NBS CIRCULAR 485

Nickel and Its Alloys

UNITED STATES DEPARTMENT OF COMMERCE

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UNITED STATES DEPARTMENT OF COMMERCE • Charles Sawyer, *Secretary*
NATIONAL BUREAU OF STANDARDS • E. U. Condon, *Director*

Nickel and Its Alloys

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Preface

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 industrial firms, or from persons engaged in special investigative work in universities and technical laboratories. Such information is rarely to be found in systematic form; some sources of such information are not readily accessible, and the accuracy of the results given is not always certain.

There have, therefore, been issued from time to time, in response to these demands, Circulars on individual metals or alloys. The intent is to combine in each Circular all of the best information on the subject that the Bureau has as a result of its own tests and investigations, together with that available in records of published tests and investigations of such material.

The Circulars are concerned primarily with the physical properties of the metal or alloy. Except for a brief historical review and a few statistics of production, other features such as methods of manufacture, presence of impurities, thermal and mechanical treatment, etc. are discussed primarily in their relation to these physical properties. It is generally recognized that the physical properties of any metal or alloy are often in great degree dependent upon such factors, and any statement of values for such properties should be accompanied by 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 mentioned above, all statements, numerical or otherwise, made relative to the characteristics of the metal.

The present Circular, Nickel and Its Alloys, is more than a revision of the circular of the same title that was published by this Bureau in 1924. In the quarter century since 1924, many new alloys have been developed and a better understanding of metallurgical principles has resulted in improved properties, better control, and wider applications of existing alloys.

M. R. Meyerson assembled information and prepared the first draft of the present Circular, which represents a complete survey of the literature through 1946 and includes selected results published in 1947 and 1948. The manuscript was revised by J. G. Thompson with the assistance of W. E. Lindlief and M. R. Meyerson. Acknowledgment is made to Lura F. Roehl for assistance in the preparation of the figures, to Mary E. Connor, Margaret S. Corry, and J. L. Baker for the laborious task of proofreading, to W. Blum, H. A. Bright, T. G. Digges, G. A. Ellinger, W. F. Roeser, S. J. Rosenberg, and R. L. Sanford of the Bureau staff for comments and critical reading of portions of the manuscript within their fields of specialization, and particularly to O. B. J. Fraser, V. N. Krivobok, E. R. Patton, E. M. Wise, and other members of the staff of The International Nickel Co. Inc. for comments, suggestions, and for supplying published and unpublished information that was not readily available elsewhere.

E. U. Condon, *Director.*

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Nickel and Its Alloys

This Circular reviews available information about nickel and its alloys, with particular attention to the physical properties and applications of the metal, and its ferrous and nonferrous applications. It is a revision of National Bureau of Standards Circular 100, issued in 1924.

Introduction

Nickel, combined in its "natural" alloys, was used thousands of years before the element was isolated and recognized. The invincible blades of legendary warriors in China, Persia, and northern Europe were frequently described as Heaven-sent and probably were made from meteoric nickel-bearing iron. Alloys of copper and nickel, obtained by smelting complex sulfide ores, were first produced by the Chinese and were called "paktong," meaning white copper. The oldest example of copper-nickel alloys in existence today is a coin, containing 78 percent of copper and 20 percent of nickel, which was struck about 235 BC in the small Asiatic kingdom of Bactria. In later operations zinc was added to improve the malleability of paktong, which thus became the forerunner of "German silver" or nickel brass [104,247].[1]

The element nickel was isolated by Cronstedt in 1751; his results were confirmed by Bergmann in 1755. Richter, in 1804, announced the production of malleable ductile nickel, and the first commercial production of malleable nickel, which could be worked under a hammer, was by Joseph Wharton in 1865. Fleitman, in 1879, reported that additions of magnesium improved the malleability of nickel and subsequently found that manganese had a similar effect.

In the early stages of the nickel industry, ore was produced in Saxony, France, Norway, Sweden, Italy, Spain, Austria, Great Britain, and in the Ural Mountains of the USSR. Norway was the world's most important producer until 1877. New Caledonia succeeded Norway as the principal producer of nickel ore until about 1890, when Canadian pyrrhotite-chalcopyrite ores assumed the leading position that they still occupy in the nickel industry. Domestic ores of the United States have not been an important factor in the nickel industry, although there was some production in the latter half of the nineteenth century and in the early part of the present century.

In the European zone, the production of metallic nickel for subsequent conversion into alloys began about 1830 in Birmingham, England when the firm of Henry Merry developed "Merry's plate" and "Merry's metal blanc," efficient substitutes for the naturally alloyed paktong from China. The industry developed slowly; prior to 1870 the world production of nickel never exceeded 200 tons per annum. The introduction of nickel coinage in Germany, after the Franco-Prussian War, was an important stimulus to the nickel industry.

In the United States, Joseph Wharton, in 1862, established a refinery at Camden, N. J. to produce nickel from ores of the Lancaster Gap Mine in Pennsylvania. 130 tons of nickel were produced in 1885 [78] but production dwindled thereafter.

The Canadian nickel industry developed largely through the efforts of R. M. Thompson and S. J. Ritchie. The former developed improved processes for converting the ore to metal; the latter developed mines and markets for the products. The Canadian industry really started on the road to success about 1890, when the United States Government purchased $1,000,000 worth of Canadian nickel for the production of armor plate [58].

Part 1. Nickel

I. Sources

It has been estimated [291] that the earth's crust to a depth of 10 miles contains 0.016 percent of nickel, which makes nickel twenty-fourth in order of abundance of the elements. Other elements of the same order of abundance are zinc, boron, copper, and rubidium.

Nickel ores are widely distributed over the face of the earth. The most important deposits of today are in Canada, USSR, Cuba, New Caledonia, Norway, and Finland. Promising deposits are known to exist in Brazil, Venezuela, the East Indies, and the Philippines. Of less importance

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[1] Figures in brackets indicate the literature references at the end of this paper.

are the deposits in China, Tasmania, Saxony, South Africa, Borneo, India, Burma, and other countries. In the United States, small amounts of nickel ore have been mined in California, Connecticut, Missouri, Nevada, North Carolina, and Pennsylvania [212, 223].

The three most important classes [402] of ore are: (1) Sulfides, represented by the pyrrhotite-chalcopyrite ores of Canada and Norway, which contain from 3 to 6 percent of copper plus nickel in ratios varying from 1:1 to 3:1, with pentlandite as the nickel carrier; (2) silicates and oxidized ores, which are found in New Caledonia, Brazil, USSR, Venezuela, and other countries, containing up to 5 percent of nickel (plus cobalt), with garnierite as the principal nickel carrier. Included in this group are the lateritic chromium-nickel iron ores of Cuba and of Mindanao in the Philippines, containing about 1 percent of nickel, 2 percent of chromium and 45 percent of iron [305]; (3) arsenical ores, which are found in Canada, Continental Europe, and elsewhere. At the present time, the sulfide ores supply about 85 percent of the world output of nickel.

Canadian production of nickel ore reached an all-time peak in 1944 when 12,947,821 tons of ore were mined, yielding 137,299 short tons of nickel. More than 90 percent of this production was accomplished by the International Nickel Co. of Canada, Ltd., and the remainder by Falconbridge Nickel Mines, Ltd. Proved ore reserves for these two companies at the end of 1945 were reported as 217,373,000 short tons for International and 13,682,000 for Falconbridge [310, 352]. Canadian reserves of nickel ore have been materially increased by the recent discoveries of large quantities of high grade ore in Manitoba [348].

Large reserves of nickel ore exist in Cuba, the Philippines, and in Brazil. The Cuban ores are believed by Bailey [305] to comprise more than 2 billion tons averaging 1 percent of nickel. Cuban ores were successfully exploited as a wartime operation [293], and in 1946 Cuba ranked third in the list of nickel producers; but according to recent information supplied by the War Assets Administration, Cuban operations ceased in March 1947, and the plant and refinery have been offered for sale. The Philippines are reported to have 1 billion tons of ore, similar to the Cuban ore, which has not been exploited. Brazil has two large deposits of nickel silicate ore but, because of labor, transportation, power, and other difficulties, neither has been extensively worked [250, 295].

