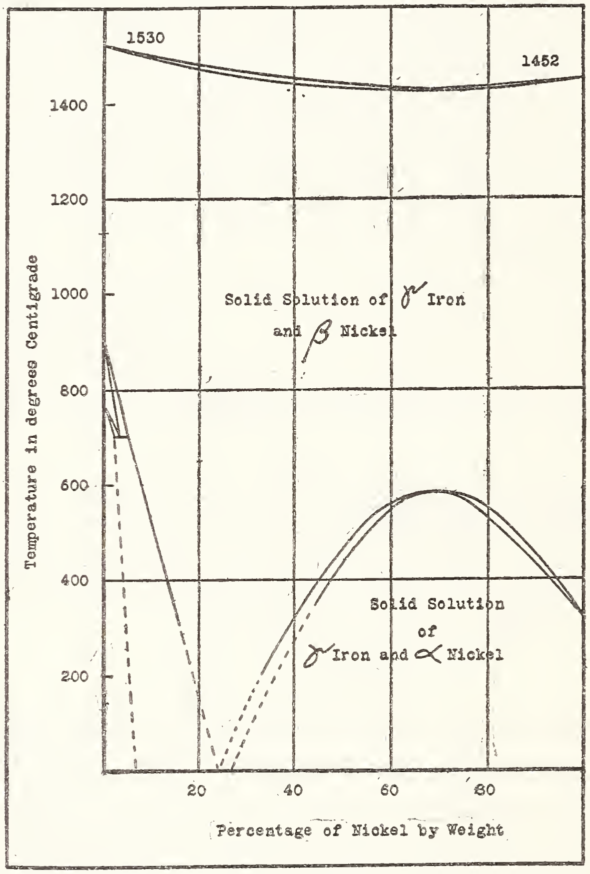


FIG. 24.—*Equilibrium diagram of iron-nickel alloys according to Guertler (595).*

peratures at which iron loses its magnetism upon heating and regains it upon cooling, respectively. This temperature range, between Ac_2 and Ar_2, within which the alloy may be either magnetic or nonmagnetic, depending on whether it has been heated or cooled to that range, is widened from practically zero for pure iron to about 500° C. for an alloy containing 25 per cent of nickel; at the same time the magnetic transformation range is lowered to ordinary temperatures and below. With increasing nickel content the temperature range of magnetic transformation again rises and becomes quite narrow; that is, there is little lag in the transformation on heating and cooling. Steels of the former group, containing from 3 to about 30 per cent nickel have become known as irreversible steels, whereas those of higher nickel content are called reversible ones. Accompanying these magnetic changes which characterize reversible and irreversible steels are corresponding ones in other properties, such as thermal expansivity, elasticity, electrical resistivity, the thermal alterations of which are also reversible or irreversible depending on the composition. It will be noted that within the range of approximately 5 to 25 per cent of nickel at ordinary temperatures nickel-iron alloys are not homogenous in phase, although this is not, in general, evident in microscopic examination. Meteorites often have a composition within this range and are prominently heterogeneous in structure (Kamacite and Taenite). The nonhomogeneous character of the alloys in this range has recently been confirmed by Bain (705a) by means of X ray analysis. Andrews (715) and McKeehan (708) have independently determined, in an X ray analysis of pure iron-nickel alloys, that with from 0 to 25 per cent nickel the structure is in the body-centered cubic arrangement, while with from 0 to 70 per cent iron it is in the face-centered cubic arrangement which is characteristic of pure nickel. In other words, nickel or iron can be substituted by amounts up to 25 per cent of iron or 70 per cent of nickel, respectively, without altering the original crystal structure, viz, the body-centered lattice of iron in the first case or the face-centered lattice of nickel in the latter case. It appears that within the 25–30 per cent nickel range either of the cubic arrangements or a mixture of both may occur. Andrews found no evidence of the existence of the compound, Fe_2Ni, containing 34.45 per cent nickel, which had been previously assumed by several investigators to be the cause of the above-noted anomalous behavior in the iron-nickel alloys. He did not find any indication of a change in structure in this range of nickel content that might throw light on the peculiar properties of invar (36 per cent nickel).

The presence of carbon causes further complications in the properties and behavior of these alloys and will be considered only in connection with the nickel steels of low nickel content.

Nickel in amounts from 1 to 5 per cent is being added to cast iron for special purposes, particularly rolls, automobile cylinders and pistons, bottle molds, and resistance grids. Its effect is to harden gray iron, which carries from 0.30 to 0.60 per cent combined carbon, by changing the pearlite into sorbite. At the same time it tends to aid graphitization and to prevent the mottling of the iron when poured into thin sections. In other words, it appears that the addition of nickel in the above amounts provides a method of increasing the hardness and strength of gray iron without impairing its machinability. The effect of nickel and chromium on cast iron, as is obtained by the use of Mayari pig iron, has been studied by Moldenke (1222b). He concluded that increasing percentages of nickel and chromium definitely increase the hardness. The increase is not large, but it shows that softer irons may be obtained with higher percentages of total carbon and that they can be kept strong enough by reducing the content of graphite and silicon. Nickel-chromium irons are now used in grinding plates for feed mills, flour machinery, stone crushers, piercing plugs and die bushings for projectile work, mill guides, wire-drawing dies, bending blocks, pipe balls, balls for tube mills, bottom plates for grinding mills, sand-blast nozzles, etc.

(a) NICKEL STEELS.

Nickel steel was the fourth alloy steel to be introduced and was first described in some detail by James Riley (1047). The general subject of nickel steels is too broad for anything but the merest mention in this place, and references should be consulted for further details.

The principal effects of the addition of nickel to steel are the following:

1. Nickel depresses the critical temperature ranges of steel, and according to the degree of such depression we may consider three groups of nickel steels—namely, pearlitic steels, which have normal transformation and heat treatment or critical ranges and are similar to ordinary carbon steels in a general sense; martensitic steels, self-hardening but too brittle to be of any importance commercially; and austenitic steels, which are not susceptible to hardening by thermal treatment, and may perhaps more properly be considered as ferronickel alloys containing carbon. The nickel and carbon content of the steel determine its inclusion in any one of the above groups. Figure 25 according to Guillet gives a classification of different compositions of nickel steels.

2. Nickel dissolves in the ferrite of steel and increases the hardness and strength without a corresponding loss of ductility. Thus, Bullens (1028) states that for forging grades of ordinary

nickel steels in the natural—that is, not heat treated—condition, the addition of each 1 per cent of nickel up to about 5 per cent will increase the tensile strength and elastic limit by from 4,000 to 6,000 lbs./in.² without loss of ductility.

3. Nickel exerts an influence on the grain size of ferrite and pearlite, tending to produce a finer grain structure and finer pearlite, shading into sorbite. In the same sense it diminishes the rate of grain growth within the heat treatment temperature ranges, and thus minimizes the danger of overheating during heat treatment.

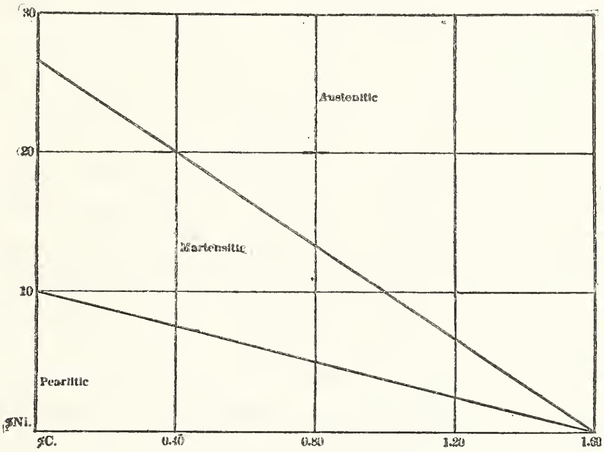


FIG. 25.—*Structural classification of nickel steels according to Guillet.*

The improvements to be attributed to these structural effects of nickel are manifold:

1. The presence of nickel in heat-treated steel, by refining both the pearlite grain and the structure of the pearlite itself, effects an increase in hardness, yield point, and tensile strength without loss of ductility; in other words, nickel increases the toughness of steel. This is evident from a consideration of the following comparative figures taken from the well-known data collected by the Society of Automotive Engineers.

TABLE 42.—Comparison of Tensile Properties of 0.40 per cent Carbon Steel With and Without 3.5 per cent Nickel.

Material.	Yield point.	Tensile strength.	Elongation in 2 inches.	Reduction of area.
	Lbs./in.^{2}	Lbs./in.^{2}	Per cent.	Per cent.
0 Ni; quenched 1,450° F. in water, drawn 1,300° F	53,000	90,000	25	62.5
3.5 Ni; quenched 1,400° F. in water, drawn 1,260° F	83,000	108,000	25	66
0 Ni; quenched 1,450° F. in water, drawn 940° F	86,000	123,000	20	51
3.5 Ni; quenched 1,400° F. in oil, drawn 935° F	107,000	124,000	20	57
0 Ni; quenched 1,450° F. in water, drawn 750° F	117,000	154,000	15	40
3.5 Ni; quenched 1,400° F. in oil, drawn 725° F	158,000	168,000	15	48

By retarding the rate of the chemical reaction of hardening its presence increases the penetration of the hardening zone.

2. The depression of the critical ranges allows the use of lower quenching temperatures for nickel steels in commercial heat treatments, and consequently less warpage is experienced and there is less wear and corrosion of heat-treating furnace linings.

3. The structural effects of nickel noted above make a nickel steel of low-carbon content, 0.10 to 0.20 per cent, invaluable for casehardening and superior to carbon steels in (*a*) uniformity of zone of carburization and (*b*) in mechanical properties of the core after heat treatment. The carburized case of nickel steels will harden well with an oil quench only.

The beneficial effects of nickel are intensified in some respect by the presence of other alloying elements, particularly chromium; nickel-chromium steels as well as straight nickel steels are widely used in the automotive industry to-day. Recent investigations made by Dawe (1020a) have indicated that molybdenum in amounts ranging from 0.25 to 0.40 per cent also improves the properties of nickel steel.

Burgess and Woodward (1022a) found that nickel steel containing 3 to 3.25 per cent nickel, 0.40 to 0.50 per cent carbon, 1 to 1.50 per cent silicon, and 0.60 to 0.80 per cent manganese and deoxidized with a simple deoxidizer, such as aluminum, can be produced, which in the heat-treated condition has a tensile strength of about 300,000 lbs./in.^{2}, and excellent ductility and toughness.

Nickel steels of the following compositions are most commonly used in commercial practice, particularly in the automotive industry. They are produced both in the open-hearth and in the electric furnace; nickel is not appreciably oxidized in the melting of nickel scrap in the former:

Three and one-half Per Cent Nickel Steel (S. A. E. 2300 Series).—This is the oldest and best known composition of nickel steel and still constitutes the bulk of the commercial production of nickel-bearing steels. The following table of compositions for the various grades, based mainly on the carbon content, is taken from the Society of Automotive Engineers' Handbook:

S. A. E. steel number.	Nickel.	Manganese.	Carbon.
	Per cent.	Per cent.	Per cent.
2315	3.25–3.75	0.30–0.60	0.10–0.20
2320		.50–.80	.15–.25
2330	3.25–3.75	.50–.80	.25–.35
2335			.30–.40
2340	3.25–3.75	.50–.80	.35–.45
2345			.40–.50
2350			.45–.55

This steel is used both in the heat treated and in the natural—that is, not heat treated—condition, and, in fact, is the principal alloy steel which is used commercially without heat treatment.

With about 0.30 to 0.40 per cent carbon it is used without heat treatment for structural purposes in bridge construction; that is, for eyebars, plates, shapes, and, with about 0.25 per cent carbon, for rivets. With slightly more carbon it has been used for rails, although its economic advantage for this purpose has not yet been demonstrated. In the cold-drawn condition (carbon about 0.30 per cent) it is also much used for bolts, studs, keys, etc., in automobile construction where heat treatment with the consequent scaling off of threads is undesirable. This steel is a standard one for heavy forgings to be heat treated, such as ordnance, engine, and locomotive forgings.

Steel having lower carbon contents, ranging from 0.10 to 0.25 per cent, is used for casehardened parts, particularly in automobile construction, such as pivot pins, steering ball joints, steering gear and worm, for ball rods, cam shafts, piston pins, valve tappets, gears, and pinions.

With from 0.25 to 0.40 per cent carbon it is used for stressed parts and forgings, such as rear axle shafts, jackshafts, front axle centers, connecting-rod forgings, steering knuckles and arms, crank shafts, etc. In the form of seamless tubing it is used for front axle tubes, propeller shaft tubes, rear axle housings, and frame torsion tubes.

With from 0.40 to 0.55 per cent carbon it is a standard material for heat-treated transmission gears requiring a scleroscope hardness as high as 70 to 80. At this hardness the steel still retains sufficient ductility to withstand successfully the clashing of teeth in sliding gear and at the same time is hard enough to resist the wear.

Table 43 and Figure 26 give the physical properties of some 3½ per cent nickel steels, according to chemical composition (see above table) and heat treatment.

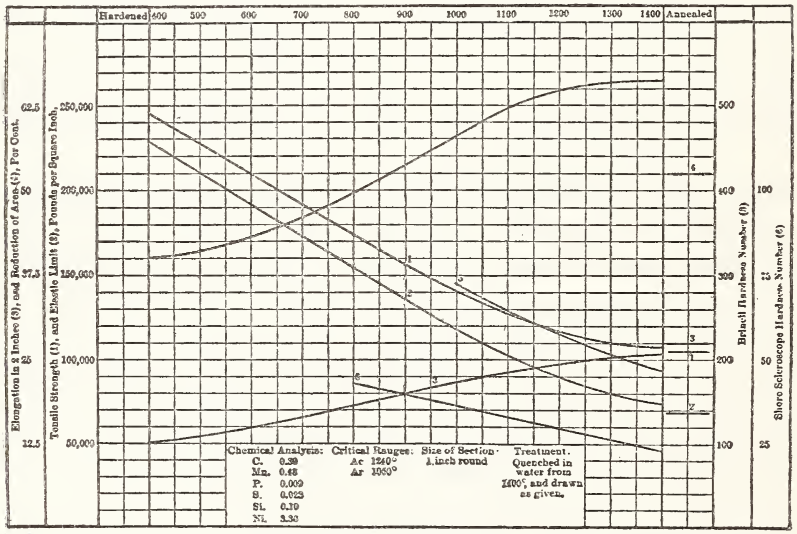


FIG. 26.—*Mechanical properties of 3½ per cent heat-treated nickel steel, Society of Automotive Engineers (Bullens, 1028).*

TABLE 43.—Range of Tensile Properties of Annealed and Heat-Treated 3 1/2 Per Cent Nickel Steel. (S. A. E. Handbook, Vol. 1, Sec. D.)