The USSR was a large producer of nickel in 1939 and 1940, but exact figures are not available [199, 241]. The Petsamo mines in Finland were taken over by the Germans and supplied them with 300 to 350 tons of ore per day. In 1944, the Soviet Government took possession of the Petsamo district, agreeing to pay indemnity to the International Nickel Co. [295].

II. Extraction, Recovery, and Refining

The Canadian sulfide ores are concentrated by sorting, crushing, grinding, and selective flotation to effect a rough separation of the nickel and copper sulfides from the gangue. In the International Nickel Co.'s practice, the flotation product is dewatered and roasted in multiple-hearth furnaces to dry it and reduce the sulfur content, and the hot material is discharged into reverberatory furnaces for smelting. During smelting, copper, nickel, and iron sulfides sink to the bottom of the melt, and the slag floats to the top where it is separated [158]. Silica is added to slag out iron, and the remaining metal is blown in Bessemer-type converters to form a matte containing about 48 percent of nickel, 27 percent of copper, 2 percent of iron, and 23 percent of sulfur.

The Orford (top and bottom) process is used to separate copper and nickel in the matte from the Bessemer converter, as indicated by the flow sheet, figure 1. The matte is first melted in cupolas with niter cake (sodium sulfate) and coke to form sulfides of sodium, copper, and nickel. This product is cast in large pots, where the difference in specific gravity of the molten sulfides causes a separation; the upper portion or "first tops" consists of the greater part of the copper and sodium sulfides, the lower portion or "first bottoms" consists of the greater part of the nickel sulfides. These layers can be readily split apart when cold. The "first bottoms" are resmelted, and a "second tops" with about 12 percent of nickel and a "second bottoms" with about 72 percent of nickel and 1.5 percent of copper are formed. The "second bottoms" are calcined to reduce the sulfur content and put through a series of leaching and roasting operations, the resulting product being black nickel oxide with about 77.5 percent of nickel, 0.1 percent of copper, 0.25 percent of iron, and 0.008 percent of sulfur. The oxide is reduced in reverberatory furnaces to metallic nickel (approximately 99.4 percent of nickel including less than 1 percent of cobalt).

Some of this metal is marketed in the form of pig or shot metal but most of it is further refined electrolytically. In this process the nickel anodes are dissolved electrolytically in a nickel sulfate electrolyte, in a two-compartment cell in which the anode and cathode compartments are separated by canvas. The anode liquor is circulated through a purification process before it reaches the cathode chamber. Starting sheets for cathodes are produced by plating and stripping thin sheets of nickel on stainless steel blanks. The product is 99.95 percent of nickel, including 0.3 to 0.5 per-

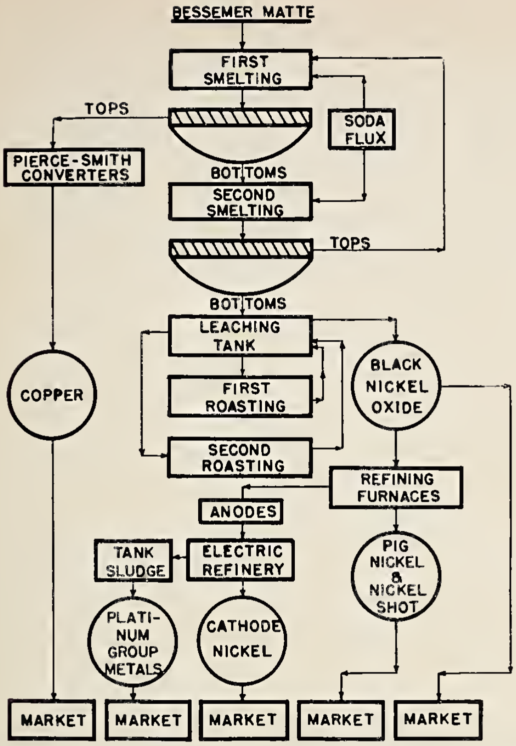

FIGURE 1. *Flow sheet of the International Nickel Company's process of refining copper-nickel matte.*

(Liddell [315])

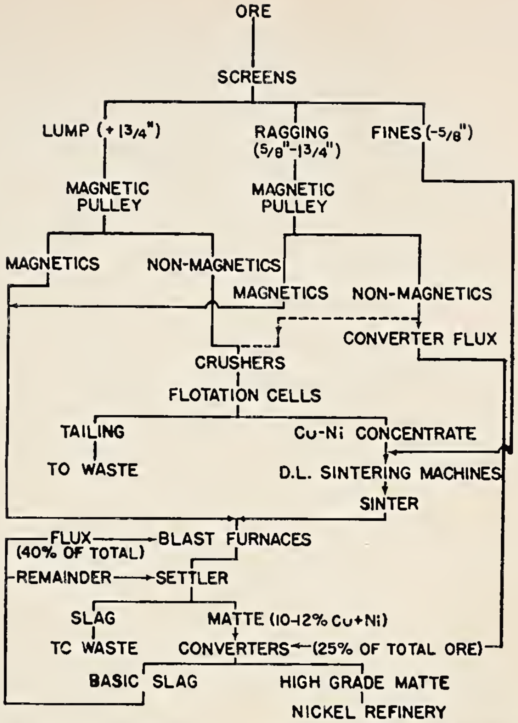

FIGURE 2. *Flowsheet of the Falconbridge Nickel Mines, Ltd. procedure.*

(Howat [267])

cent of cobalt. Sludge from the process contains platinum and other valuable metals, which are recovered [65, 81, 327a].

Either converter matte or second bottoms of the Orford process may be shipped to England for refining by the Mond process [96]. In this process, the raw material is calcined to reduce the sulfur content to about 1 percent, and is then reduced to impure nickel powder by treatment with water gas. Carbon monoxide is passed over the impure nickel powder at approximately 60° C, forming nickel carbonyl vapor $Ni(CO)_4$. The vapor is decomposed in towers heated to about 180° C, the nickel deposits on small pellets and the carbon monoxide is returned to the reaction chamber. Nickel deposits on the pellets in successive layers, like the layers on an onion. Six to eight months are required for the pellets to reach a diameter of 10 mm. Mond nickel contains a minimum of 99.5 percent of nickel, and is readily identified by breaking a pellet to reveal its layered structure [158].

A different method of treating Canadian sulfide ores is practiced by the Falconbridge Nickel Mines, Ltd., as indicated by the flow sheet in figure 2. In this procedure the copper is not separated from the nickel in the smelting operations, but, instead, the final matte contains both the copper and nickel that are separated by the Hybinette process, briefly, as follows: The high grade matte is roasted to remove most of the sulfur and is leached with dilute sulfuric acid to dissolve most of the copper and only a small amount of the nickel. The insoluble residue is melted and cast into anodes that contain about 65 percent of nickel and from 3 to 8 percent of sulfur. The anodes are dissolved electrolytically, copper is removed from the electrolyte by cementation, and refined nickel is deposited on the cathodes.

Prior to World War II, the Falconbridge matte was shipped to Kristiansand, Norway for refining as described in the preceding paragraph. During the war period, when the Norway refinery was not available, the matte was refined in Canada. Since the end of hostilities, refining is again being done in Norway.

Silicate ores such as are found in New Caledonia are sulfur- and copper-free. Sulfur-bearing materials, such as gypsum or pyrites, are added to the ore along with recovered flue dust. The briquetted mixture is smelted with coke in water-jacketed furnaces to produce a 30- to 45-percent matte, which is Bessemerized in small converters, with added silica to slag off the iron. The converter matte, approximately 80-percent nickel and 20-percent sulfur, is roasted to remove nearly all of the sulfur and to form nickel oxide. The oxide and a reducing agent are formed into cubes or rondelles, which are reduced in horizontal retorts at 1,200 or 1,300° C. The product is about 99.25-percent nickel [51,315]. Prior to World War II, the converter matte from New Caledonia was refined in this manner in France and Belgium, but during the war this matte was refined at Huntington, W. Va. [310].

The lateritic iron ore of Cuba was treated, during World War II, as follows: The finely ground ore was reduced by producer gas in Herreshoff furnaces. The reduced product was leached with ammonia solution, from which the nickel was precipitated as carbonate. This was calcined to nickel oxide, which was shipped to the refinery in Wilmington, Del. At the refinery the nickel oxide was mixed with reducing and fluxing agents and was reduced to metallic nickel in electric furnaces [293]. As previously stated, recent information indicates that operations for the recovery of nickel from Cuban ores ceased in March 1947.

III. Forms and Uses: Electroplating

The forms in which metallic nickel has appeared on the market include cathodes, ingots and shot, malleable nickel, anodes and anode bars, pellets, powder, cubes, rondelles, and grains. Ingot and shot formerly were the largest items, but, by 1940, electrolytic cathodes constituted more than one-half of the world's production. The nominal compositions of the various forms of nickel are shown in table 1.

TABLE 1. *Nominal composition of commercially available forms of nickel*

Form	Nickel and cobalt	Copper	Iron	Carbon	Silicon	Sulfur	Manganese
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Cathodes	99.90 to 99.95	0.01 to 0.03	0.01 to 0.04	trace	trace	trace	----------
Ingot and shot (several grades)	92.0 to 99.6	0.04 to 0.20	0.15 to 1.65	0.02 to 0.55	0.10 to 5.50	0.01 to 0.06	----------
Malleable (various grades, see table 2)	94.0 to 99.7	0.03 to 0.1	0.05 to 0.25	0.25 max	0.01 to 0.40	0.005 to 0.010	4.5 max
Anodes and anode bars	92.0 to 99.0	----------	----------	----------	----------	----------	----------
Cubes, rondelles, grains	99.2 to 99.5	----------	----------	----------	----------	----------	----------
Powder [a]	98.7 to 99.0	----------	----------	----------	----------	----------	----------
Pellets [a]	99.5 to 99.9	----------	----------	----------	----------	----------	----------

[a] Pellets and powder made from nickel carbonyl and cobalt-free. Powder prepared by other processes contains cobalt.

The cathodes weigh about 135 lb. each and are sheared to the various sizes required by consumers. The principal use is as an alloying addition to steel and other metals.

Ingot and shot nickel are made by remelting electrolytic nickel or reduced nickel oxide and casting it, without added deoxidizers, in molds or in water, respectively. Various grades of both ingot and shot nickel are available primarily for use in making alloys. "XX" ingot contains 99.45 Ni; another grade contains about 99.2 Ni; a third grade, "F" ingot, is a high-silicon, high-carbon product with a low melting point (1,250° to 1,285° C) and is used to make nickel additions to cast iron. "A" ingots are high in carbon content, about 0.45 percent. Nickel shot is also available in several grades. "XX" shot contains about 99.45 Ni, with low impurities content. "F" shot, like "F" ingot, is high in silicon and carbon contents and has a low melting point, which makes it particularly useful for ladle additions. Two grades of shot, "X" and "A", are still listed, although their production has been discontinued recently; according to advice from the International Nickel Co. "X" shot was slightly less pure and was formerly used for the same purposes as "XX" shot. "A" shot contains high carbon (about 0.45 percent) and was used in the manufacture of anodes for electroplating.

Cubes, rondelles, and grains are obtained by reduction of nickel oxide at low temperatures and are used for the production of alloys and nickel salts. Nickel powder, 100-mesh and finer, for use in powder metallurgy is prepared by low-temperature reduction of the oxide, by decomposition of nickel carbonyl, or by mechanical grinding. Pellets are produced by the carbonyl process and are characterized by their layered and unfused structure. Nickel produced by the carbonyl process is free from cobalt.

Malleable (wrought) nickel is manufactured by the addition of a deoxidizer and sulfur stabilizer, prior to casting into shape. According to Merica and Waltenberg [28], the principal cause of brittleness in nickel is the presence of sulfur as Ni_3S_2. Additions of magnesium or manganese convert the sulfur to MgS or MnS, in which state it has little effect on malleability.

Several grades of malleable nickel are on the market, differing in composition. Actually some grades are high-nickel alloys rather than pure malleable nickel, but because all contain more than 93 percent of nickel and for convenience of discussion, all are listed in this section. Representative compositions of the various grades of malleable nickel are shown in table 2 [299, 346, 351].

TABLE 2. *Nominal compositions of malleable nickels*

Type [a]	Ni (+Co)	Fe	Mn	Cu	C	Si	S	Others
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
"A"	99.4	0.15	0.2	0.1	0.1	0.05	0.005	--------------
"D"	95.2	.15	4.5	.05	.1	.05	.005	--------------
"E"	97.7	.10	2.0	.05	.1	.05	------	--------------
"L"	99.4	.15	0.2	.1	.02	.05	.005	--------------
"Z" [b]	94.0	.25	0.25	.05	.16	.40	.005	Aluminum, 4.30.
"Z–B" [c]	98.75	.10	.17	.03	.26	.13	.005	Titanium, 0.33. Magnesium, 0.30

[a] The type designations in this table are those of the International Nickel Co., Inc.

[b] Now known as Duranickel.

[c] Now known as Permanickel.

"A" nickel is commercially pure malleable nickel and is the product commonly known as "nickel." It has good mechanical properties, workability, appearance, and corrosion resistance in a variety of media. It can be hardened by cold work but not by heat treatment. Its uses include food-processing equipment, chemical apparatus, cyanide fusion pots, television, radio and radio sonde equipment [341], variable time-fuse tube electrodes, and many other applications. A large amount of "A" nickel is used in nickel and nickel-alloy coinage. "A" nickel is available commercially in many forms, including cold-rolled sheet and strip, cold-drawn rods and bars, seamless and welded tube and pipe, forged shapes, hot-rolled plates, sheet, rods, and bars, hot- and cold-rolled angles, castings, wire, and fabricated forms such as screen, wool, and cloth. Four modifications of "A" nickel, identified by the trade-marks "220," "224," "225," and "330," are used in special electronic applications. They differ from "A" nickel in that the copper, iron, manganese, and certain other elements they contain are more closely controlled [330, 354].

"D" nickel has special properties due to its high manganese content. At high temperatures it has better mechanical properties than "A" nickel, and it resists attack by oxidizing sulfurous conditions. Among its uses are spark plug electrodes, marine boiler refractory bolts, and vitreous enameling and annealing furnace parts. Commercial forms commonly available are cold-drawn rods and bars, seamless tube and pipe, and hot-rolled rods and bars.

"E" nickel resembles the "D" variety except for a lower manganese content. It is used for furnace lead-in wires and support wires in incandescent lamps and is produced primarily as wire, rod, and strip.

"L" nickel, also known as low-carbon nickel, has the same composition as "A" nickel except for its carbon content. It is softer than "A" nickel, is not as susceptible to work hardening. It is used in the manufacture of articles requiring difficult drawing, spinning, or stamping, such as crucibles, combustion boats, and containers for fused oxidizing salts. The commonly available forms are cold-rolled sheet and strip.

"U" and "V" nickels are used as anodes for electroplating. High carbon, sulfur, and silicon in "U" nickel improve the "activity" of the nickel in the plating bath. This is achieved in "V" nickel by the presence of nickel oxide and nickel sulfide [351].

The term "Z" nickel denotes a malleable nickel that is susceptible to precipitation hardening, that is, can be hardened by heat treatment. The first "Z" nickel contained 98.75 percent of nickel with small amounts of manganese, carbon, silicon, titanium, and magnesium. In 1945 an improved heat-treatable nickel was introduced by the International Nickel Co. and the term "Z" nickel was transferred to the new product, which contains 94 percent of nickel with 4.3 percent of aluminum as the principal minor constituent. Since 1945 the former "Z" nickel has been designated "Z nickel type B", by the International Nickel Co.; for the present paper this cumbersome phrase has been condensed to "Z–B". Early in 1949, while this Circular was in process of preparation, the International Nickel Co. again revised the designations of these alloys, "Z" nickel becoming Duranickel and "Z–B" nickel becoming Permanickel.