S. A. E. steel number.	Annealed.			Heat-treated.		
	Yield point.	Elongation in 2 inches.	Reduction of area.	Yield point.	Elongation in 2 inches.	Reduction of area.
	Lbs./in.²	Per cent.	Per cent.	Lbs./in.²	Per cent.	Per cent.
2315	35,000–45,000	35–25	65–45	40,000– 80,000	35–15	65–40
2320	40,000–50,000	30–20	65–40	50,000–125,000	25–10	65–40
2330	40,000–50,000	30–20	60–40	60,000–130,000	25–10	60–30
2335	45,000–55,000	25–15	55–35	65,000–160,000	25–10	55–25
2340	55,000–65,000	25–15	50–30	70,000–200,000	25– 5	55–15

FIVE PER CENT NICKEL STEEL (S. A. E. 2500 SERIES).—This steel, containing about 0.12 per cent carbon, is used particularly for casehardening where the requirements are severe, such as on rear axle pinions with spiral bevel teeth. It requires only a very low heat-treating temperature (750° C. or 1,350° F.) and may be air-hardened, thus reducing to a minimum the amount of warpage.

A similar steel containing 7 per cent of nickel has also been used, particularly abroad, as an air-hardening carburizing steel.

LOW NICKEL-CHROMIUM STEEL (S. A. E. 3100 SERIES).—This steel has the following chemical composition:

	Per cent.
Nickel	1.00–1.50
Chromium	.45– .75
Manganese	.30– .80

It is used in the carbon ranges for casehardening and for forging, for the same applications as have already been indicated for the 3½ per cent nickel steel.

MEDIUM (S. A. E. 3200 SERIES) AND HIGH NICKEL-CHROMIUM (S. A. E. 3300 AND 3400 SERIES) STEELS.—These steels have the following average compositions:

S. A. E. series number.	Nickel.	Chromium.	Manganese.
	Per cent.	Per cent.	Per cent.
3200	1.50–2.00	0.90–1.25	0.30–0.60
3300	3.25–3.75	1.25–1.75	.30– .60
3400	2.75–3.25	.60– .95	.45– .75

They are used where particularly high tensile properties are required in all carbon ranges.

In Figures 27 and 28 and Table 44 are given the physical properties of low and of high nickel-chromium steels in the annealed or heat-treated condition.

The high nickel-chromium compositions are also standard for armor plate of various kinds as well as for armor-piercing projectiles, the compositions used for the various materials being as follows:

	Nickel.	Chromium.	Carbon.
	Per cent.	Per cent.	Per cent.
Heavy armor plate	3–5	1.5–2.25	0.30–0.40
Medium armor and deck plate		(1)	
Bullet-proof light armor	5		.30– .40
Armor-piercing projectiles	0.5	2.5	.50

[1] Low nickel-chromium.

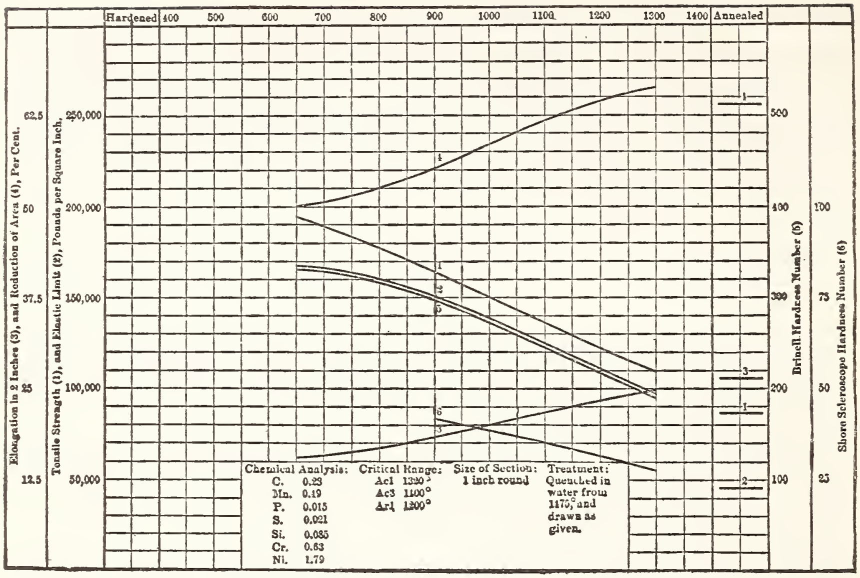


FIG. 27.—*Mechanical properties of heat-treated "low" nickel-chromium steel, Society of Automotive Engineers (Bullens, 1028).*

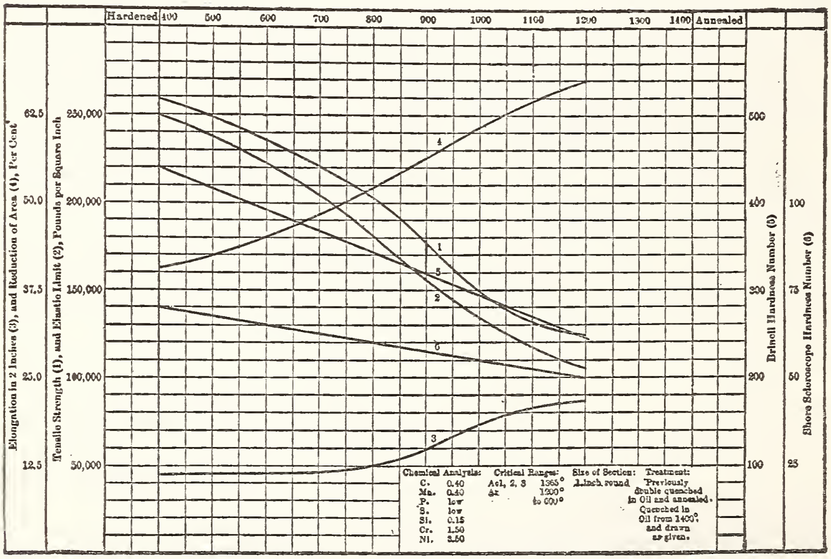


FIG. 28.—*Mechanical properties of heat-treated "high" nickel-chromium steels, Society of Automotive Engineers (Bullens, 1028).*

TABLE 44.—Range of Tensile Properties of Annealed and Heat-Treated Nickel-Chromium Steels. (S. A. E. Handbook, Vol. 1, Sec. D.)

S. A. E. steel number.	Carbon content.[1]	Annealed.			Heat treated.		
		Yield point.	Elongation in 2 inches.	Reduction of area.	Yield point.	Elongation in 2 inches.	Reduction of area.
	Per cent.	Lbs./in.[2]	Per cent.	Per cent.	Lbs./in.[2]	Per cent.	Per cent.
3120	0.15–0.25	30,000–40,000	35–25	55–40	40,000–100,000	25–15	65–40
3125 3130	.20– .30 .25– .35	40,000–55,000	30–20	50–35	50,000–125,000	25–10	55–25
3135 3140	.30– .40 .35– .45	45,000–60,000	25–15	45–30	55,000–150,000	20–5	50–25
3220 3320	.15– .25	35,000–45,000	25–20	60–45	45,000–120,000	20–5	65–30
3230 3330	.25– .35	40,000–50,000	25–15	55–40	60,000–175,000	20–5	60–30
3240 3340	.35– .45	45,000–60,000	25–15	50–40	65,000–200,000	15–2	50–20
3250 3450	.45– .55	50,000–60,000	25–15	50–40	150,000–250,000	15–2	25–15
3415	.10– .20	35,000–45,000	25–20	60–45	40,000–100,000	20–5	65–30
3435	.30– .40	45,000–55,000	25–15	55–40	60,000–175,000	20–5	60–30

[1] See beginning of this and last preceding subsections for the nickel, chromium, and manganese content.
[2] See S. A. E. Handbook for heat treatments recommended.

ONE-HALF PER CENT NICKEL STEEL.—The use of this steel has recently been introduced for casehardening purposes as a substitute for ordinary carbon steel. It is claimed that a tougher core is produced, and, in addition, the case hardens well with an oil quench.

MAYARI STEEL FROM CUBAN ORES.—This is a steel produced from pig iron obtained from Cuban ores carrying about 1 per cent nickel and 2 per cent chromium. It has essentially the same chemical composition and properties as low nickel-chromium steel, already referred to above, and has been used for similar purposes.

It will be seen that the nickel and the nickel-chromium steels are chiefly used for structural purposes. Nickel does not appear to benefit ordinary metal-cutting tools, although it has been used to some extent in carbon tool steels to increase the penetration of the hardened zone. In particular, it does not improve ordinary high-speed steels.

It is used, however, in a variety of metal and woodworking tool compositions. Thus, one company uses 3.5 per cent nickel steel with about 0.70 per cent carbon in band saws. Low nickel-chromium steel with from 0.60 to 0.70 per cent carbon is used for pneumatic chisel steel, sledges, and hatchets, and is a favorite material for drop-forging dies.

HIGH-NICKEL STEELS.—These are, more properly, ferronickel alloys.

	Per cent.
Nickel	25 –38
Carbon	.3– .5

These alloys are austenitic and not subject to heat treatment. They are, however, naturally quite tough and strong, have a low thermal expansivity, and are very resistant to corrosion in air, fresh or sea water. They are used for gas-engine valves, boiler tubes for water or fire, and valve stems in salt-water lines. The alloys may be rolled and forged, but are not so readily machined as ordinary steel. They may have the following average tensile properties in the natural state without heat treatment.

TABLE 45.—Tensile Properties of High-Nickel Steels.

Tensile properties.	25 to 28 per cent nickel.	30 to 35 per cent nickel.	35 to 38 per cent nickel.
Tensile strength ....lbs./in.[2]	85,000–92,000	85,000–95,000	100,000–115,000
Yield point ....do	35,000–50,000	40,000–50,000	64,000– 78,000
Elongation in 2 inches ....per cent	30–35	30–40	25–35
Reduction of area ....do	50–60	40–60	50

The alloys containing about 25 per cent of nickel are much used for electrical-resistance wire in the construction of rheostats and electrical heaters. Tables 46 and 47 give values of the electrical and thermal properties of binary alloys of nickel and iron.

TABLE 46.—Electrical Resistivity of Pure Ferronickels, in microhm-cm.

Per cent Ni.	Yensen (724).[1] Without additions.	Yensen (724).[1] With additions. Added element.	Yensen (724).[1] With additions. Resistivity.	Burgess and Aston (743).[2]	Ruer and Schüz (741).[3]
		Per cent.			
0.00				12.1	12
0.27				13.1	
0.50	11.5	0.2 Si	12.7		
0.56				15.4	
1.00	12.7	.2 Si	14.3		
1.07				16.9	
1.48	13.8	.2 Si	15.1		
1.93				16.4	
1.96	14.9	.2 Si	16.5		
2.44	16.1	.2 Si	18.0		

[1] Alloys prepared from electrolytic iron and electrolytic nickel, the former containing 0.014 per cent C, and traces of Mn and Si, the latter 0.030 per cent C, trace of Mn and 0.040 per cent Si. Small additions of silicon and manganese were made to a number of the alloys, as indicated in the third column of table, to render them more easily forgeable.

[2] Alloys produced in magnesia crucible from electrolytic iron and electrolytic nickel; carbon less than 0.10 per cent. A determination by analysis is reported for only one alloy, 0.088 per cent C for the 13.11 per cent Ni alloy.

[3] Alloys prepared in graphite crucible lined with magnesite, from pure iron (0.08 per cent C and 0.06 per cent Mn) and granulated nickel. The melt contained 0.15 per cent C.

TABLE 46.—Electrical Resistivity of Pure Ferronickels, in microhm-cm—Contd.

Per cent Ni.	Yensen (724).			Burgess and Aston (743).	Ruer and Schüz (741).
	Without additions.	With additions.			
		Added element.	Resistivity.		
		Per cent.			
2.84	17.1				
2.90		0.2 Si	19.1		
3.85	19.4	.2 Si	20.7		
4.62	20.3				
4.76		.2 Si	21.4		
5.0					29
5.67	22.0	.2 Si	25.8		
7.00		.2 Si	25.7		
7.05				26.9	
7.33	24.8				
8.00	25.2	.1 Mn	26.2		
8.17				26.7	
9.52		.2 Si	29.6		
9.61	27.1				
10.0		.2 Si+ .1 Mn	28.9		31
10.20				28.6	
11.29				29.4	
12.07				30.3	
13.11				34.8	
14.92	29.8				
15.0		.2 Si	31.0		39
19.21				36.2	
20.0					39
22.11				38.7	
25.0					40
25.20				63.2	
26.40				65.5	
28.42				82.0	
30.0		.2 Si	82.0		87
34.5		.2 Si	81.3		
34.81	80.4				
35.0					94
35.09				81.1	
40.0					81
45.0					48
47.8				44.7	
50.0		.75 Mn	42.8		43
50.0		.1 Mn	45.6		
55.0					41
60.0					30
65.0					27
70.0					27
75.0					19
75.06				22.1	
80.0					18
85.0					20
90.0					22
95.0					19
100.0				[4] 12.4	9

[4] Value taken from "a standard handbook."

TABLE 47.—Electrical and Thermal Properties of Pure Ferronickels. (L. H. Ingersoll and Others, 722.)

Nickel, per cent.	Specific resistance 20° C.	Temperature coefficient of resistance 0–100° C.	Thermoelectric power (against copper) 0–96° C.	Thermal conductivity 20–100° C.	Specific heat 25–100° C.
	Microhm-cm		Micro-volts/° C.	Cgs units.	Cal./g
0				[1] 0.1428	
1.07				.1035	0.1162
1.93				.1009	.1170
4.0	20.9	0.0020	2.32		
7.0	25.2	.0023	7.32		
7.05				.0727	.1163
10.20				.0687	.1168
13.0	33.0	.0018	16.9		
13.11				.0534	.1160
14.0	33.9	.0016	17.2		
18.0	35.9	.00084	21.0		
19.21				.0502	.1163
21.0	38.8	.0018	23.5		
22.11	40.0	.0018	21.0	.0490	.1163
25.20				.0320	.1181
26.40	35.9	.0016	16.7		
28.42				.0278	.1191
35.09	92.0	.0011	9.79	.0262	.1228
40.0	74.1	.0022	22.4		
45.0			29.0		
47.08	47.5	.0036	31.9	.0367	.1196
75.06				.0691	.1181
90.0	15.5	.0034	17.9		
100.00				[1] .1402	.1168

[1] Values for pure Fe and pure Ni taken from measurements of Jäger and Dieselhorst.

For further information on these applications of the ferronickel alloys see also Section X, 5 (p. 97), on "Alloys for electrical purposes."

Within the range of compositions from 20 to 30 per cent nickel the ferronickel alloys may readily be obtained in a nonmagnetic condition by cooling at normal rates from rolling or forging temperatures. They are used in this condition for the production of nonmagnetic parts requiring strength and toughness. Table 48 gives some values of the magnetic properties of ferronickel alloys. Information concerning the effect of high temperatures on the tensile properties of 30 per cent nickel steel will be found in Table 31 on page 61.

TABLE 48.—Magnetic Properties of Nickel-Iron Alloys.

Nickel, per cent.	Hegg, 1910 (745).					Curie constants.[1]
	Density, D.	Transformation temperatures (Curie points).		Saturation values at 0° absolute.		
		Heating.	Cooling.	Magnetic moment per unit mass.	B-H.	
	g/cm³	° C.	° C.			
0	7.875	758	....	223.2	22,090	0.072
10	7.89	730	532	221.0	21,910	.0577
20	8.02	625	218	210.8	21,240	.0460
30	8.06	533	127	203.6	20,620	.0315
40	7.63	365	....	184.2	17,660	.0251
50	8.05	527	....	169.2	17,120	.0227
60	8.29	599	....	146.8	15,290	.0185
70	8.39	613	....	127.1	13,400	.0157
80	8.52	562	....	103.1	11,040	.0126
90	8.60	480	....	80.6	8,710	.0100
100	8.86	374	....	58.8	6,550	.0056

[1] Weiss and Foëx, 1911.

More recently Yensen (724) has made a thorough study of the electrical and magnetic properties of iron-nickel alloys prepared by melting in vacuo. In Figures 29 and 30 (the latter figure has been taken from another source and includes the results of other investigators as well as those of Yensen) are reproduced some of his typical results. He finds that the alloys containing approximately 50 per cent of nickel can be forged and worked, and that they have the following average electrical and magnetic properties which may be compared with those of pure iron and nickel:

Metal.	Flux density $H=100$ gausses.	Saturation value.	Hysteresis loss $B=10000$ ergs/cm/cycle.	Electrical resistivity.
		Gausses.		Microhm-cm
Pure iron	18,500	22,500	1,100	11
50 per cent alloy	15,500	15,500	800	45
Pure nickel	6,000	6,000	25,000	8

As the 50 per cent alloys are relatively incorrodible, they should be of value under special conditions in the construction of electromagnetic equipment. Another interesting magnetic characteristic of this alloy is the fact that the B–H curve up to $B=2,000$ to 4,000 gausses is nearly linear, which makes it of value for certain electromagnetic meters.

"Permalloy," an iron-nickel alloy having the following typical composition

	Per cent.		Per cent.
Ni	78.23	S	0.035
Fe	21.35	P	Trace.
C	.04	Co	.37
Si	.03	Cu	.10
Mn	.022		

possesses a much greater magnetic susceptibility than iron. It was recently developed by Arnold and Elmen (707), who based their work upon the fact that iron-nickel alloys with more than 30 per cent nickel possesses high magnetic properties when given

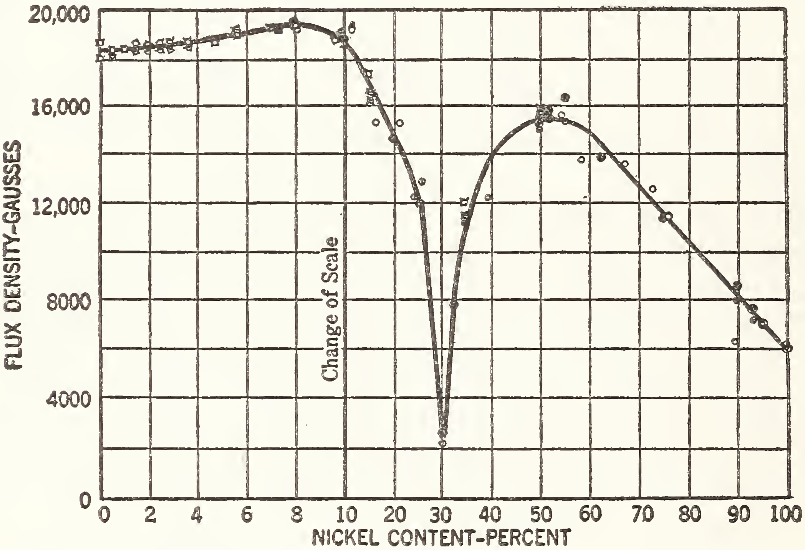


FIG. 29.—*The magnetic permeability of iron-nickel alloys melted and annealed in vacuo for H equals 100* (*Yensen, 724*).

a proper heat treatment. By careful exploratory work they found that the region with 80 per cent nickel and 20 per cent iron promised the highest initial permeability. They then determined the most suitable heat treatment for this composition. Applying the heat treatment thus found, they relocated the composition, with the result that the composition 78.5 Ni and 21.5 Fe offered the best values. The largest value for initial permeability at room temperature obtained so far in a ring permeameter is about 13,000, more than 30 times as great as that for the best soft iron. The effect of the presence of impurities on the permeability was studied. Carbon was found to be especially harmful, but the effects of changes in the heat treatment were much greater than those due to small quantities of impurities; consequently the heat treatment is of the greatest importance. Since "Permalloy" possesses so much greater magnetic susceptibility than pure iron, such as "Armco," in weak fields (0 to 1 gauss), it offers important possibilities in communication engineering. The maximum permeability ($\mu = 87,000$) often obtained for it is

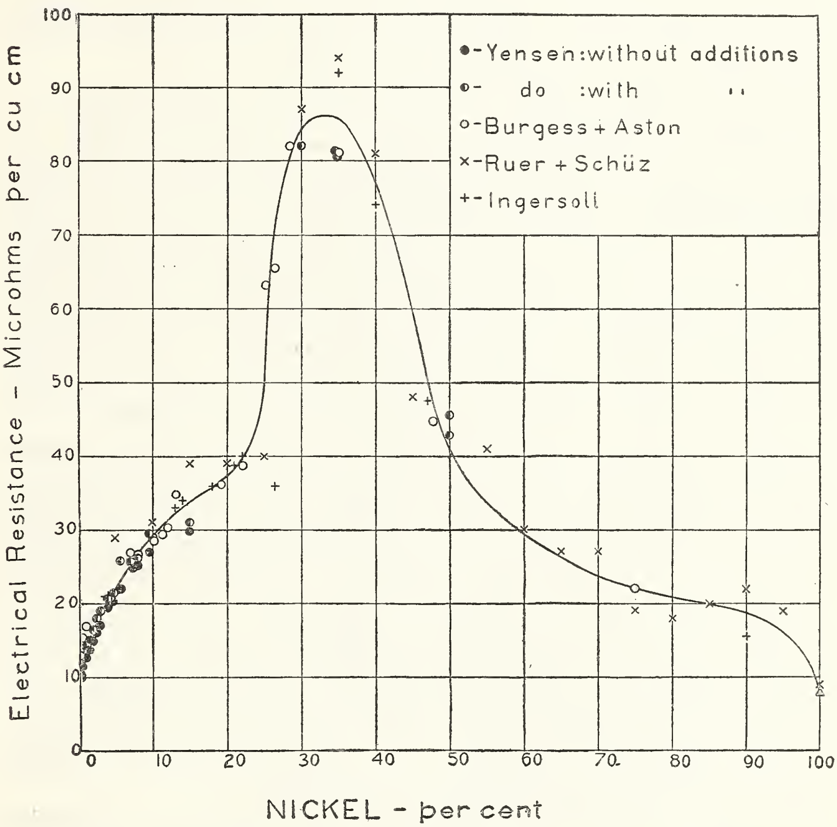


FIG. 30.—*The electrical resistivity of pure iron-nickel alloys. (Bureau of Standards Circular No. 58, 2d ed.).*

largely in excess of the highest values found for silicon steels. Preliminary tests have shown that it possesses a larger magnetostriction than iron. The behavior of "Permalloy" demonstrates, as Arnold and Elmen state, that ferromagnetism is associated with the body structure in a different manner than are the usual chemical and physical properties.

(*b*) INVAR AND RELATED ALLOYS.

As the nickel content is increased from 25 to 35 per cent, the thermal expansivity of the ferronickel alloys at 20° C. (68° F.) diminishes rapidly; with a further increase in nickel content, it again increases at first rapidly and then more slowly to that of pure nickel. These curious changes are utilized in the manufacture of the following patented alloys: Invar, Elinvar, Dilver, Platinite, and A D R alloy. The main characteristics which govern the uses of these alloys are as follows:

Invar, an alloy containing about 36 per cent of nickel, has a very low thermal expansivity at ordinary temperatures, or more specifically a mean coefficient of linear thermal expansivity of about one-millionth per degree centigrade between 0 and 40° C. (32 and 104° F.). It melts at 1,425° C. (2,597° F.), has a density of about 8.0 g/cm^3, and an electrical resistivity of about 85 microhm-cm. It is very resistant to corrosion in water and may be immersed in it for days without the appearance of rust spots. It finds extensive use in length measures, such as tapes and length standards, and is also used in the construction of clocks and watches.

Elinvar, a recently developed 36 per cent nickel alloy to which about 12 per cent chromium (or its equivalent, where small quantities of manganese, tungsten, or carbon are used in conjunction with the chromium addition) has been added, possesses at ordinary temperatures a practically invariable modulus of elasticity coupled with a very low thermal expansivity. The development of this alloy has extended the possibilities of the use of single metal balances in high-grade watches and chronometers, thus securing a considerable degree of compensation in a cheap manner.

Dilver possesses a coefficient of thermal expansivity nearly equal to that of ordinary glass (0.000008 per ° C.).

Platinite, a 46 per cent nickel alloy, has a thermal expansivity equal to that of platinum (approximately 0.000009 per ° C.). It was formerly used in place of platinum for sealing in leads of electric-light bulbs. A compound wire with 38 per cent nickel steel core incased in copper and sometimes coated with platinum is now used. The core of such a composite wire if free will expand less than the glass, and the copper more, so that each compensates the other and the wire as a whole will have the desired rate of expansion.

A D R alloy possesses, in the temperature range 0 to 500° C., a total expansion which is less than that of ordinary metals. It is used particularly in the construction of rotary distributors.

Another patented alloy is the A M F alloy, which has been found adaptable for use in mechanical parts subjected to very low temperatures, as in liquid-air plant machinery, since it possesses great ductility and resistance to shock at low temperatures.

Table 49 gives values of the thermal expansivity of some ferronickel alloys.

TABLE 49.—Thermal Expansivity of Nickel-Iron Alloys Between 0 and 38° C. (Guillaume, 1088.)

Nickel, per cent.	Mean coefficients of linear expansions×10⁶.	Nickel, per cent.	Mean coefficients of linear expansions×10⁶.
0	$10.354+0.00523t$	44.4	$8.506-0.00251t$
5.0	$10.529+.00580t$	48.7	$9.901-.00067t$
19.0	$11.427+.00362t$	50.7	$9.824+.00243t$
26.2	$13.103+.02123t$	53.2	$10.045+.00031t$
27.9	$11.288+.02889t$	70.3	$11.890+.00387t$
28.7	$10.387+.03004t$	100.0	$12.661+.00550t$
30.4	$4.570+.01194t$	12.2+1 Cr	$11.714+.00508t$
31.4	$3.395+.00885t$	16.8+1 Cr	$11.436+.00170t$
34.6	$1.373+.00237t$	16.2+2.5 Cr	$19.496+.00432t$
35.6	$0.877+.00127t$	21.3+3 Cr	$18.180+.00426t$
37.3	$3.457-.00647t$	34.8+1.5 Cr	$3.580-.00132t$
39.4	$5.357-.00448t$	35.7+1.7 Cr	$3.373+.00165t$
43.6	$7.992-.00273t$	36.4+0.9 Cr	$4.433-.00392t$

For further information concerning invar and high nickel-iron alloys Bureau of Standards Circular No. 58, 2d and revised edition (705), should be consulted.

5. ALLOYS FOR ELECTRICAL PURPOSES.

The chief electrical appliances for which alloys containing nickel are used are thermocouples, rheostats, and electrical heating devices. The use of an alloy containing from 3 to 6 per cent manganese for spark-plug terminals has already been mentioned in Section II, 2 (p. 15). The properties which render nickel alloys of value for these purposes are (1) resistance to oxidation and alteration at temperatures up to 1,100° C. (2,000° F.), (2) high electrical resistivity, and (3) a marked thermal electromotive force against iron or copper. Nickel-chromium alloys are not resistant to the action of alternate reducing and oxidizing gases, and consequently suffer considerable deterioration under these conditions.

The principal alloys now employed commercially as elements of base-metal thermocouples are Chromel, Alumel, Constantan, and to some extent Nichrome and Copel; the combinations generally used are Chromel-Alumel, iron-Constantan and copper-Constantan, the latter two combinations being used for operation at low temperatures. Variation in the composition of base-metal alloys is so great that a standard calibration made for a certain combination, such as, for example, iron-Constantan, would be of no value. Average values for the temperature-electromotive force relations of Chromel-Alumel, iron-Constantan, and copper-Constantan couples are given in Tables 50 and 51. The nickel in these alloys shows the effect of the transformation which it undergoes at about 360° C., and for this reason thermocouples used in the temperature range of about 300 to 450° C. (570 to 840° F.) may show uncertain results. A variation in the electromotive force corresponding to a few degrees of temperature may be obtained according to the heat treatment (above 360° C.) given the alloy.

The alloys used for electrical heating and for the construction of rheostats or electrical resistances may be divided into the following groups: (1) The nickel-chromium alloys which have a high electrical resistivity and low temperature coefficient, together with high resistance to oxidation and alteration at higher temperatures; (2) the ferronickel alloys which have somewhat lower resistivity and resistance to oxidation but are considerably cheaper; (3) the copper-nickel alloys which have a lower resistivity and inferior heat-resisting properties than the nickel-chromium alloys, but have a practically negligible temperature coefficient of resistivity at ordinary temperatures (this is a very necessary property in the construction of precise electrical resistances for measuring instruments); (4) the alloys similar to nickel silver, which are the oldest alloys used for electrical purposes, although they are being displaced by the above-mentioned alloys.

The composition, electrical resistivity, and other physical properties of alloys now manufactured commercially, principally as described by the manufacturers, are listed in Table 52.

TABLE 50.—Calibration Data of Representative Couples. Cold-Junction Temperature, 0° C. (Foote, Harrison, and Fairchild, 1246.)

[B represents mean calibration by United States Bureau of Standards of iron-Constantan couples from all sources. L represents mean calibration of Leeds & Northrup's iron-Constantan couple.]