The heat-treatable malleable nickels are used where tough, hard, strong materials with corrosion-resistant characteristics are needed. Applications include coil springs, hand tools, wire brushes, flexible diaphragms, automobile radio antennae, pump parts, and extrusion dies for plastics. Both "Z" and "Z–B" nickel are commonly available as hot-rolled and cold-drawn rods, wire, and strip. Seamless tubing, sheet, and plate in limited sizes have been produced in "Z" nickel but not in the older "Z–B" nickel [355]. The heat treatment and resulting properties of "Z" and "Z–B" nickel are discussed in subsequent sections of this circular.

Electrodeposition plays a prominent part in the uses of nickel as well as in the operations of its production. In the production-refining operations, electrodeposition is the final step in the production of massive cathodes of high-purity nickel, which are subsequently cut or remelted to obtain it in useful forms. Electrodeposition, as a use for nickel, is called electroplating or nickel plating and is used to produce, on the cathode object, coatings of nickel usually less than 0.002 in. in thickness, for decorative and protective purposes. The extent of the nickel-plating industry is indicated by the fact that it accounts for approximately 10 percent of the total annual consumption of nickel.

The first record of the use of nickel as a bright electrodeposit was in 1843, but, because of the high price and poor quality of nickel in the early days, the nickel plating industry did not become established until about 1870. Today nickel plating is widely applied, for decorative and protective purposes, to steel, brass, zinc, aluminum, and numerous alloys. An undercoat of copper is frequently employed, to prepare a better surface for the subsequent application of the nickel coating. For many applications the nickel plating is covered with a thin coating of electrodeposited chromium for further improvement in appearance and resistance to tarnish. In the early days of nickel plating, good finishes could not be obtained on deposits thicker than a small fraction of one thousandth of an inch, and any porosity in these plates was objectionable from the corrosion-resistance standpoint. Nickel normally is more noble than iron or steel and, therefore, exposure in the presence of nickel accelerates the corrosion of the other metals. Improved plating procedure and the production of thicker plates have diminished the dangers of porosity, and, in modern practice, thicknesses of 0.001- or 0.002-in. are required when the nickel coat is the principal protection against atmospheric corrosion. Thinner coatings are used when the demands for protection against corrosion are not so severe. Table 3 summarizes the requirements of three ASTM specifications for thicknesses of nickel plate or nickel plus copper plate, on steel, zinc, and copper alloys, for different conditions of use.

Table 3. *ASTM Standards (B141–45; B142–45T; A166–45T) for plated nickel coatings*

Base metal; coating	ASTM symbol and type of service			
	D, very severe	F, severe	K, general	Q, mild
Steel:				
Cu+Ni, min (thickness, in.)	[a] 0.0020	0.00125	0.00075	0.0004
Final nickel, min (thickness, in.)	.0010	.0006	.0004	.0002
Cr, if required, min (thickness, in.)	.00001	.00001	.00001	.00001
Withstand 20% NaCl spray, continuous at 95° F, hr	96	72	48	16
Zinc:				
Cu+Ni, min (thickness, in.)	------	.00125	.00075	[b] .0005
Cu, min (thickness, in.)	------	.0004	.0003	.0002
Final Ni, min (thickness, in.)	------	.0005	.0003	.0003
Cr, if required, min (thickness, in.)	------	.00001	.00001	.00001
Withstand 20% NaCl spray, continuous at 95° F, hr	------	48	32	16
Copper and its alloys, over 50% Cu:				
Ni, min (thickness, in.)	------	.0005	.0003	.0001
Cr, if required, min (thickness, in.)	------	.00001	.00001	.00001

[a] When copper is used in excess of a thickness of 0.0001 in. its minimum thickness shall be 0.00075 in.

[b] Total of 0.0003 in. of nickel if used without copper undercoating.

As is indicated by the data in table 3, the undercoat of copper may vary from a thin flash to a fairly heavy copper coating. Flashes of copper are sometimes plated on copper and brass to insure cleanliness; heavy coatings of copper are applied to zinc prior to its plating in Watts type baths [260] or bright nickel baths; deposition of copper from a cyanide bath is preferred in plating steel. According to Blum and Strausser [227] an undercoat of copper adds little to the protective value of thin nickel coatings; the protective value of a composite nickel-copper coat with a thick nickel layer does not exceed that of a nickel coat of the same total thickness.

Prior to plating, some degree of preparation of the base metal is always required to insure good adhesion, corrosion resistance, and appearance. The degree of polishing and buffing applied to the work prior to plating varies with the individual article and with economic aspects. The better the surface before plating, the less polishing and buffing of the plated object is required, particularly when a bright polished finish is desired. The final step before plating is to clean the prepared surface by appropriate pickling or washing procedures to remove tarnish films, buffing dirt, and other foreign matter.

Nickel anodes for plating operations are made of nearly pure nickel, sometimes with small additions of nickel oxide or carbon to depolarize or improve the solution behavior of the metal. The anodes may be cast or rolled and cut to size.

Several types of plating baths, each with several variations, are used for nickel plating. Typical examples [228, 268, 354, 368] are as follows:

For plating on steel or brass at low current density:

Nickel sulfate $NiSO_4.7H_2O$	16 oz
Ammonium chloride NH_4Cl	2 oz
Boric acid H_3BO_3	2 oz
Water	1 gal

pH=5.3; temperature=70 to 90°F; current density=10 to 20 amp/ft^2.

For plating on steel, brass, or aluminum, and over copper on zinc, at high current densities:

Nickel sulfate $NiSO_4.7H_2O$	30 to 40 oz
Nickel chloride $NiCl_2.6H_2O$	6 oz
Boric acid H_3BO_3	4 oz
Water	1 gal

pH=either 2.0 to 2.5 or 5.0 to 5.2; temperature=100 to 150°F; current density=25 to 50 amp/ft^2. Prior treatment of the aluminum is required to secure adhesion. The common practice is to dip aluminum into a zincate solution to facilitate the subsequent deposition of copper, or nickel.

For plating directly on zinc die castings:

Nickel sulfate $NiSO_4.7H_2O$	10 oz
Sodium sulfate Na_2SO_4	15 oz
Ammonium chloride NH_4Cl	2 oz
Boric acid H_3BO_3	2 oz
Water	1 gal

pH=5.5; temperature=70 to 80°F; current density=20 to 30 amp/ft^2.

For plating on magnesium:

Nickel sulfate $NiSO_4.7H_2O$	8 oz
Boric acid H_3BO_3	4.6 oz
Ammonium fluoride NH_4F	4.6 oz
Duponol ME	0.0067 oz
Water	1 gal

pH=5.5, adjusted by additions of hydrofluoric acid; temperature=104° F; current density=10 to 30 amp/ft^2.

Bright nickel baths usually are similar to the first of the foregoing baths, with additions of organic compounds and with a wide range of operating conditions (pH, temperature, and current density). According to Halls [252], the main structural difference between ordinary and bright nickel deposits is the finer grain of the latter, but Blum [369] believes that the presence of parallel layers in the bright deposits differentiates them from ordinary deposits. The bright coats are harder but less ductile and are equal in protective value to dull nickel [327].

All-chloride baths have been developed that have advantages and disadvantages as compared to the sulfate-chloride baths [224, 337, 345]. Deposits from the all-chloride baths are finer-grained, harder, stronger, and less ductile; the throwing power is good and the conductivity is about twice that of the chloride-sulfate baths. The addition of organic compounds permits bright plating at high speed from the all-chloride baths.

Various processes have been developed for the codeposition of nickel with cobalt, cadmium, zinc, iron, tungsten, copper, and other metals [174, 245, 290, 327, 344]. These deposits are used for the special properties they possess, particularly for colorful decorative purposes.