Copper-Constantan.		Iron-Constantan.			Chromel-Alumel.	
Emf.	Temperature.	Emf.	Temperature.		Emf.	Temperature.
			B	L		
Millivolts.	° C.	Millivolts.	° C.	° C.	Millivolts.	° C.
0	0	0	0	0	0	0
1	25	5	105	95	5	122
2	49	10	204	186	10	243
3	72	15	299	277	15	363
4	94	20	392	367	20	482
5	115	25	483	457	25	601
6	136	30	574	546	30	721
7	156	35	662	632	35	844
8	175	40	749	713	40	970
9	194	45	836	792	45	1,100
10	213	50	924	871	....	....
11	232	55	1,011	950	....	....
12	250	60	....	1,030	....	....
13	268	....	....	....	....	....
14	285	....	....	....	....	....
15	302	....	....	....	....	....
16	319	....	....	....	....	....
17	336	....	....	....	....	....
18	353	....	....	....	....	....

TABLE 51.—Chromel-Alumel Thermocouple.[1]

Temperature.		Electromotive force.	Temperature.		Electromotive force.
° C.	° F.	Millivolts.	° C.	° F.	Millivolts.
38	100	1.50	760	1,400	31.60
94	200	3.90	815	1,500	33.90
149	300	6.22	872	1,600	36.20
204	400	8.45	927	1,700	38.45
261	500	10.72	984	1,800	40.60
316	600	13.00	1,038	1,900	42.70
371	700	15.25	1,092	2,000	44.80
427	800	17.60	1,150	2,100	46.90
482	900	20.00	1,205	2,200	49.00
538	1,000	22.30	1,260	2,300	51.06
594	1,100	24.70	1,316	2,400	53.05
650	1,200	27.00	1,371	2,500	55.08
705	1,300	29.30			

[1] Data from Hoskins Mfg. Co.

TABLE 52.—Composition and Properties of Electrical Alloys and Heat-Resisting Alloys (the Latter Being in the Form of Castings).

Name of alloy.	Form in which produced.	Chemical composition.					Electrical resistivity.				Tensile strength.	Density.	Melting point or range.	Recommended maximum working temperature.	Thermal expansivity.[a]
		Ni	Cr	Cu	Fe	Mn	Resistivity.	Temperature coefficient.	Resistivity.	Temperature coefficient.					
A. Nickel - Chromium Alloys:		Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Microhm-cm	Per °C.	Ohm/mil/ft.	Per °F.	Lbs./in.²	g/cm³	°C.	°C.	Per °C.
Nichrome [1,2]	Castings	67	16		12	1					64,000	8.15	1,350	1,100	0.0000121
Do.[1]	Wire, ribbon	60	12		26	2	109.5	0.00020	660 (20° C.)		100,000	8.15	1,350	1,000	.0000125
Nichrome II [1]	do	66	22		10	2	109.5	.00015	660 (20° C.)		100,000	8.15	1,370	1,050	.0000130
Nichrome III (Kromore).[1]	do	85	15				89.5	.000187	540 (20° C.)		110,000	8.5	1,390	1,100	.0000132
Nichrome IV (Chromax).[1]	do	80	20				103.0	.000179	620 (20° C.)		120,000	8.5	1,390	1,150	.0000132
Chromel A [3]	do	80	20				104	.00011	625 (24° C.)	0.00006	119,000	8.3	1,420	1,100	.0000162
Chromel C [3]	do	64	11		25		109	.00018	655 (24° C.)	.00010	97,000	8.16	1,390	750	.0000162
Chromel P [3]	do	90	10				70.6	.0054	425 (24° C.)	.0003			1,435	1,250	
Calido [1]	do	59	16		Bal.		110	.00012	660 (20° C.)	.000067	160,000 hard 90,000 soft	8.15	1,400	1,000	.000013
Calorite	do	65	12		15	8	110		662						
Excello [4]	do	85	14		.5	.5	91.6	.00016	550 (15° C.)		95,000	8.9			
Karma [5]	do	80	20				103	.000095	620 (20° C.)	.000052	160,000 hard 95,000 soft	8.15	1,415	1,100	.0000135
Nichroloy I [6]	do	75	16		7–9	3									
Nichroloy II [6]	do	40	7		50	3									
Nichroloy [6,7]	Castings	23	20		50	1								1,100	
Q-Alloy: Grade K-1 [8]	do	68	20								100,000			1,275	
Rayo [5]	Wire, ribbon	85	15				95.7	.000102	575	.000057	160,000 hard 95,000 soft	8.43	1,410	1,100	.0000135
Tophet		61	10		26	3	107		644						
Cronite		60									60,000–64,000		1,410	1,100–1,200	
Reactol															
B. Ferronickel Alloys:															
No. 141 [9]	Wire	69			29	1.3			182 (20° C.)						
No. 193 [1]	Wire, ribbon	30	2		67	1	92.0	.00080	550 (20° C.)		82,000	8.15	1,415	600	.0000171
Climax [1]	Wire	25			74	1	83.0	.000978	550 (20° C.)		75,000	8.15	1,415	600	.0000171

Comet [5]	Wire, ribbon	30	5		65		95.7	.000344	575	.000191	160,000 hard; 90,000 soft	8.3	1,480	600	.000016
Superior [4]	do						87.2	.00081	525 (15° C.)			8.04	1,250		
Ferrozoid [10]							84.0		506						
Kruppin [10]		28			Bal.		85.0		512						
Vestalin [10]		28			Bal.		85.1		512						
C. Nickel-Copper Alloys:															
Advance [1]	Wire, ribbon	44		54	.5	1	48.8	±.00001	294 (20° C.)		62,000	8.9	1,300	500	.0000144
Constantan		40–45		55–60			50.2		302						
Copel [8]	Wire, ribbon	45		55			49.5	Nil.	298 (24° C.)	Nil.	60,000		1,290	450	.0000144
Eureka [10,11]	Similar to Constantan.						50.2		302						
Ferry [10,11]							47.2		284						
Ia-Ia [4]	Wire, ribbon	40		60			47.1	.000005				8.92			
Ideal [5]	do	45		55			49.2	.000005	296	.000003	115,000 hard; 60,000 soft	8.9	1,210	500	.000014
Lucero [5]	do	65		30			46.5	.00076	280	.00039	140,000 hard; 65,000 soft	8.9	1,350	600	.000014
Monel [1]	do	68		28	2.5	1.5	42.5	.0019	256	.00106	75,000	8.9		425	.0000188
Nickelin [10,11]		18–32		55–68			43.0		258						
S. M. L. Alloy (Monel) [1]	Wire	68		28	2.5	1.5	45.0	.0019	270 (20° C.)		75,000	8.9	1,360	500	.0000188
D. Nickel-Copper-Zinc Alloys:															
7 per cent [10]		7					18.0		108						
10 per cent [10]		10					21.0		126						
18 per cent [1]	Wire	18	Zn=27	55			30.0	.00027	180 (20° C.)		60,000	8.5		260	.0000173
20 per cent [10]		20					29.0		174						

[1] These alloys manufactured by the Driver-Harris Co.; these data were taken from their catalogue and from information kindly supplied by them in a private communication. See also paper by Leon Hart on "Nickel-Chromium Alloys," Trans. A. I. M. M. E., **64**, p. 554; 1920.

[2] Specific heat of this alloy=0.111 cal./g at 100° C.; elongation=1 per cent; Brinell hardness=179 (3,000 kg).

[3] Alloys manufactured by Hoskins Manufacturing Co.; data were taken from their catalogue and from information kindly supplied by them in a private communication.

[4] Sold by H. Boker & Co. (Inc.). These data were taken from their catalogue.

[5] These alloys manufactured by the Electrical Alloys Co.; these data were taken from their catalogue and from information kindly supplied by them in a private communication.

[6] Alloys manufactured by Hiram Walker & Sons Co.; data were taken from their catalogue and from information kindly supplied by them in a private communication.

[7] Chemical composition includes also Si, 0.5; Al, 0.5; C, 1.0; and V, 1.0.

[8] Manufactured by General Alloys Co. Chemical composition includes also Si, 2; Al, 1; Fe and other impurities balance. Information kindly supplied by manufacturer in a private communication.

[9] Data taken from Hunter and Jones's paper "Some Electrical Properties of Alloys at High Temperatures," Trans. Am. Electrochem. Soc., **42**, p. 162; 1922.

[10] Data by Law (564). [11] Chemical composition includes also Zn, 0–20. See Campbell's list of alloys (545a).

[a] The temperature ranges within which the values for thermal expansivity per °C. were determined have been reported by the following manufacturers: Driver-Harris Co., 20 to 100° C. (68 to 212° F.); Hoskins Manufacturing Co., 21 to 870° C. (70 to 1,600° F.); Electrical Alloys Co., information not available.

TABLE 52.—Composition and Properties of Electrical Alloys and Heat-Resisting Alloys (the Latter Being in the Form of Castings)—Continued.

Name of alloy.	Form in which produced.	Chemical composition.					Electrical resistivity.				Tensile strength.	Density.	Melting point or range.	Recommended mxaimum working temperature.	Thermal expansivity.[17]
		Ni	Cr	Cu	Fe	Mn	Resistivity.	Temperature coefficient.	Resistivity.	Temperature coefficient.					
D. Nickel-Copper-Zinc Alloys—Continued.		Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Microhm-cm	Per °C.	Ohm/mil/ft.	Per °F.	Lbs./in.²	g/cm³	°C.	°C.	Per °C.
30 per cent[10, 12]	Wire	30					40.2	0.000199	241 (20° C.)		60,000	8.7		260	0.0000173
Platinoid[10]	do	24.8	Zn=20.4	54	0.5	0.15	41.0		246						
Rheotan II[13]		25	Zn=18	52.5	5										
E. Miscellaneous Alloys:															
Alloy No. 473[3]	Wire, ribbon, flats.	96				4									
Alumel[3]	Wire	94			.5	2.5	33.3	.0012	206	0.0007			1,400	1,250	
Calite[14]	Castings	35	5		50	Al=10					36,800	7.03	1,525	1,200 1,300	
M-M-M[15]	do	60–65		24–27		Sn=9–11					70,200				
Magno[5]	Wire	95				5	20	.002	120 (20° C.)	.0011	140,000 hard 65,000 soft	8.8	1,420	800	
Manganese nickel[1]	do	Bal.				1.5–2	13.95	.0036	84 (20° C.)		79,000	8.9	1,435	500	.0000137
Manganin[12]	do	2–5		70–85	.5	12–25	45	±.00001	270 (20° C.)		70,000	8.15			
Nickel-electrolytic[9]	do	99+							58.6 (20° C.)					500	
Nickel-grade A[1]	Wire, ribbon	98.9		.25	.65	.1	10.63	.00537	64 (20° C.)		61,000	8.9		500	.0000137
Nickel-grade C[9]	Wire	96.2		.4	.9	2.1			84 (20° C.)					500	
Nickel-grade D[9]	do	94.1		.2	.75	4.75			117 (20° C.)					500	
Nickel-"pure"[5]	Wire, ribbon	99+					10.0	.00385	60 (20° C.)	.0021	140,000 hard 70,000 soft	8.84	1,450	700	.000014
Nickel-"pure"[16]	Wire	99		.12	.60	Trace.			73 (25° C.)			8.87			.0000125
Nickel-pure[3]	do						8.55		51.4 (24° C.)	.00267					
Special manganese-nickel.[1]	do	Bal.				4.25–5	21.6	.0036	130 (20° C.)		74,000	8.9	1,435	500	.0000137
Resistin[10]	Cupromanganese alloy.			84.3	1.9	13.5	50.2		302						
Tarnac[10]	do						41		246						

[1] These alloys manufactured by the Driver-Harris Co.: these data were taken from their catalogue and from information kindly supplied by them in a private communication. See also paper by Leon Hart on "Nickel-Chromium Alloys," Trans. A. I. M. M. E., **64**, p. 554: 1920.

[3] These alloys manufactured by the Hoskins Manufacturing Co.: these data were taken from their catalogue and from information kindly supplied by them in a private communication.

[5] These alloys manufactured by the Electrical Alloys Co.; these data were taken from their catalogue and from information kindly supplied by them in a private communication.

[9] Data taken from Hunter and Jones's paper "Some Electrical Properties of Alloys at High Temperatures," Trans. Am. Electrochem. Soc., **42**, p. 162: 1922.

[10] Data by Law (564).

[12] Data taken from Driver-Harris Co.'s catalogue. Chemical analysis reported for manganin determined from analyses taken from various sources.

[13] Chemical composition includes also Zn, 18.

[14] Manufactured by the Calorizing Co. of Pittsburgh, Pa. See paper by G. R. Brophy on "Calite: A New Heat-Resisting Alloy," Trans. A. S. S. T., **2**, p. 384; 1922.

[15] Manufactured by Manning, Maxwell & Moore (Inc.). Chemical composition includes Sn, 9–11; impurities as Fe, Mn, Si, 1–3. Brinell hardness=146. Information kindly supplied by manufacturers in a private communication.

[16] Manufactured by American Nickel Corporation; data taken from their catalogue and from an article by E. F. Cone in Iron Age, June 17, 1920.

[17] The temperature ranges within which the values for thermal expansivity per °C. were determined have been reported by the following manufacturers: Driver-Harris Co., 20 to 100° C. (68 to 212° F.); Hoskins Manufacturing Co., 21 to 870° C. (70 to 1,600° F.); Electrical Alloys Co., information not available.

Most of these alloys are furnished in wire and in ribbon form. They are manufactured by melting in either the crucible or electric furnace and pouring into small ingots, which are first hot-rolled and annealed. They are then cold-drawn (with annealing) into the finished form. Nickel-chromium alloys without any iron are less ductile and malleable, and hence more difficult to draw into wire than those containing iron.

The general subject of electrical resistance has received much attention by Hunter and Sebast and Sebast and Gray (1266, 1268). Some of their principal conclusions are as follows: High-resistance alloys must be sought for along those combinations in which the metals are in solid solution. An increase in the resistivity is usually associated with a decrease in temperature coefficient, although the two may not be strictly parallel. An alloy containing 17 per cent chromium, 71 per cent nickel, and 12 per cent copper was found, which has a very high resistivity (113 microhm-cm) and a negligible temperature coefficient (0.000078 per ° C. at 20° C.). This alloy appears to have commercial possibilities, as it resists oxidation at higher temperatures to a remarkable degree and is easily drawn. An alloy was found, containing 48 per cent copper, 39 per cent nickel, and 13 per cent manganese, which has a resistivity of 70 microhm-cm and a zero temperature coefficient at 20° C.; this alloy has a higher resistivity than manganin. The highest resistivity values were found in the binary alloys of nickel and manganese and of nickel and chromium, and the ternary alloys of iron, nickel, and manganese; iron, nickel, and chromium; and copper, nickel, and chromium. The ternary alloys have, in general, a higher resistivity than the binary alloys. Low-temperature coefficients were found chiefly in the copper-nickel-manganese alloys.

In Figure 9, there are presented graphically some results of an investigation made by Hunter, Sebast, and Jones (339) on the specific resistance and its temperature coefficient for electrolytic and commercial nickel and Monel metal. Further work on the metals and other alloys used for electrical resistance has recently been reported by Hunter and Jones (1242). The specific resistance was found to increase with temperature to a degree depending upon the nature of the alloy. They also determined that the useful life of nickel-chromium wires at high temperatures is longer the higher the chromium content. Nichrome wires containing 15 and 20 per cent chromium lasted from 200 to 250 hours when kept at 1,000° C. (1,832° F.) in free air.

6. HEAT-RESISTING ALLOYS.

An interesting sequel of the development of electrical resistance alloys for rheostats and heaters has been that of heat-resisting alloys. Many alloys which were at first used because of their electrical properties and their ability to withstand high temperature are now used for the latter reason alone. Rapid strides are now being made in the application of heat-resistant alloys in industrial operations at elevated temperatures and often at considerable pressures. The nickel-chromium alloys in the form of castings are now much used for furnace muffles, carbonizing, and annealing boxes and tubes, lead, cyanide, and salt pots, retorts, pyrometer protection tubes, certain parts of continuous-type furnaces, and other equipment exposed to high temperatures. These and other alloys to be described (see also Table 52) withstand very well the action of gas and oil flames, as well as that of molten lead, cyanide, or carbonizing mixtures up to 1,260° C. (2,300° F.). These alloys have an important advantage over cast steel in the more rapid penetration of heat through their thinner sections, which are rendered possible by their much greater resistance to oxidation and their relatively high strength at the high temperatures.

In Table 53 are given the results of some tensile tests on cast Nichrome, communicated by the Driver-Harris Co. Data for a chromium-iron alloy, containing 28 per cent Cr and 72 per cent Fe, is included for comparative purposes, inasmuch as both materials resist oxidation equally well, yet show markedly different tensile properties. The Driver-Harris Co. has informed the bureau that one concern has obtained an average of 8,000 hours' service on a lot of Nichrome carburizing boxes guaranteed for 3,500 hours. One box ran 11,000 hours. This same concern has obtained as high as 20,000 hours' life on some cylindrical retorts in gas-fired furnaces. When used as a liquid container, as in lead or cyanide baths, Nichrome has shown a shorter life than when used as carburizing boxes.

TABLE 53.—Tensile Properties of Cast Nichrome at Elevated Temperatures.

[Driver-Harris Co., Private Communication, July 12, 1923.]

NICHROME.

Temperature.		Size of specimen.	Ultimate tensile strength.	Elongation in 2 inches.	Reduction in area.
°F.	°F.	Inch.	Lbs./in.²	Per cent.	Per cent.
Room	Room	0.320×0.608	61,660	None.	None.
Do	....do	.320× .611	67,000	None.	None.
300	572	.328× .686	48,900	None.	None.
400	752	.319× .697	48,800	None.	None.
600	1,112	.255× .616	44,000	None.	None.
800	1,472	.320× .618	30,350	2.5	4
850	1,562	.325× .601	20,481	7.5	9
900	1,652	.302× .582	18,500	7.5	9
1,000	1,832	.324× .600	11,676	15	16
1,100	2,012	.325× .629	6,360	20	18

Cr—Fe ALLOY.

Room	Room		81,415	None.	None.
1,003	1,837		1,500	113.5	100

The following table of tensile properties, as furnished by the Hoskins Manufacturing Co., are for Chromel alloys in several forms.

TABLE 54.—Tensile Properties of Chromel Alloys.

[Hoskins Manufacturing Co.]

Alloy.	Temperature.	Ultimate tensile strength.	Elongation.
Wire:		Lbs./in.²	Per cent.
Chromel A	Room	119,000	[1] 25
Chromel C	.....do	96,750	[1] 16
Chromel A	1,095° C. (2,000° F.)	5,000	[1] 19
Chromel C	.....do	4,100	[1] 15
Hot-rolled rod:			
Chromel A	Room	93,250	[2] 52
Chromel C	.....do	88,225	[2] 47
Cast:			
Chromel A	.....do	30,000	0
Chromel C	.....do	30,000	0

[1] On 6 inches. [2] On 1.5 inches.

"Calite" is an iron-nickel alloy, to which about 10 per cent aluminum and 5 per cent chromium have been added, and is manufactured by the Calorizing Co., of Pittsburgh. It resists oxidation very well, even up to 1,300° C. (2,372° F.), although 1,200° C. (2,200° F.) is recommended for prolonged service. The protective oxide film formed on the surface of the casting is adherent and does not snap off, even on quenching from high temperatures. According to tests reported by Brophy (1279), samples of calite lost only 3,000 mg per 100 cm² after 100 hours' heating at 1,200° C. and 300 mg per 100 cm^2 after 25 hours' additional heating at 1,300° C. Calite annealing boxes have been run at furnace temperatures for 1,500 hours without showing any warpage or growth. Calite in the cast condition can neither be machined nor cut with oxyacetylene, so grinding must be resorted to. It runs easily when in the molten condition, and castings with sections three-sixteenths inch thick have been successfully made.

"Q-Alloys," a series of nickel-chromium alloys manufactured by the General Alloys Co., may be furnished in sheet form, in addition to the usual castings made for high-temperature work. The manufacturers state that the sheets can be successfully fabricated by welding into practically any form desired, drawn or stamped into shapes, and welded to castings or to other metal parts. A tensile strength in excess of 27,000 lbs./in.^{2} at 950° C. (1,750° F.) is claimed for these alloys.

A recently developed alloy, known as "M-M-M" (modified Monel metal) and manufactured by Manning, Maxwell & Moore (Inc.), New York, N. Y., finds useful application in valves and turbines for superheated steam where resistance to extremely high temperatures and pressures is a requisite. This alloy contains tin, which is added in the form of a copper-tin alloy to a nickel-copper alloy, such as Monel metal. This forms a harder product, which is not brittle and possesses a high elastic limit at elevated temperatures. (See Table 52 for range of chemical compositions.) It is a free-flowing metal which is easily cast into difficult shapes and even into sections as thin as one-eighth inch. More power is, however, required for machining this alloy than for steels of similar tensile strength. The data for this alloy in Table 55 have been communicated by the manufacturers.

TABLE 55.—Tensile Properties of "M-M-M Alloy."

[Chemical Composition, per cent: Ni, 60.90; Cu, 26.05; Sn, 11.30; Si, 0.05; Mn, 0.40; and Fe, 1.26.]

Temperature of test.		Tensile strength.	Percentage of tensile strength at 70° F.	Elastic limit.		Elongation in 2 inches.	Reduction of area.
				Tension.	Compression.		
° C.	° F.	Lbs./in.^{2}		Lbs./in.^{2}	Lbs./in.^{2}	Per cent.	Per cent.
20	70	70, 200	....	43, 500	40, 000	5. 0	4. 0
316	600	67, 500	96	46, 000	....	2. 0	3. 5
482	900	59, 150	84	43, 900	....	2. 0	3. 5

Rezistal, a patented chromium-nickel-silicon steel (U. S. Patents Nos. 1420707 and 1420708) manfuactured in several grades by the Crucible Steel Co. of America, is finding application in fields where nonmagnetic properties and resistance to heat, flame, and acids are required. Much data on the various properties of this steel have been given by C. M. Johnson (1115). The specific gravity of this alloy is 7.76, 10 to 12.5 per cent less than that of Monel metal (sp. gr. = 8.87). It casts very fluid, lies quietly in the mold, and the castings are sharp in outline and the lettering very distinct. The castings machine well and take a good finish. Unannealed cast rods one-eighth inch in diameter can be bent through 180° without fracture. For rolling and forging this steel should never be heated up to a white heat, but brought to a mild yellow heat, 1,095° C. (2,000° F.) and thoroughly heated throughout at this temperature. No heat treatment is required to bring out its resistant qualities. To soften the steel for machining, it should be annealed at 900 to 955° C. (1,650 to 1,750° F.) for four or five hours and cooled down naturally with the furnace, all the gas being shut off at once at the end of the annealing period. It can not be hardened by quenching. Where a polish is desired, as for table and kitchen ware, the steel should be wet polished with emery and oil or some other suitable fluid. It can not be buffed, as the buffing brings out a grain similar to that in wood. This steel can be butt or spot welded best with the oxyacetylene flame or electric arc, using fluxes ordinarily employed for such welding. The welding is best accomplished on sand-blasted or pickled sheets, as the presence of scale may seriously interfere with the success of the welding. Excellent welds can be obtained by the electric-welding method on cast iron with this steel in the form of welding rods, thus producing a weld much stronger than the cast iron itself. This steel offers high resistance to the cutting action of the oxyacetylene torch, being 10 to 12 times harder to cut with the burglar's torch than is a 1 per cent chromium steel.

Table 56 gives some data, furnished by the manufacturers, on the tensile properties of Rezistal steel. The tensile strength can be raised considerably by increasing the carbon content, although at the expense of machinability. Wires of higher tensile strength can be produced, but with a reduction in ductility. Wires as fine as 0.005-inch diameter are produced from grade No. 4.

TABLE 56.—Tensile Properties of Rezistal Steel in Various Forms.

[Crucible Steel Co. of America.]

Form.	Ultimate tensile strength.	Yield point.	Elongation.	Reduction in area.	Brinell hardness.
	Lbs./in.²	Lbs./in.²	Per cent.	Per cent.	
Cast (grade No. 4), not annealed	84,000	47,000	19.5	16.6	....
Forged (grade No. 2):					
Natural	146,000	107,000	25.0	40.0	302
Treated from 1,000° C. (1,832° F.)	125,800	67,000	40.5	54.0	241
Forged (grade No. 3):					
Natural	117,990	85,700	32.0	48.2	228
Treated	113,140	75,080	39.0	60.0	228
Forged (grade No. 4):					
Natural	113,000	90,000	31.5	49.0	228
Treated from 1,040° C. (1,900° F.)	109,000	62,000	38.5	52.7	192
Forged (grade No. 5):					
Natural	129,000	83,370	16.0	27.7	255
Treated	91,500	46,100	33.0	41.3	156
Drawn wire, 0.03-inch diameter	150,000	....	....	....	....

The compression, torsion, and shear values obtained on bars and 0.038-inch sheets of Rezistal are reported as follows:

	Tension (on bar).	Compression.	Torsion.	Shear.
	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²
Ultimate tensile strength	122,560	130,300	....	82,420
Elastic limit	63,660	81,610	52,150	....
Modulus of elasticity	27,170,000	....	11,713,000	....

In Table 57 the tensile properties of Rezistal at high temperatures are given, together with data for a plain 0.10 per cent carbon steel included for comparison.

TABLE 57.—Tensile Properties of Rezistal at Elevated Temperatures.

[Crucible Steel Co. of America.]

Grade of steel.	Temperature.		Tensile strength.	Elongation in 2 inches.	Reduction in area.
	° C.	° F.	Lbs./in.²	Per cent.	Per cent.
Rezistal No. 3	700	1,292	71,470	20.0	24.7
	800	1,472	44,900	28.5	62.3
	960	1,760	17,800	48.5	70.1
Rezistal No. 4	960	1,760	22,600	36.0	53.8
0.10 per cent carbon steel	960	1,760	5,100	90.0	100.0

With specimens of Rezistal heat treated for 10 minutes at 1,100° C. (2,012° F.), impact values as high as 53 foot-pounds are obtained, though no fracture of the specimen results. The natural, untreated, hot-rolled steel specimens give impact values from 18 to 33 foot-pounds with fracture. Immersion in boiling liquid air (−185° C.) has no embrittling effect on Rezistal. A 2-inch piston rod of this steel used in the liquefying cylinder of a liquid air machine has been in continuous service for two years at about 3,000 lbs./in.^{2} pressure, during which time the rod was exposed to cooling water that was contaminated with mine water.

Some values obtained on the thermal expansivity of Rezistal are as follows:

Temperature range.		Average coefficient of expansion per degree Centigrade.	
° C.	° F.	Sample No. 3.	Sample No. 4.
20–300	68–572	0.0000163	0.0000159
300–600	572–1,112	.0000180	.0000179
600–900	1,112–1,652	.0000200	.0000204

The permeability of Rezistal No. 4 is 1.02 and remains practically constant between the limits of magnetizing force, 50 to 800 H. The residual magnetism after charging does not exceed 4 lines/cm^2.

The electrical resistance at room temperature of this steel is about 93 microhm-cm, or 560 ohms per mil-foot. The steel can be used for electrical heating elements up to 1,040° C. (1,900 °F.).

All grades of Rezistal are highly resistant to oxidation or scaling up to 980° C. (1,800° F.). Grade No. 4 shows the best results; after being held at 1,040° C. (1,900° F.) for 30 minutes it is only slightly stained, while a 13 per cent chromium steel heated under like conditions loses (presumably by flaking) 8,060 mg/100 cm^2 and is covered with a heavy scale. Comparative data upon the change of weight, in milligrams per 100 cm^2, observed on specimens of the different grades of Rezistal and various other metals and alloy sheets which had been heated to 1,095° C. (2,000° F.) for 30 minutes are as follows:

	Loss.	Gain.
Rezistal:		
Grade No. 2	None.	74.4
Grade No. 3	None.	71.3
Grade No. 4	4.7	None.
Monel metal	5,239.0	None.
95 per cent Ni	232.5	Adherent scale.
High Ni-Cr steel	885.1	
High Cr steel	8,067.8	
Copper steel	14,994.7	

A crucible made from Rezistal No. 3 showed no loss in weight when exposed to molten lead for eight hours at 900° C. (1,650° F.). A sample each of Rezistal No. 3 and of wrought iron immersed in molten cyanide at 900° C. lost 2,334.3 mg/100 cm^2 and 7,409.0

mg/100 cm^2, respectively. Rezistal No. 2 offers the greatest resistance of any of the grades of Rezistal to the action of molten aluminum. A sample thus exposed at 750° C. (1,380° F.) for three hours showed a loss of 2,498.6 mg/100 cm^2, while under like conditions a sample of 13 per cent chromium steel lost 11,563.0 mg/100 cm^2, and a sample each of chromium-nickel-molybdenum steel and of molybdenum steel containing 0.8 per cent molybdenum were almost completely destroyed.

The recommended uses for Rezistal are door lock pins for safes and vaults; parts of enameling furnaces, such as rails, racks, and trays; valves and other parts in internal combustion engines; spark-plug electrodes and primer coils for automobiles; rods for skimming brass; bushings in rotary bottle-blowing machines; punches for hot glass; bottom plates of hardening furnaces; baffle plates in carbonizing furnaces; baking pans; furnace tongs; etc.

The acid-resisting qualities of this steel are dealt with in the next section.