Sintered nickel powder (see page 4) is used for filtering and purifying concentrated alkaline solutions, and porous cups made from nickel powder are used in proximity fuses where the delayed action mechanism is controlled by the time required for mercury to seep through [303, 338]. The effects of variations in the pressing and sintering treatment on the density, tensile, and impact properties of dense nickel parts made from carbonyl powder were reported by Hardy [282]. Other powder metallurgy uses include aluminum-cobalt-iron-nickel magnets, iron-nickel magnet cores, cobalt-iron-nickel glass to metal seals, copper-nickel-tungsten "heavy metal," and silver-nickel contact points.

Nickel flake, for use in the production of alkaline storage batteries, is manufactured by depositing alternate layers of copper and nickel and subsequently dissolving the copper. Other methods of making nickel flake are described in U. S. Patent 2,365,356 and British Patents 576,144 and 545,962.

Nickel-clad steel plate, sheet, and strip consist of open-hearth steel with a layer of nickel on one or both surfaces. These composite materials are formed by pressure welding, in a rolling mill, of the cladding material and the steel slab, at a temperature of about 2,200° F. The clad products combine the corrosion-resistance of nickel with the mechanical properties, heat conductivity, and thermal expansion of the steel, and are used where solid nickel is not required and where items are too large to be nickel plated by electro-deposition. Applications of nickel-clad steel include tank cars and pots for handling caustic soda, water-storage tanks, dye tanks, soap kettles, varnish kettles, and corrosion-resistant equipment for the food, photographic, viscose, leather, rubber, and other industries. Nickel-clad steels are regularly supplied with cladding of 5, 10, 15, or 20 percent of the thickness, one or both sides, of the composite product. Steel clad with Monel or with Inconel is also available [242, 249, 256, 397].

About 1 percent of the total world consumption of nickel is used in nonmetallic forms. The salts generally used in electroplating are nickel sulfate, nickel-ammonium sulfate, nickel chloride, and nickel carbonate. Aside from this the two principal commercial applications of nickel compounds are the use of nickelous hydrate in the Edison cell and the use of sulfate, formate, or carbonate to produce a finely divided nickel catalyst for hydrogenation of oils. Nickel sulfate solutions are used as a dip bath for steel shapes prior to vitreous enameling. Some use is being made of the sintered oxide as an addition to steel in lieu of metallic shot. Nickel oxide is also available in both green and black forms, for use in the production of under coats of enamel on steel, and for coloring glazes on pottery.

IV. Statistics of Production and Consumption

Most of the data included here were obtained from various issues of the Minerals Yearbook, Mineral Industry, or were supplied by H. W. Davis of the U. S. Bureau of Mines. Some of the statistics relating to production, imports, exports, and consumption of metals during the war years 1941 to 1945 are not yet available.

Table 4 records available production data for the principal producers of nickel ore. In prewar years Canada produced more than 80 percent of the world's production of ore, but increased output in other countries, particularly USSR and Cuba, during the war years, reduced this figure to about 70 percent for 1945 to 1946. Intermittent and generally small scale production of ore during this period was reported from Australia, Brazil, Burma, Egypt, Germany, Greece, Iran, Italy, Morocco, Netherlands Indies, Rhodesia, and South Africa. Figures for these minor producers are included in the world totals.

Table 4. *Nickel content (short tons) of ore produced, 1937–1946*

Country	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946
Canada	112, 452	105, 286	113, 052	122, 779	141, 128	142, 605	144, 008	137, 298	122, 565	94, 833
USSR	2, 205	2, 756	-------	9, 535	-------	-------	-------	12, 302	-------	14, 771
Cuba	-------	-------	-------	-------	-------	-------	2, 679	5, 158	12, 015	12, 391
New Caledonia	12, 787	12, 897	11, 712	11, 613	11, 459	10, 378	8, 128	8, 945	4, 771	-------
Finland	-------	-------	-------	-------	-------	1, 797	9, 888	345	4, 079	-------
Japan	-------	-------	-------	-------	2, 547	1, 380	1, 778	1, 896	717	3, 063
Norway and Sweden	967	1, 372	1, 219	1, 110	1, 111	1, 420	1, 410	1, 353	491	-------
United States	219	416	394	554	660	612	642	988	1, 155	352
World total	[a] 132, 500	[a] 127, 500	[a] 134, 500	[a] 154, 500	[a] 179, 000	[a] 182, 000	[a] 190, 000	[a] 180, 000	[a] 169, 000	[a] 140, 000

[a] Estimated.

Production, import, and export data for the United States and Canada during and immediately after the war years, are shown in table 5. Data for 1937 are included for comparison. The base price for electrolytic nickel in carload lots, f. o. b. Port Colborne, Ontario, was 31½ cents per pound from 1937 through 1945 and was 35 cents per pound in 1946. These quotations include U. S. Customs duty of 2½ cents per pound.

Table 5. *Production, imports, and exports of nickel metal (short tons) for the United States and Canada*

	1937	1941	1942	1943	1944	1945	1946
United States							
Production:							
Primary [a]	219	660	612	642	988	1, 155	352
Secondary [b]	2, 400	5, 315	4, 142	6, 917	4, 321	6, 483	8, 248
Imports	54, 435	124, 130	132, 954	141, 249	134, 932	122, 528	104, 734
Exports	4, 473	7, 125	7, 096	9, 464	7, 931	3, 876	7, 977
Canada							
Production	112, 395	141, 129	142, 606	144, 009	137, 607	122, 565	94, 833
Imports	491	1, 011	499	545	424	762	-------
Exports	111, 385	137, 595	138, 795	135, 547	133, 599	108, 222	111, 939
World production (approximate)	127, 000	179, 000	182, 000	109, 000	180, 000	169, 000	140, 000

[a] Chiefly byproduct of copper refining.
[b] Recovery from scrap and other sources, and in alloys and salts.

Table 6 presents available data on world consumption of nickel for various uses in 1937, 1938, and 1939, and for U. S. consumption in 1945 and 1946. The figures for world consumption indicate a fairly constant distribution, the increased consumption of nickel in steel in 1938 and 1939 being compensated at least in part by a decrease in electroplating activities. U. S. consumption for the last war year and the first postwar year follows the general pattern of world consumption. A sharp drop in the proportion of nickel consumed in ordnance steels would be expected at the close of the war. In the 1946 figures, the decreased proportion of nickel consumed in steel is compensated by increases in the nonferrous uses, resistance alloys, and electroplating. Fluctuations from year to year in the amount of nickel used for specific purposes frequently are more pronounced than the corresponding fluctuations in the class that includes the specific purpose.

Table 6. *Nickel consumption according to uses in prewar years and in 1945 and 1946*

Use	World consumption consumption			United States consumption	
	1937	1938	1939	1945	1946
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Steel (including heat- and corrosion-resisting steels and high-iron alloys).	56	61	61	58	42
Cast iron	5	3	3	3	4
Copper-nickel, nickel silver, brass, bronze, aluminum alloys, Monel, Inconel, malleable nickel.	24	25	22	27	32
High-temperature and electrical resistance alloys.	3	3	3	4	8
Electroplating	10	6	8	7	12
Catalysts, ceramics, and miscellaneous.	2	2	3	1	2
Total	100	100	100	100	100

V. Metallography

1. Crystallography

The normal crystal form of nickel is face-centered cubic at all temperatures. The lattice constant has been reported as 3.5168 A by Jette and Foote [117], 3.5169 A by Bradley, Jay, and Taylor [152], and 3.5174 A by Lee and Chang [258]. Computations based on Jette and Foote's determination of the lattice constant indicate that the distance of closest approach of the atoms is 2.4869 A.

Another crystal form of nickel, hexagonal close packed, has been prepared by cathodic sputtering in hydrogen, nitrogen, or argon, and by annealing nickel in carbon monoxide for several days at 170° C [57, 68, 213]. Its lattice constants are 2.49 A for the "a" axis and 4.08 for the "c" axis; the distance of closest approach of the atoms is 2.49 A [312]. At room temperature this form of nickel is nonmagnetic. It reverts to face-centered cubic at temperatures about 300° C.