7. ACID-RESISTING ALLOYS.

Many of the nickel alloys display an even greater resistance to acid corrosion than does nickel itself. The acid-resisting properties of Monel metal have already been discussed (p. 62).

The chromium-nickel alloys are acid-resisting, and hence are used for dipping baskets and other articles exposed to acid corrosion. The results of tests given in Table 58, communicated by the Driver-Harris Co., indicate the resistance of Nichrome castings to acid corrosion.

TABLE 58.—Resistance of Nichrome Castings to Acid Corrosion.[1]

Acid.	Loss in weight per day in per cent of initial weight (125 g).			
	20 per cent acid.	30 per cent acid.	50 per cent acid.	60 per cent acid.
Sulphuric	0.009	0.005	0.005	0.005
Hydrochloric	.14	.34	....	....
Nitric	.08	.13	.22	.30

[1] Samples (125 g weight) immersed in cold acid (300 cc) for 200 hours.

According to Brophy (1279) "calite" shows good corrosion resistance toward many chemicals. It is slowly attacked by hydrochloric acid and hardly at all by nitric acid (showing a loss of 40 mg/100 cm^2 when immersed in 25 per cent nitric-acid solution for 48 hours), while a 25 per cent sulphuric-acid solution attacks it rapidly. It is not attacked by acetic acid, molten carbonates, chlorides, nitrates, cyanides, lead, zinc, tin, type metal, sulphur, and sulphur vapor, nor by sulphurous acid vapor at 900° C. (1,652° F.), while fluxes such as cryolite, borates, and silicates attack it rapidly. Polished samples of calite subjected to a spray test with a saturated sea-salt solution for 200 hours at 38° C. (100° F.) retained their polish; hence calite should answer satisfactorily for fittings and other parts exposed to marine atmospheres.

Rezistal, which has already been referred to at length in Section X, 6 (p. 108), shows excellent acid-resisting qualities toward many chemical solutions. Well-polished specimens of Rezistal No. 4 that are free from roll or hammer scale show no rust stains after several days' exposure to the weather or immersion in ordinary drinking water, sea water, or mine water. A high degree of resistance is shown by the different grades of Rezistal to all fruit acids, and, at room temperatures, to nitric acid, 32 per cent and concentrated sulphuric acid, glacial acetic acid, and carbonic acid. Table 59 gives comparative data upon the acid resistance of Rezistal and other alloys.

TABLE 59.—Corrosion Tests of Rezistal and Other Alloy Steels.

[Crucible Steel Co. of America.]

[Loss of weight of polished specimens after 24 hours' exposure at room temperature, in milligrams per 100 cm².]

Material.	Sulphuric acid.			Nitric acid.		Hydrochloric acid.	Glacial acetic acid.
	10 per cent.	32 per cent.	99 per cent.	32 per cent.	60 per cent.	19 per cent.	
Rezistal:							
Grade No. 3	83.7	97.7	213.9	7.8	5.6	635.5	5.1
Grade No. 4	49.6	51.2	100.8	6.4	5.7	516.2	95.3
Grade No. 5	....	31.0	4.7	....	....	....	....
High Cr-Ni steel	1,725.2	16,197.5	....	4.2	4.7	7,162.6	122.9
High Cr-Si steel	....	33,790.0	....	7.8	(1)	....	0.0
25 per cent Ni steel	170.5	139.5	....	26,086.5	(2)	345.7	121.1
38 per cent Ni steel	63.6	63.6	....	53,614.5	(2)	294.5	213.9
High Cr steel (stainless)	19,561.0	19,561.0	108.5	1.6	(1)	7,088.2	10.4
Wrought iron	7,595.0	17,391.0	74.4	26,582.5	(2)	4,053.3	299.2
Copper steel	1,137.7	1,492.7	....	32,953.0	(2)	3,118.6	189.1
Monel metal	20.2	18.6	279.0	33,433.5	(2)	203.1	10.9

[1] The high chromium steels possess high resistance to concentrated nitric acid (60 per cent; sp. gr.=1.42).
[2] Dissolves rapidly.

A specimen each of Rezistal No. 4 and Rezistal No. 5 showed a loss of 118.3 and 58.6 mg/100 cm², respectively, when tested in a 1 per cent sulphuric acid solution at boiling temperature for 45 minutes.

For further details as to the corrosion-resisting qualities of Rezistal in various media and the different successful applications found for this material, the pamphlet recently issued by the Crucible Steel Co. of America should be consulted.

The alloy "M-M-M" already referred to in the preceding section resists well most chemicals and is successfully used in the chemical industries for fittings and machinery. The following corrosion data, reported by the manufacturers, were obtained on ring-shaped samples 2 inches in diameter and one-half inch in thickness, with a central hole one-half inch in diameter.

TABLE 60.—Resistance to Corrosion of "M-M-M" Alloy in Various Solutions.

[Chemical composition: Ni, 60.54 per cent; Cu, 26.60 per cent; Sn, 10.24; Si, 0.19 per cent; Mn, 0.50 per cent; and Fe, 1.89 per cent.]

Corroding medium.	Strength of solution.	Percentage loss in weight in 10 days.	Milligrams lost in 10 days, per 100 cm²	Depth of corrosion, centimeters per year.
Acetic acid	36 per cent	None.	None.	None.
Citric acid	Strong solution	None.	None.	None.
Hydrofluoric acid	30 per cent	None.	None.	None.
Do	50 per cent	0.033	113	0.0048
Oleic acid	Pure	None.	None.	None.
Oxalic acid	Concentrated	.009	30	.0013
Sulphuric acid	66° Bé	.001	37	.0016
Do	50 per cent	.041	128	.0053
Do	10 per cent	.052	163	.0069
Do	1 per cent	.062	199	.0084
Sulphurous acid	Concentrated	.054	173	.0074
Ammonium hydroxide	27° Bé	.020	70	.0028
Do	16° Bé	.009	34	.0014
Sodium hydroxide	Strong solution	None.	None.	None.
Ferric chloride	do	1.530	4,690	.1981
"Perchloride of iron"	do	.990	3,300	.1397
Lysol	do	None.	None.	None.

"Tuc Tur," a copper-nickel-zinc alloy already referred to in Section X, 3 (p. 79), is at most only slightly attacked by sulphuric and hydrochloric acids; alkalies, such as potassium, sodium, and ammonium hydroxides; salts such as ammonium chloride, magnesium chloride, and acid sulphates; and corrosive gases, such as hydrogen sulphide, sulphurous acid; and in the absence of moistures to the oxides of nitrogen. This alloy is close-grained and takes a high polish.

An alloy, as yet unnamed, recently developed by the American Nickel Corporation has been found to resist hot sulphuric acid and is well adapted for pump parts in apparatus for liquefying sulphur dioxide. The chemical composition of this alloy is as follows: Copper, 18.7 per cent; nickel, 52.1 per cent; lead, 21.8 per cent; antimony and tin present, but not determined.

Illium, an alloy developed by Prof. S. W. Parr (1315) has the following composition:

	Per cent.		Per cent.
Copper	6.42	Aluminum	1.09
Manganese	.98	Iron	.76
Silicon	1.04	Chromium	21.07
Tungsten	2.13	Molybdenum	4.67
Nickel	60.65		

It is practically unattacked by 25 per cent nitric acid, and has been successfully applied in the construction of combustion chambers of calorimeters. The alloy may be cast and machined, although with some difficulty; it has a tensile strength of about 50,000 lbs./in.^{2}

Tungsten-nickel alloys have been prepared by Irmann (1313), who studied their resistance to the action of sulphuric acid. He found that the resistance of nickel to the action of 65 per cent acid, which itself is considerable, is increased fourfold by the addition of 5 per cent of tungsten and twelvefold by the addition of 10 per cent. Alloys containing under 18 per cent have sufficient ductility to be formed into sheets. The constitutional diagram of the nickel-tungsten alloys has recently been determined by Vogel (804).

Fairlie (1316) has reported some tests of nickel-lead alloys for acid-resisting purposes. Alloys containing from 1 to 3 per cent of nickel and the balance lead were more resistant to the action of 50 to 60° Bé. sulphuric acid, both hot and cold, than pure lead, and had a tensile strength of about 3,200 lbs./in.^{2}, about 30 per cent greater than that of lead. The antimony-lead alloys were considerably harder and stronger, and although resistant to the action of cold acid were not resistant to the action of hot acid. Some of his results are reproduced in Table 61 below.

TABLE 61.—Acid Resistance of Nickel-Lead Alloys (Fairlie, 1316).

Composition.	Elongation in 0.5 inch.	Tensile strength.	Loss in weight in 50 Bé. H_2SO_4.		Loss in weight in 62 Bé. H_2SO_4.	
			Cold; loss in 1 week.	Hot (184° C.); loss in 1 week.	Cold; loss in 1 week.	Hot (184° C.); loss in 1 week.
	Per cent.	Lbs./in.^{2}	Per cent.	Per cent.	Per cent.	Per cent.
100 per cent Pb	110	2,360	0.014	0.357	0.078	0.419
80 per cent Pb, 20 per cent Sb	5	5,540	.015	2.425	.091	5.817
99 per cent Pb, 1 per cent Ni	74	3,170	.009	.190	.035	.391
96.5 per cent Pb, 3.5 per cent Ni	32	3,260	.021	.134	.057	.199

The disadvantages of the nickel-lead alloys are their low strength and difficulty of preparation due to the great difference between the melting points of the components.

Clamer has patented compositions of ferronickel alloys for production of noncorrodible sheets, rods, etc. These contain approximately—

	Per cent.
Nickel	25–50
Copper	5–20
Iron	Balance.

An alloy of 30 per cent tantalum and 70 per cent nickel is reported to be resistant to the action of boiling aqua regia (793). Siemens-Halske has patented similar compositions for this purpose.

8. MISCELLANEOUS ALLOYS.

Besides its use as a principal alloying element in the well-known alloys just considered, nickel enters into the composition of a great variety of other commercial and experimental alloys in which it acts principally to increase the hardness without appreciable loss of ductility. However, it exercises other functions in such compositions. In Table 62 are assembled data on the chemical composition and uses of a number of miscellaneous alloys containing nickel which are in commercial use or mentioned in the literature. This table does not include alloys which have been listed in Tables 37 and 52 under nickel silver alloys and those for electrical purposes.

TABLE 62.—Miscellaneous Alloys Containing Nickel.

Name of alloy.	Chemical composition (per cent).								Remarks.
	Ni	Cu	Fe	Zn	Mn	Al	Pb	Sn	
Ajax	25–50	5–20	30–70						Bearing metal, gun mountings.
Aluminum-nickel	76.4					23.6			
Aluminum-silver	20	57		20		3			
Aphtit	20–21	70–75		5.2–2.2					Cd 4.5–1.8.
Aluminum wire (B)	1.3	1				97.7			
Ashberry metal	1–3	2–3		1–3				78–80	Sb 14–20. Tableware.
Bario metal	90								W 1.22, Si 0.29, Cr 4.25. Heat and acid resisting alloy.
Baros	90								Cr 10. Used in expansion pyrometer apparatus.
Bearing metal	10.4							83.3	6.3 W. For high speeds.
Bismuth bronze	24	25							Sb 50, Bi 1.
Complex English metal	2	2		1				87	Bi 0.5, W 1.5, Sb 6.
Cooperite	80								W 14, Zr 6. Cutting tools.
Corronil									Very similar to Monel metal; made in England.
Cuniloy	65	25			35(?)		1		Resistance to corrosion and alkalis.
Cufenium	22	72	6						Knives, forks, spoons.
Illium	60.6	6.4	.76		1	1.1			Cr 21, Mo 4.7, W 2.1, Si 1. Acid resisting (see p. 114).
Invar	36		63.5		.5				Low-expansible steel (see p. 96).
Machine bronze	25	50–90		.30			0–8	0–30	
Do	25	50						25	
Minargent	39.77	56.82				.57			W 2.84.
Do	32	46					22		
Mira metal	0.24	74.7	.43	.62			16.3	0.91	Sb 6.8. For cocks, pipes, etc., to resist acid corrosion.
Newloy	35	64						1	Noncorroding alloy, manufactured in England, used for tableware.
Nickel-aluminum bronze	10	88				2			
Do	40	10				30		20	
Nickel bronze	30	86						11	
Do	25	50						25	Known also as "Nickel Bearing" (nickel silver).
Nickeloy	1.41	4.15				93.8			Casting gives 20,000 lbs./in.[2] tensile strength, 4.5 per cent elongation.
Nickel-manganese bronze	2.5	53.4		39	1.7	.2	.3	2.6	
Nickel tungsten	25–50								W 50–75; alloy for mixing.
Nickel zirconium	86.4					6			Si 6, Zr 1.5, C 0.1. High-speed cutting tools.
Plastic bronze	1	64					30	5	Known also as "Ajax Plastic."
Platinite	46		54						46 per cent nickel steel.

Proplatinum	72								Ag 23.6, Bi 3.7, Au 0.7. A substitute for platinum.
Platnam	53.8	32.55	.48			.32		12.72	Used for valve seating.
Rosein	40					30		20	Ag 10. Used for jeweler's work.
Sea-water bronze	32.5	45		5.5				16	Bi 1. Resistant to sea water.
Sheathing bronze	32.5	45		5.5				16	Bi 1.5.
Sideraphite	23	5	63			5			W 4. Acid-resisting alloy.
Speculum	4	64						32	For telescopes. Does not always contain nickel.
Stellite	1		2						Co 75, Cr 16.5, Si 3-4, C 2. Pocket and table knives, surgical instruments, machine tools.
Trabuk	5.5							87.5	Sb 5, Bi 2. Substitute for nickel silver; resistant to vegetable acids.
Turbadium bronze	2	48		46					
Turbiston's bronze	2	55	.84	41	.16	1			Resistant to salt water.
Typewriter metal	20	57		20		3			Used for typewriter metal.
Unmagnetizable watch wheels	18	18							Pt 62.75, Cd 1.25. Used for watch wheels.
Warne's metal	26							37	Bi 26, Co 11.
White gold	59								Au 41. Substitute for platinum.
Do	15			5					Au 80. Substitute for platinum.

Nickel is used to some extent, particularly abroad, as a component of aluminum bronzes to which it appears to impart desirable properties. Parker (576) has pointed out the desirability of studying the possibilities of these alloys for the construction of high-speed blades for superheated steam, and mentions several compositions which are in commercial use in Great Britain:

Composition.	Per cent.	Per cent.	Per cent.
Copper	82.07	79.63	79.0
Aluminum	2.54	9.77	11.5
Nickel	14.64	4.13	5.0
Manganese	Nil.	.94	Nil.
Zinc	.68	Nil.	Nil.
Iron	Trace.	4.80	4.5
Silicon	.04	.14	....

Bronzes of similar composition containing aluminum and nickel have also been produced commercially as substitutes for nickel silver under such names as aluminum silver and minargent. They have a fine white color and will take a good polish.

TABLE 63.—Tensile Properties of Nickel-Aluminum-Copper-Alloys. (Read and Greaves, 837.)

[These values apply to rolled and annealed (900° C.) 1-inch diameter rods from 2¼-inch ingots.

Chemical composition.			Tensile properties.			
Cu	Ni	Al	Yield point.	Tensile strength.	Elongation in 2 inches.	Reduction of area.
Per cent.	Per cent.	Per cent.	Lbs./in.²	Lbs./in.²	Per cent.	Per cent.
89.94	....	10.06	32,200	57,500	9.0	10.4
87.66	2.46	9.88	40,500	71,500	12.3	13.0
85.11	4.95	9.94	40,400	77,400	16.2	17.4
82.82	7.48	9.70	42,100	87,200	13.1	15.1
94.98	....	5.02	11,600	49,600	82.5	78.9
93.96	.94	5.10	11,900	51,000	94.6	76.1
92.68	2.38	4.94	12,300	51,300	90.2	71.0
89.84	4.84	5.32	21,100	57,300	70.0	60.2
87.48	7.31	5.21	53,700	87,400	25.6	26.8

Read and Greaves (829, 837) have contributed results of extensive tests of aluminum-nickel bronzes of this type. These alloys were found to forge and roll satisfactorily and to have good mechanical properties, the hardness increasing with the nickel content. Table 63 contains the results of some of their tensile tests on rolled and annealed alloys. Corrosion tests in fresh and sea water carried out by these investigators indicated that the presence of nickel in aluminum bronzes decreases markedly the corrosion of the alloy in sea water; it does not seem to affect the corrosion of the alloy in fresh water. These conclusions are shown in the results of their tests given in Table 64.

TABLE 64.—Corrosion Tests of Rolled and Annealed Nickel-Aluminum-Copper Alloys. (Read and Greaves, 837.)

Chemical composition.			Corrosion loss in weight per month.		Chemical composition.			Corrosion loss in weight per month.	
Cu	Ni	Al	Sea water.	Fresh water.	Cu	Ni	Al	Sea water.	Fresh water.
Per cent.	Per cent.	Per cent.	Mg/100 cm²	Mg/100 cm²	Per cent	Per cent.	Per cent.	Mg/100 cm²	Mg/100 cm²
89.94	....	10.06	434.5	43.0	94.98	....	5.02	148.0	28.7
89.55	0.97	9.48	105.1	28.7	94.04	0.92	5.04	148.0	38.2
85.15	4.94	9.91	57.3	52.5	90.09	4.90	5.01	57.3	33.4
80.13	9.98	9.81	43.0	43.0	85.08	10.07	4.85	23.9	57.3

Bingham and Houghton (813) and Austin and Murphy (814) have recently contributed data toward the establishment of the constitutional diagram for the ternary system copper-nickel-aluminum.

The properties of light aluminum alloys containing nickel have been studied by Read and Greaves (829), Merica, Waltenberg, and Finn (824), and Merica and Karr (825). Their results showed that nickel in amounts up to 4 per cent added to aluminum produces an alloy which will roll and work very readily and have satisfactory mechanical properties. Thus, an alloy containing 3.9 per cent of nickel possessed in the form of rolled and annealed sheet the following tensile properties:

Tensile strength, pounds per square inch	20,200
Elongation in 2 inches, per cent	24

It did not appear, however, that light aluminum alloys containing nickel are as strong, hard, and resistant to corrosion as those which have been hardened with copper, manganese, or zinc in similar amounts.

Merica and Karr obtained promising results by adding 1 to 2 per cent of nickel to light aluminum castings containing also from 2 to 3 per cent copper. The tensile properties of a sand-cast alloy containing 3 per cent copper, 0.8 per cent manganese, and 1.5 per cent nickel were as follows:

Tensile strength, pounds per square inch	24,000–25,000
Proportional limit, pounds per square inch	6,000–7,000
Elongation in 2 inches, per cent	4
Reduction in area, per cent	8.5

At about the same time in England Doctor Rosenhain and his associates (821) obtained in the course of an extensive investigation an alloy, designated as "Alloy Y," containing 4 per cent copper, 2 per cent nickel, and 1.5 per cent magnesium, which after suitable heat treatment showed considerably better tensile properties than those previously met with in light aluminum alloys with the exception of Duralumin. By quenching seven-eighths-inch hot-rolled rounds from 520° C. in boiling water they obtained a tensile strength of about 54,000 lbs./in.^{2} and 20 per cent elongation on 2 inches. Thin sheets cold rolled and quenched from 530° C. (986° F.) and then aged gave upward of 63,000 lbs./in.^{2} and 17 per cent elongation on 2 inches. This "Alloy Y" compares favorably with other aluminum alloys, such as Duralumin, in tensile strength and in resistance to alternating stresses at ordinary temperatures and is superior at elevated temperatures—particularly with respect to fatigue at slightly elevated temperatures. In either the cast or rolled condition it is immune to season-cracking and it offers even better resistance to corrosion than Duralumin when exposed to sea water. From 1 to 2 per cent of nickel is used in the aluminum-copper-magnesium alloy, magnalite, and in certain varieties of magnalium produced abroad.

Nickel has been substituted for a portion of the tin in government bronze with good results (Burgess and Woodward, 560); these investigators give results of tensile tests of castings. (See Table 65.)

TABLE 65.—Tensile Tests of Government Bronze Castings Containing Nickel.

Composition (per cent).	Tensile strength.	Yield point.	Elongation.	Reduction of area.
	Lbs./in.^{2}	Lbs./in.^{2}	Per cent.	Per cent.
88 Cu, 5 Sn, 5 Ni, 2 Zn	40,700	13,100	31.8	28.0
89 Cu, 4 Sn, 4 Ni, 3 Zn	39,700	11,500	31.2	31.2

These results may instructively be compared with the American Society for Testing Materials specifications for government bronze of composition 88 Cu, 10 Sn, 2 Zn, as follows: Tensile strength, 30,000 lbs./in.^{2}; elongation in 2 inches, 14 per cent. The proposal has also been made to substitute nickel for a portion of the copper in the same composition (562) by using some cupronickel scrap in making the alloy.

Nickel shot containing from 5 to 7 per cent silicon is being produced for use as an abrasive and burnishing agent to replace steel balls. Its Brinell hardness is approximately 300 and, in addition, it is not subject to corrosion to the same degree as steel.

A nickel-tantalum alloy containing 70 per cent nickel and 30 per cent tantalum is hard, easily rolled, hammered, and drawn into wire (793). Nickel when alloyed with tantalum loses its magnetic properties. An advantage possessed by the nickel-tantalum alloy over metallic tantalum is that it can be heated in a moist atmosphere up to a high temperature without becoming oxidized. The alloy is prepared by heating at a white heat a highly compressed mixture of the two metals in powder form.

Cooperite, a nickel-zirconium alloy named after its inventor and patented for use in machine tools, has shown some interesting results in cutting tests in comparison with ordinary high-speed steels. Table 62 contains the chemical analysis of a specimen of this alloy as determined by the bureau several years ago, and reference No. 543c in the bibliography is an article descriptive of this alloy.

Nickel is a powerful decolorizing agent for metals, such as copper and gold. Several jewelers' white alloys are produced to-day as substitutes for platinum under the name of white gold; they contain from 20 to 50 per cent of nickel, with the balance of gold.

An alloy of 90 per cent of nickel and 10 per cent of tin is used to some extent for valve seats and rings.

Nickel in small amounts has been found to exert a beneficial effect on copper-lead bearing bronzes in preventing the segregation of the lead. Thus a much-used railway bearing bronze for heavy bearings, known as "Plastic Bronze" or "Ajax Plastic," contains:

	Per cent.		Per cent.
Copper	64	Lead	30
Tin	5	Nickel	1

Manganin, a copper-manganese-nickel alloy (see Table 52), has recently found use for springs and diaphragms in automobile horns. This alloy is very malleable and ductile, and possesses a considerable degree of toughness as well as an almost negligible temperature coefficient of expansion.

WASHINGTON, July 19, 1923.

PART C. APPENDIXES.

1. DEFINITIONS OF PHYSICAL TERMS.

Absorption Index.—When monochromatic light traverses a distance equal to its own wave length λ, in a material, the ratio of the amplitude of the emergent light J'_λ to that of the entering light J°_λ is

$$\frac{J'_\lambda}{J^\circ_\lambda}=e^{-2\pi\kappa}$$

where κ is the absorption index.

(A variety of usages prevails regarding the definition of this term. This definition is used in the Smithsonian physical tables.)

Density.—The density of a substance is the mass per unit volume. It is usually expressed in terms of grams per cubic centimeter.

Specific Gravity.—The specific gravity of a substance is the ratio of the mass of the body to the mass of an equal volume of water at some standard temperature, usually 4° C.

Electrical Resistivity (ρ, δ).—There are two methods of expressing electrical resistivity in common use, each being defined quantitatively in terms of the resistance of a unit specimen. The volume resistivity is ρ in the equation

$$R=\frac{\rho l}{s}$$

in which R=resistance, l=length, and s=cross section. The volume resistivity thus defined may be expressed in various units, such as microhm-cm (microhm per centimeter cube), ohms per foot of a uniform wire 1 mil in diameter, etc. The commonly used units, in abbreviated terminology, are: microhm-cm, microhm-inch, ohm (meter, mm), ohm (meter, mm^2), ohm (mil, foot).

The other kind of resistivity is mass resistivity, and is defined as δ in the equation

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

in which m=mass of the wire. The usual units of mass resistivity are: ohm (meter, gram), and ohm (mile, pound).

Per Cent Conductivity.—The term "conductivity" means the reciprocal of resistivity, but it is used very little in wire calculations. In connection with copper, however, extensive use is made of the per cent conductivity, which is calculated in practice by dividing the resistivity of the International Annealed Copper Standard at 20° C. by the resistivity of the sample at 20° C.

Temperature Coefficient of Resistance.—The temperature coefficient of electrical resistance is the fractional change of resistance per degree change of temperature. Its value varies with the temperature, and hence the temperature from which the resistance change is measured must always be stated or understood. For a temperature t_1, the temperature coefficient t_1 is defined, for a metal like copper, by

$$R_t=R_{t_1}\,[1+\alpha_{t_1}\,(t-t_1)],$$

in which R_{t_1}=resistance at the temperature t_1 and R_t=resistance at any other temperature t. The temperature coefficient that is usually used at 20°, for example, is

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

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

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 millimeters) of the spherical indentation. (Hardness numeral= H. N.)

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

where

$$t = D/_2 - \sqrt{D^2/_4 - d^2/_4}$$

P=pressure used.
t=depth of indentation.
D=diameter of sphere.
d=diameter of indentation.

Electrolytic Solution Potential (E).—At the junction of a metal and any conducting liquid there is developed 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

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

R=the gas constant.
T=absolute temperature.
n=valence of metal.
F=96,500 coulombs, the Faraday constant.
P=solution pressure of metal.
p=osmotic pressure of metal ion formed in solution.

In any electrolytic cell the sum or difference of two such potentials is measured, one of which may be a standard electrode; for example, the hydrogen or the calomel electrode. The 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, the emf of the normal hydrogen electrode is arbitrarily assumed to be zero. The sign of such single potentials is arbitrarily defined as the sign of the potential of the metal with respect to the solution. In this usage recently adopted by the American Electrochemical Society and the International Union of Pure and Applied Chemistry the "normal potential" of zinc is negative.

Emissivity (E or Eλ).—The coefficient of emissivity E for any material represents the ratio $\frac{J'_\lambda}{J_\lambda}$ of the intensity, J'_λ, of radiation of some particular wave length or color, λ, emitted by the material at an absolute temperature T to that, J_λ, emitted by a black body radiator at the same temperature.

The coefficient of total emissivity E for any material represents that ratio $\frac{J_1}{J}$ of the intensity of radiation of all wave lengths, J_1, emitted by the material at an absolute temperature, T, to that, J, emitted by a black body radiator at the same temperature.

This coefficient is always less than 1, and for metals is equal to 1 minus the reflection coefficient for normal incidence (Kirchhoff's law).

For any optical pyrometer using monochromatic light a value of the observed or "black body" temperature of any substance (not inclosed) is reduced to the true temperature by the following formula:

$$\frac{1}{T}-\frac{1}{T_0}=\frac{\lambda \log_{10} E\lambda}{6232}$$

T=true absolute temperature.
T_0=observed absolute temperature.
λ=wave length in microhm (0.001 mm).
$E\lambda$=relative emissivity of substance for wave length.

Erichsen Test.—This test is carried out to determine the ductility of sheets. An indentation is made in the sheet with a die with hemispherical end. The greatest depth of indentation which can be made without incipient cracking of the sheet, measured in inches or millimeters, is known as the Erichsen value for the sheet.

Heat of Fusion.—The heat of fusion of a substance is the quantity of heat absorbed in the transformation of unit mass (1 g) of the solid substance to the liquid state at the same temperature.

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

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

Susceptibility is given, in corresponding units, by

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

For all materials except iron and a few other ferromagnetic metals μ is very nearly unity and κ is only a few millionths. When κ is positive in sign the substance is paramagnetic, when negative diamagnetic. The susceptibility as thus defined is sometimes called volume susceptibility and indicated by κ_v. A quantity called mass susceptibility is also used, and is equal to the volume susceptibility divided by the density of the material; it is represented by κ_m.

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

Peltier Effect (π).—When at the junction of two metals current flows from one to the other, heat is, in general, absorbed or liberated (see "thermoelectromotive force" below); the coefficient, the amount of heat liberated when a unit quantity of electricity flows across the junction, is known as π (measured either in calories per coulomb or in volts), the Peltier effect.

Refractive Index.—The ratio of the velocity of light in vacuum to that in any material is called the refractive index (η) of that material. (This physical quantity ceases to have a meaning at or near an absorption band in the material.

Scleroscope Test (Shore).—A hardened hammer falls from a constant height onto a polished surface of the material, and the distance of rebound is measured on a scale 10 inches long, divided into 140 equal parts. The scleroscope hardness is expressed as the distance of rebound on this arbitrary scale, the value 100 representing the hardness on this scale of hardened steel.

Specific Heat (σ).—The true specific heat of a substance is $\frac{du}{dt}$ when u is the total internal heat or energy of unit mass of the substance. The mean specific heat is defined as $\frac{q}{t_1-t_2}$ per unit mass when q is the quantity of heat absorbed during a temperature change from t_2 to t_1. It is generally considered as the quantity of heat (calories) required to raise the temperature of unit mass (grams) by unity (degrees centigrade), either at constant volume or at constant pressure. Unless otherwise noted the specific heat of solids refers to that at constant (atmospheric) pressure. The true specific heat (constant pressure) of metals may usually be expressed by an equation of the type

$$\sigma = A + Bt + Ct^2 + \ldots\ldots$$

TENSILE TEST.—The quantities determined in the tension test are the following:

The *ultimate tensile strength* is the maximum load per unit area of original cross section borne by the material.