2. Microstructure

The microstructure of nickel is relatively simple as it has a typical pure metal structure and normally maintains only one solid modification or phase up to the melting point. In the annealed state it has simple polyhedral grains, which are often twinned on specimens that have been cold worked. Thermal and deformation treatments govern the size of these grains. Of the impurities found in commercial nickel, iron, copper, manganese, cobalt, silicon, and carbon are soluble in the solid state in the amounts in which they are usually present, and hence do not affect the microstructure, but oxides, sulfides, and graphite or carbides are at times visible as separate constituents.

Nickel is subject to a peculiar type of intercrystalline brittleness when it is exposed at high temperatures to the action of sulfurous gases [24, 69]. The boundaries of the grains at the surface are attacked, the cohesion between the grains is destroyed, and subsequent cold work may develop a network of fine surface cracks. The nickel sulfide thus produced between the grains, if present in sufficient quantity, appears yellow after light etching with cyanide-persulfate solution. Oxidizing atmospheres also sometimes cause intercrystalline brittleness at high temperatures. The presence of cracks along the grain boundaries indicates a faulty heating operation; either the flame was too oxidizing and "burnt" the metal, or it introduced sulfur into the metal. Nickel with high manganese content has increased resistance to these harmful conditions. Modern commercial nickel is less susceptible to intergranular attack in oxidizing atmospheres than older nickels, probably because of a lower carbon content [386].

3. Preparation for Metallographic Examination

The two procedures generally employed to prepare nickel for metallographic examination are mechanical and electrolytic.

(a) Mechanical Methods [320]

If the specimen is larger than about 1 in. in diameter, preliminary cutting is necessary. Care must be used in cutting to insure proper lubrication, to prevent dragging and undesirable heating effects. If the specimen is too small for convenient handling, it may be mounted in bakelite, lucite, or similar products, or mechanically held in clamps. A preliminary filing or abrasive grinding is helpful if the surface is rough. The specimen is then ground, either by hand or on a slowly revolving wheel (less than 600 rpm), followed by grinding on a series of abrasive papers of increasing fineness such as emery papers Nos. 1G, 1, 0, 00, and 000, or carborundum Nos. 240, 320, and 400. Each succeeding grind on the above papers should be made at right angles to the preceding grind, and should continue until the scratches caused by the preceding grind are eliminated. A final grinding may be made on a graphited sheet of No. 000 emery or No. 400 carborundum. When this final grinding operation is omitted, wet polishing is begun with a thick water suspension of No. 600 alundum on a wheel covered with broadcloth rotating at 500 to 800 rpm. The final wet polishing, which may follow directly after polishing on graphited paper, is done with a water suspension of magnesium oxide or levigated alumina on a wheel covered with velveteen, broadcloth, or flat silk crepe.

A method for dry-polishing nickel has been described by Hall [281], in which preliminary grinding through 000 emery paper is similar to that described in the preceding paragraph. The specimen is then placed on a wheel covered with broadcloth impregnated with levigated alumina. Further polishing is done on a second wheel, the cloth of which is impregnated with a 50–50 mixture of paraffin and beef tallow, with fine levigated alumina as the abrasive. The final polish is carried out on a wheel covered with kitten's ear velvet, with green chrome rouge in grease as the abrasive.

(b) Electrolytic Methods

Electrolytic polishing is usually applied, not in lieu of the entire mechanical process, but only in the final operations. As developed by Jacquet [137], the rough-ground specimen is connected as an anode in an electrolytic bath under regulated conditions of composition, temperature, and current density. This causes a selective attack on the protruding irregularities and results in a highly polished surface. Table 7 lists some combinations that have been used for electrolytic polishing of nickel.

TABLE 7.—*Recommendations for electrolytic polishing of nickel*

Electrolyte	Current density	Temperature	Time	Reference
210 ml perchloric [a] acid (55° Be) 790 ml glacial acetic acid	50 amp/dm^2			[210].
Sulfuric acid (45 to 62 °Be)	280 to 560 amp/ft ^{2}	85° to 140° F	10 to 25 sec	[214].
2 vols absolute methyl alcohol 1 vol concentrated nitric acid	5 to 10 amp/in ^{2}	20° to 30° C	5 to 20 sec	[244, 238].
2 vols glacial acetic acid 1 vol perchloric [a] acid	High		1 to 5 min	[244].
Dilute sulfuric acid (73% by wt)	250 amp/ft^2	30° C	0.5 to 2.5 min	[232].
15% sulfuric acid 63% orthophosphoric acid 22% water [b]	100 amp/ft^2	40° C	20 min	[279].

[a] Employ caution when using. May be explosive under certain conditions.
[b] Also used for Monel, Nichrome, and Chromel.

Advantages claimed [244,271,294] for electrolytic polishing include absence of stress distortion of the surface from the polishing operation; time required is independent of specimen size; high quality of surface is regularly obtained; operation does not require a high degree of personal skill; mounting may be omitted; curved or as-rolled surfaces may be polished.

Disadvantages [244,271,294] of electrolytic polishing include the tendency to remove inclusions; the surface is not suitable for low magnification examination, pitting sometimes occurs, and certain grains or twins sometimes stand out in relief; the solutions are corrosive, disagreeable to handle, and some of the solutions, particularly those containing perchloric acid, may be explosive under certain conditions.

(c) Etching

A number of etchants, as indicated in table 8, have been developed for various purposes and for various alloys of nickel. After etching, the specimen should be washed in water and alcohol and dried in an air blast, to prevent staining.

The three solutions most frequently used are numbers 1, 2, and 9 in table 8. The flat solution number 1, is used for the study of inclusions, flaws, and porosity; the electrolytic contrast solution number 2, is preferred for grain size studies; and solution number 9 is frequently preferred for the study of inclusions. Uses for the other etchants are indicated in the table.

TABLE 8. *Etching reagents for nickel and its alloys*

[From Am. Soc. Test. Mat. Standards E3–46T unless indicated]

No.	Etching reagent	Composition [a]	Remarks	Use
1	Flat solution	HNO_3, 50 ml; glacial acetic acid, 50 ml.	Make up fresh daily; use colorless HNO_3 to avoid staining. Etch by immersion at room temperature for 5 to 20 sec.	For nickel, Monel, and other nickel-copper alloys. Dilute with 25 to 50% acetone for alloys of less than 25% nickel.
2	Electrolytic-contrast [b]	Glacial acetic acid, 5 ml; H_2O, 85 ml; HNO_3, 10 ml.	Etch as anode for 20 to 60 sec using 1.5 v. and platinum cathode.	Very satisfactory for grain size studies. Stains less than flat solutions.
3	Electrolytic-sulfuric [b]	H_2SO_4, 5 ml; H_2O, 95 ml	Etch as anode for 5 to 15 sec using 3 to 4.5 v and platinum cathode.	For nickel and Inconel.
4	Aqua regia	HNO_3, 5 ml; HCl, 25 ml; H_2O, 30 ml.	Etch by immersion 30 sec to 2 min	Inconel.
5	Nitric-hydrofluoric	HNO_3, 20 ml; HF (48%), 15 drops	Warm specimen in bunsen flame or boiling water and etch by immersion 15 to 45 sec.	Inconel. Caution must be employed to avoid damage to lenses.
6	Nitric acid	HNO_3, 30 ml; H_2O, 70 ml	Etch by immersion	Macro-etch for nickel brass.
7	Potassium cyanide	KCN, 5 g; H_2O, 95 ml; H_2O_2, few drops.	Etch by immersion	For low zinc nickel brass.
8	Ammonium hydroxide-hydrogen peroxide.	NH_4OH, 85 ml; H_2O_2, 15 ml	Etch by immersion	For high zinc nickel brass.
9	Cyanide-persulfate [b]	Sodium cyanide and ammonium persulfate 10% aqueous solutions. Mix equal volumes when ready to use.	Caution—use hood—poisonous fumes given off when solutions are mixed. Immerse or swab specimen for 5 to 90 sec.	Grain boundaries of nickel, Monel, and nickel-copper alloys. Does not stain. Suitable for detecting sulfur embrittlement.
10	Monel contrast etch [b]	Chromic acid, 3 g; HNO_3, 10 ml; NH_4Cl, 5 g; H_2O, 90 ml.	Immerse or swab specimen for 10 to 60 sec.	Grain contrast for Monel.
11	Ferric chloride solution [b]	$FeCl_3$, 10 g; HCl, 5 ml; H_2O, to make 100 ml.	Immerse or swab specimen for 5 to 30 sec.	Grain contrast, for nickel, Monel and nickel-copper alloys. An auxiliary etchant for Inconel and nickel-chromium alloys.