The *yield point* (American Society for Testing Materials) is the load per unit of original cross section at which a marked increase in the deformation of the specimen occurs without increase of load.

The *elastic limit* (American Society for Testing Materials) is the greatest load per unit of original cross section which does not produce a permanent set.

The *proportional limit* (American Society for Testing Materials) is the load per unit of original cross section at which the deformations cease to be directly proportional to the loads.

The *percentage elongation* is the ratio of the increase of length at rupture between arbitrary points on the specimens to 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.

MODULUS OF ELASTICITY (YOUNG'S MODULUS).—The modulus of elasticity, in either tension or compression, is the ratio of stress, within the proportional limit, to the corresponding strain, as determined with a precise extensometer.

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

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

THERMAL EXPANSION.—If l_t is any linear dimension of a solid at any temperature, $\frac{dl}{ldt}$ is the linear coefficient of thermal expansivity of that solid 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:

$$\frac{dl}{ldt} = a + bt + ct^2 \ldots$$

For small temperature intervals a mean coefficient (α) is often determined, for example

$$\alpha = \frac{l_t - l_{t_o}}{l_{t_o}(t - t_o)}$$

THERMOELECTROMOTIVE FORCE (E).—In an electric circuit composed of two dissimilar conductors, the two junctions being at different temperatures, there exists in general an electromotive force, called the thermoelectromotive force, between the two metals, the value of which is a function both of the temperature and the difference of temperature between the two junctions. It is shown thermodynamically that this emf is related to the Thomson and Peltier effects in the following manner:

$$\left.\begin{aligned} \pi &= \frac{T}{J}\frac{dE}{dt} \\ \sigma_1 - \sigma_2 &= -\frac{T}{J}\frac{d^2E}{dt^2} \end{aligned}\right\} \text{and expressed in calories per coulomb when } J = \frac{418 \text{ dynes} \times 10^6}{\text{calories}}$$

when E is the thermal emf, T the absolute temperature, $\frac{dE}{dt}$ the thermoelectric power (see below), and $\sigma_1 - \sigma_2$ the difference in the Thomson effect of two materials. The form of the function $E = E(T)$ is not known. In general, the equation $\frac{dE}{dt} = A + BT$ satisfactorily fits the experimental data over a limited range of temperature of a few hundred degrees.

It has been shown that the Thomson effect for lead is practically zero. This metal has served as a comparison metal in studying the thermoelectric forces of others.

THERMOELECTRIC POWER.—If E is the thermoelectromotive force of any two dissimilar metals, $\frac{dE}{dt}$ = the thermoelectric power; it is at any temperature therefore approximately the thermal emf of a couple of which the temperatures of the two junctions differ by 1° C.

THE THOMSON EFFECT.—When a current flows in a conductor from a point at one temperature to one at another, heat is in general liberated, or absorbed, and an emf or counter emf is produced. The coefficient of the Thomson effect is the amount of heat liberated or absorbed when unit quantity of electricity flows from a point at temperature, t, to one at a temperature, $t + dt$, and is equal to σdt calories per coulomb where σ is the so-called Thomson specific heat of electricity. It is called positive for any material when heat is generated in that material as a current flows from a region of higher to one of lower temperature.

2. TYPICAL SPECIFICATIONS FOR NICKEL ALLOYS.

46M1b
FEB. 2, 1920.

SUPERSEDING
46M1a
Mar. 1, 1916.

NAVY DEPARTMENT SPECIFICATIONS.

CAST MONEL METAL, COMPOSITION Mo-c.

(Standard Stock Catalog designation: Monel metal (Composition Mo-c), cast.)

GENERAL SPECIFICATIONS.

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

TYPES.

2. Cast Monel metal furnished under these specifications shall be castings; ingots for forging or rolling; ingots for remelting; or shot, as required.

WORKMANSHIP.

3. (*a*) Castings and ingots for forging or rolling shall be in accordance with the required dimensions. They shall be sound, clean, free from blowholes, porous places, cracks, or any other defects which may materially affect their strength or appearance or which indicate an inferior quality of metal.

(*b*) Ingots for remelting and shot shall be clean, and will not be rejected on account of blowholes or surface defects.

CHEMICAL REQUIREMENTS.

4. The chemical properties shall be as follows:

Copper, minimum.	Nickel, minimum.	Iron, maximum.	Aluminum, maximum.	Manganese, maximum.	Carbon and silicon combined, maximum.
Per cent. 23.0	Per cent. 60.0	Per cent. 3.5	Per cent. 0.5	Per cent. 3.5	Per cent. 2.0

PHYSICAL REQUIREMENTS.

5. (*a*) The physical properties of the metal for all types shall conform to the requirements of the table given below:

Minimum tensile strength (pounds per square inch).	Minimum yield point (pounds per square inch).	Minimum elongation in 2 inches.
65,000	32,500	Per cent. 25

(*b*) The color and the grain of the metal shall be uniform throughout the fractured section of the test pieces.

77276°—24——9

TEST COUPONS.

6. (*a*) One test coupon shall be cast attached to each casting (including ingots for forging or rolling) which weighs 250 pounds or more. Additional coupons may be cast at the option of the manufacturer. When a heat is composed of castings weighing less than 250 pounds, one or more coupons run from the same gate as the casting shall be cast in the first flask and like coupons shall be cast in the last flask, poured from each heat. Coupons shall not be detached from the castings except in the presence of the inspector or until he has stamped same for future identication. The dimensions of the coupons shall be in accordance with the sketch incorporated in and forming part of these specifications.

(*b*) For ingots for remelting and shot one or more coupons shall be cast from each heat when required. Coupons for ingots for remelting may be gated to the ingot or cast separately at the option of the manufacturer. Coupons when cast separately shall not be poured except in the presence of the inspector.

NOTE FOR SUPPLY OFFICERS AND OTHERS.

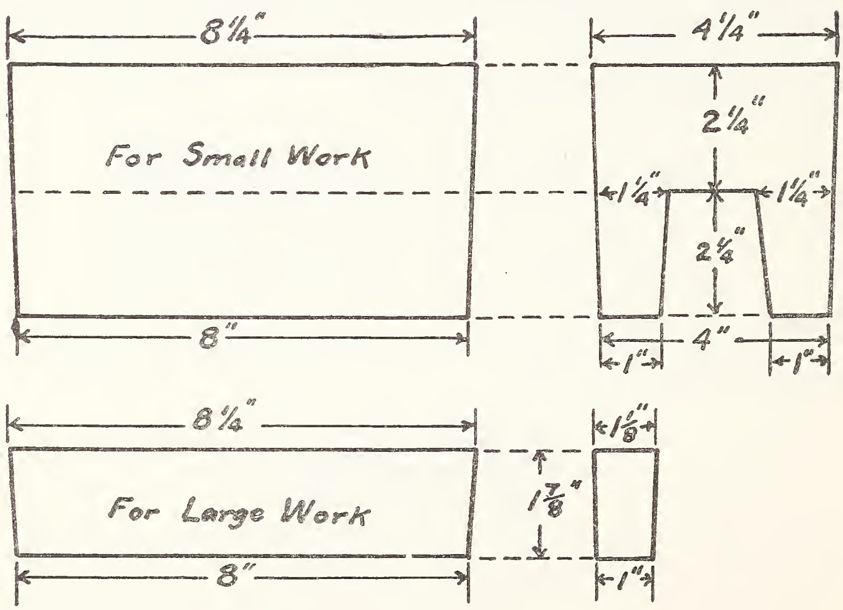
7. Cast Monel metal is suitable for the following purposes: Valve fittings, boat fittings, propellers, propeller hubs and blades, engine framing, pump liners, valve seats, shaft nuts and caps, composition castings requiring great strength and high resistance to corrosion, and for forging or rolling to shapes requiring similar properties.

SPECIFICATIONS, WHERE OBTAINABLE.

NOTE.—Copies of the above specifications may be obtained upon application to the Bureau of Supplies and Accounts, Navy Department, Washington, D. C.

REFERENCES:

S. E. 323156–687–4–S, July 25, 1918.
C. & R., Z46M1(S), July 31, 1918.
Ord., 34641/86(B2)–O, Aug. 12, 1918.
S. & A., 380–938.



STANDARD TEST COUPONS

46M7c
JAN. 3,
1922.
SUPERSEDING
46M7b
May 1, 1917.

NAVY DEPARTMENT SPECIFICATIONS.

ROLLED MONEL METAL (COMPOSITION Mo-r), BARS, PLATES, RODS, SHEETS, ETC.

GENERAL SPECIFICATIONS.

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

CLASSES.

2. Rolled Monel metal bars, plates, rods, and sheets shall be of the following classes, as required:

(*a*) Bars or rods.

(*b*) Plates or sheets.

MATERIAL AND WORKMANSHIP.

3. (*a*) Rolled Monel metal shall be clean, straight, smooth, of uniform color, quality, and size, and shall be free from all injurious defects. Scrap shall 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. The workmanship shall be first class in every respect.

(*b*) Monel metal in accordance with these specifications shall be hot rolled or forged.

GENERAL REQUIREMENTS.

4. The general requirements shall be as stated in paragraph 5 below.

DETAIL REQUIREMENTS.

5. (*a*) The chemical properties shall be as follows:

Copper, minimum.	Nickel, minimum.	Iron, maximum.	Aluminum, maximum.	Manganese, maximum.	Carbon and silicon, combined maximum.
Per cent. 23.0	Per cent. 60.0	Per cent. 3.5	Per cent. 0.5	Per cent. 3.5	Per cent. 0.8

(*b*) The physical properties of the metal shall conform to the requirements of the tables given below:

RODS AND BARS.

	Minimum yield point per square inch.	Minimum ultimate tensile strength per square inch.	Minimum elongation in 2 inches.	Cold bend—radius equal to diameter or thickness of test bar.
	Pounds.	Pounds.	Per cent.	Degrees.
Rounds and squares:				
Up to and including 1 inch	40,000	80,000	30	180
1-1/16 inches to and including 2 inches	48,000	85,000	30	180
2-1/16 inches to and including 3-1/2 inches	35,000	80,000	35	180
Over 3-1/2 inches	40,000	80,000	32	180
Hexagons and rectangles	40,000	80,000	32	180

SHEETS AND PLATES.

Tensile strength, minimum pounds per square inch.	Yield point, minimum pounds per square inch.	Elongation, minimum in 2 inches.	Cold bend—radius equal to diameter or thickness of test bar.
		Per cent.	Degrees.
65,000	30,000	15	120

NOTE.—No material less than 1/4 inch in thickness or diameter need be tested physically.

(*c*) *Rods and bars.*—Rods and bars will be received in stock lengths unless it is specifically stated that exact lengths are required. Stock lengths shall be as follows:

1 to *4* inches, *8* to *20* feet.
Over *4* inches, *6* to *20* feet.

(*d*) Rods and bars measured on their diameter or parallel faces shall not vary from the specified dimensions by more than the following amounts:

	Plus.	Minus.
	Inch.	Inch.
Rounds and rectangles:		
Up to and including 1 inch	0.016	0.016
1-1/16 to 2 inches inclusive	.031	.016
2-1/16 to 4 inches inclusive	.047	.031
Over 4 inches	.125	.062
Hexagons and squares (hot rolled):		
Up to and including 1-3/16 inches	.016	.016
Over 1-3/16 inches	.031	.031
Hexagons and squares (forged):		
Up to and including 1-1/2 inches	.031	.016
Over 1-1/2 inches	.031	.031

(*e*) *Plates and sheets.*—Plates and sheets shall be cut to the required dimensions and shall be ordered in as narrow widths as can be used.

(*f*) No excess weight will be paid for, and no single piece that weighs more than *8* per cent above the calculated weight will be accepted. The base or unit weight for such calculations shall be taken as *558* pounds per cubic foot, or *0.323* pound per cubic inch.

(*g*) The tolerances that will be allowed for undergauge at the thinnest point are as follows:

Widths of sheets or plates:	Tolerance (per cent).
Up to 48 inches	5
48 to 60 inches	7
Over 60 inches	8

METHOD OF INSPECTION, TESTS, ETC.

6. (*a*) Test specimens shall be taken from each lot of 500 pounds or less of the same cross-sectional square form and from the same heat and subjected to the following tests.

Chemical: As required in paragraph 5.

Bend and tension tests: As required in paragraph 5.

Hammer tests: Bars or rods shall stand hammering to a fine point.

(*b*) The color of the fracture section of test pieces and the grain of the material shall be uniform throughout.

PACKING AND MARKING OF SHIPMENTS.

7. (*a*) Shipments shall be packed as required by contract or order.

(*b*) Each shipment shall be marked with contract or order number, name of the contractor or manufacturer, and the contents.

NOTES TO SUPPLY OFFICERS, BIDDERS, MANUFACTURERS, AND OTHERS.

8. (*a*) The material is suitable for parts requiring strength or incorrodibility, such as propeller-blade bolts, air-pump and condenser bolts, and pump rods.

(*b*) Copies of these specifications may be obtained upon application to the Bureau of Supplies and Accounts, Navy Department, Washington, D. C.

REFERENCES:

C. & R., Z46M7(S), April 13, 1921.
Eng., 557419-687-4-S, April 19, 1921.
Ord., 34641/501-(E4)-O, April 22, 1921.
S. & A., 380-938.

46N1a
MAR. 1, 1917.
SUPERSEDING
46N1
June 20, 1913.

NAVY DEPARTMENT SPECIFICATIONS.

BENEDICT NICKEL, ROLLED, OR COMPOSITION Be-r.

(Standard Stock Catalog designation: Nickel, Benedict (composition Be-r), rolled.)

GENERAL SPECIFICATIONS.

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

SCRAP.

2. Scrap will not be used, except such as may result from the process of manufacture of articles of similar composition.

CHEMICAL PROPERTIES.

3. The chemical requirements are as follows: Copper, *84-86* per cent; nickel, remainder.

PURPOSES FOR WHICH USED.

4. The material is suitable for the following purposes: Tubes for condenser distillers and feed-water heaters.

SPECIFICATIONS, WHERE OBTAINABLE.

NOTE.—Copies of the above specifications can be obtained upon application to the Bureau of Supplies and Accounts, Navy Department, Washington, D. C.

REFERENCES:

Ord. 29752/273 (B2)-o, Jan. 17, 1917.
C. & R. Z46N1, Jan. 22, 1917.
S. E. 212218-687-9-S, Feb. 2, 1917.
S. & A. 380-933.

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