See footnotes at end of table.

TABLE 8. *Etching reagents for nickel and its alloys*—Continued

[From Am. Soc. Test. Mat. Standards E3-46T unless indicated]

No.	Etching reagent	Composition [a]	Remarks	Use
12	Aqua regia-cupric chloride solution.[b]	HCl, 30 ml; HNO_3, 10 ml; $CuCl_2$ saturate.	Prepare fresh. Immerse specimen for 5 to 30 sec.	Grain contrast for Inconel and nickel-chromium alloys.
13	Oxalic acid solution [b]	Saturated solution of oxalic acid in water.	Etch for 15 to 40 sec using platinum cathode and 1.5 to 6 v.	Grain boundaries in nickel and carbides in Inconel.
14	Ferric chloride solution [c]	$FeCl_3$, 5 g; HCl, 2 ml; C_2H_5OH, 99 ml.	Swab lightly or immerse for 2 sec to several minutes depending on alloy.	General use for nickel and nickel-copper alloys. Defines grain boundaries and structural detail; develops grain contrast in Monel.

[a] Acids are concentrated unless otherwise stated.
[b] Reference [256].
[c] Reference [390a].

VI. Chemical Properties

1. Behavior in Corrosive Media

Nickel is not an active element chemically; it does not readily evolve hydrogen from solutions; it requires the presence of an oxidizing agent for most of its corrosion reactions.

In sulfurous industrial atmospheres, as found in many cities, nickel will corrode at a rate not greater than 0.0002 in./yr., and will become coated with colored tarnish films. Indoors the corrosion is much less, although extended indoor exposure with relative humidity more than 70 percent will form a film or fog on the surface. Light speeds up the formation of this fog [88].

Distilled water and ordinary tap water have little effect on nickel. Salt water is more corrosive than the fresh waters, but the metal is resistant to a sufficient degree to be useful. Friend [39] immersed nickel bars (99.84 percent) in the Bristol Channel for 4 years, along with bars of other metals and alloys. On the basis of this test, two tin samples were first and second in order of merit. The nickel bars were rated third; they had been attacked uniformly and only slightly. Nickel and its alloys find many uses under marine conditions, as is indicated in subsequent sections of this Circular.

Neutral and alkaline salts corrode nickel to a slight degree, usually less than 0.005 in./yr., nonoxidizing acid salts to a greater degree, about 0.02 in./yr. Oxidizing acid salts and mixtures of these salts with mineral acids are severely corrosive, as are some oxidizing alkaline salts such as hypochlorites where the available chlorine concentration exceeds 3 g/liter [375].

The rate of corrosion in acids varies according to concentration, air content, impurity content, agitation, and temperature [375]. Table 9 lists the effects of common mineral acids on commercial nickel.

TABLE 9. *Effect of mineral acids on commercial nickel* [*286,375*]

No.	Acid	Rate of corrosion	Remarks
		Inch per year	
1	Hydrochloric (air free)	0.01 to 0.08	Increase with concentration, solution cool.
2	Hydrochloric (aerated)	0.03 to 0.25	Increase with concentration, solution cool.
3	Hydrochloric (above 120° F, concentrated above 2%).	Severe	Very corrosive in hot solutions.
4	Hydrogen sulfide	0.002	Water saturated with hydrogen sulfide at 78° F.
5	Nitric	Severe	
6	Phosphoric	Variable	Governed principally by purity of acid. Corrosion becomes more severe with increase of oxidizing impurities.
7	Sulfuric (air free)	0.005	Increases with concentration, solution cool.
8	Sulfuric (aerated)	0.087	5-percent solution at 86° F.
9	Sulfuric (hot concentrations above 15%).	Severe	
10	Sulfurous	Severe	Fairly good resistance in very dilute solutions.

Organic acids and acid compounds are moderately corrosive to nickel, but neutral and alkaline compounds are practically noncorrosive. Nickel is used in cooking vessels, particularly in the large-scale preparations of food products, not only because of this relative freedom from corrosion, but also because of its nonflavoring characteristics, and ease of cleaning. Nickel utensils generally are considered safe for the preparation of food [231, 270]; the amounts of nickel that would dissolve in the food are very slight, whereas the toxic dose for orally administered nickel in the form of soluble salts is probably between 20 and 40 milligrams of nickel per kilogram of body weight of the consumer [292]. However, the use of nickel vessels in the preparation of beer, pineapple juice, rhubarb, and other acid foods has been questioned because of the corrosive action of these materials.

Most alkalies have little corrosive effect on nickel even at high temperatures and high concentrations, except in the presence of sulfur. Anhydrous ammonia is also noncorrosive, but ammonium hydroxide in concentrations over 1 percent corrodes nickel appreciably [375]. The excellent resistance of nickel to alkalies results in many commercial applications.

Common dry gases do not corrode nickel, but many gases are corrosive when wet, including nitric acid, chlorine (above 1,000° F), bromine, and sulfur dioxide. Sulfur gas attacks nickel above 600° to 700° F. In the synthesis of ammonia, the mixture of nitrogen, hydrogen, and ammonia is destructive, but nickel is useful in the nitriding process below 1,075° F [375].

Steam at temperatures below 450° C corrodes nickel only slightly, and most of the corrosive effect is due to carbon dioxide and other impurities in the steam [53].

Campbell and Thomas [353] determined the rate of oxidation of "A" nickel, which had been rolled 6 numbers hard. The results obtained at temperatures of 194°, 256°, and 302° C are shown in figure 3.

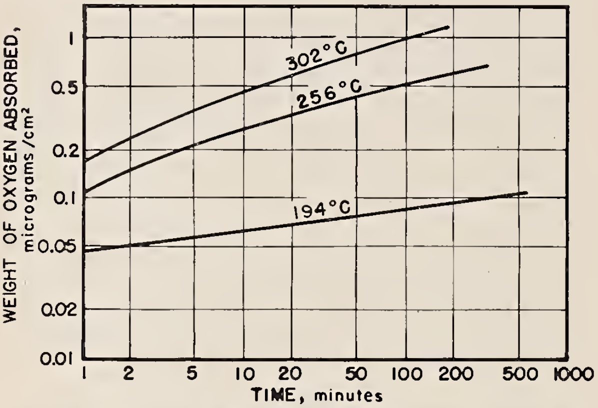

FIGURE 3. *Oxidation rate curves for commercial nickel at various temperatures.*

(Campbell and Thomas [353])

Nickel is not useful for handling molten metal, except for mercury below 371° C. Molten aluminum, tin, lead, solder, bismuth, antimony, brass, and zinc attack nickel rapidly [69].

Galvanic corrosion between nickel and other metals usually can be avoided by using a metal or alloy that is close to nickel in the galvanic series, and by having the area of the less noble metal almost as large as that of the more noble metal [321].

The corrosion resistance of alloys of nickel is discussed in subsequent sections of this circular.

2. Catalytic Action

Probably the first record of a catalytic effect of nickel and its compounds was made by Thenard about 1818 in a study of the decomposition of hydrogen peroxide. In 1842 Marchand decomposed ethylene over heated nickel. Mond and Langer apparently made the first commercial use of nickel catalysts, by producing hydrogen from mixtures of carbon monoxide, hydrocarbons, and steam. In 1896 Sabatier and Senderens started their classical experiments which showed that nickel catalyzed the hydrogenation of unsaturated hydrocarbons and other organic compounds to saturated ones. There was thus initiated the process of commercial production of edible saturated oils and fats from cheaper unsaturated ones.

The use of nickel in hydrogenation processes accounts for approximately 70 percent of all the nickel catalyst material. The principal catalyst used in hardening fats and oils is Raney nickel, a patented product prepared by leaching aluminum out of a granular nickel-aluminum alloy. According to Dupont and Piganiol [204], Raney nickel is a much more active catalyst than Sabatier's nickel.

Although the principal use of nickel catalysts is in hydrogenation processes, Fraser [156] listed approximately 40 fields in which nickel catalysts are used, including artificial aging of liquors, drying oils, bleaching, waste water purification, dehydrogenization and polymerization of organic compounds, and the removal of organic sulfur compounds from coal gas [297].

3. Action of Gases

Hydrogen is strongly adsorbed by nickel. Other gases such as carbon monoxide, carbon dioxide, and ethylene are also adsorbed; in the case of carbon monoxide, dissociation occurs and free carbon is deposited [127]. According to Benton and White [60], physical adsorption is greatest at very low temperatures; as the temperature is raised the adsorption decreases until a temperature of approximately −190° C is reached, at which point the hydrogen physically adsorbed is at a minimum. Increase in pressure increases the adsorption. Activated adsorption or chemisorption begins at −190° C; below −100° C physical adsorption is probably present to some degree. The volume adsorbed reaches a maximum at about −90° C and then begins to drop with increasing temperature, as shown in figure 4. Maxted and Hassid [84] obtained somewhat similar curves, but they found the maximum adsorption at 50° C rather than −100° C.

Activated adsorption is distinguished from the physical type by its much higher heat of adsorption. Eucken and Hunsmann [205] have determined the heat of activated adsorption of hydrogen on nickel to be from 21,000 to 4,000 cal/mole, the value decreasing as the percentage of the occupied surface increases, and the heat of physical adsorption to be a mean value of 800 cal/mole. Additional values for the heat of activated adsorption on nickel, obtained by various investigators, were reported by Smithells [172].

Under favorable conditions some gases, for example, hydrogen, oxygen, carbon monoxide and dioxide, will diffuse through solid nickel. Baukloh and Kayser [110] found that the diffusion capacity for hydrogen was higher in nickel than in aluminum, copper, iron, nickel-copper, or nickel-iron. Under the conditions of their experiments nickel was impervious to helium, neon, argon, and krypton. Ham [159] showed that the slope of diffusion isobars changes sharply in the vicinity of the Curie point, around 365° C, but a further rise in temperature, of 10 degrees, restores the slope of the curve to its normal value.

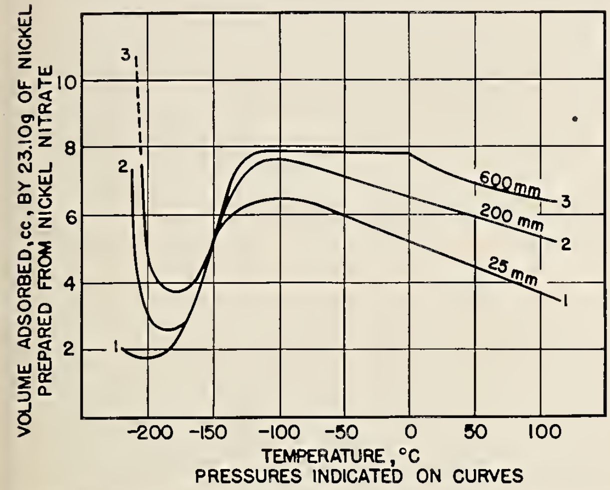

FIGURE 4. *Effect of temperature on the adsorption of hydrogen by nickel.*

(Benton and White [65])

Many values have been obtained for the constants for nickel in the diffusion formula $D=k/d\sqrt{P}.e^{-\frac{b}{T}}$, where D is the rate of diffusion at NTP in cm³ per sec, per cm² of surface 1 mm thick; d is the thickness in mm; P is the pressure in mm of mercury; and T is the absolute temperature [127]. Table 10 gives some of the values for k and b.

TABLE 10. *Diffusion constants for hydrogen-nickel* [*127, 147, 191*]

Author	Date	b	k
Lombard	1923	7710	2.3×10^{-2}
Deming, Hendricks	1923	6930	0.85
Borelius, Lindblorn	1927	6900	1.4
Ham	1933	6700	1.05
Smithells	1935	7000	1.5
Smithells, Ransley	1936	6630	1.44
Post, Ham	1938	6590	1.9

Smithells and Ransley [147] found that the gases evolved from nickel on heating contained 84 to 98 percent of CO and 2 to 16 percent of CO_2 and H_2, regardless of the method of manufacture of the metal. Köster [211] found that gas began to evolve from electrolytic nickel at 200° C, and most of the hydrogen was expelled between 400° and 500° C. Appreciable amounts of CO were evolved at 600° C, and the evolution increased with increasing temperature. The metal retained its toughness while the hydrogen was being expelled but became brittle when the carbon monoxide was evolved. Some recent values for the gases evolved from electrolytic nickel at 1,100° and 1,200° C are presented in table 11.

Sieverts [11] found that hydrogen formed with nickel a homogeneous solid solution. The solubility of hydrogen both in solid and molten nickel was proportional to the square root of the hydrogen pressure. Data from the principle investigations of the solubility of hydrogen in nickel at one atmosphere, between 300° and 900° C, were compiled by Armbruster [274] and are shown in table 12.

TABLE 11. *Gases evolved from electrolytic nickel*

Norton and Marshall [302]

Temperature	Time	Gas composition				Amount of gas in sample
		H_2	CO	CO_2	N_2	
° C	*min*	*Percent*	*Percent*	*Percent*	*Percent*	*mm³/g*
1,100	177	2	77	10	11	13.1
1,100	730	----	87	7	6	3.6
1,200	240	14	75	4	7	2.6
Total						19.3

TABLE 12. *Solubility of hydrogen in nickel at 300 to 900° C and 1 atmosphere*

Armbruster [274]

Form of sample	Solubility (micromoles/100 g) at—							Mean molal heat of solution (cal/gmole)	Investigator
	300° C	400° C	500° C	600° C	700° C	800° C	900° C		
Sheet 0.14 mm	111	164	218	271	323	373	419	5,900	Armbruster.
Wire 0.02 mm	135	183	244	297	349	393	436	5,300	Smittenberg.
Wire 0.5 and 3 mm; powder chips	105	161	186	245	301	356	411	6,100	Sieverts.
	89	112	145	192	251	312	381	4,300 (300 to 500°) 9,000 (500 to 900°)	Luckemeyer, Hasse, and Schenck.

Gases, particularly hydrogen, are found in freshly deposited electrolytic nickel, in amounts considerably in excess of the normal solubility, the actual amounts depending upon the conditions of electrodeposition. As long ago as 1908, Rommler reported that electrodeposited nickel contained from 4 to 14 times its volume of hydrogen. The hydrogen content increased as the temperature and acidity of the chloride or sulfate electrolyte decreased.

The solubility of nitrogen in nickel was reported by Juza and Sackze [313] to be about 0.07 percent by weight.

4. Electrolytic Solution Potential: Passivity

Values for the electrolytic solution potential of nickel have been reported as −0.227±0.002 volts at 20° C [97] and −0.231±0.002 volts at 25° C [50]. In nickel sulfate of molar concentration the potential of powdered nickel was −0.2508 volt at 18° C and −0.2496 at 25° C [41].

Nickel becomes passive, that is, behaves like a noble metal, when it is immersed in strong oxidizing agents (nitric acid or bichromate solutions) or when nickel is used as an anode in electrolytes containing salts of oxidizing acids. Under most conditions the tendency for nickel to become passive is not dependable; consequently, the passivity of nickel is not of practical importance. The passivity developed by simple immersion may be destroyed by slight changes in the chemical environment or by scratches or mechanical shock. Anodic passivity is affected by the presence of impurities in the metal or in the electrolyte [12, 321]. Chlorides in particular tend to destroy anodic passivity, and use is made of this phenomenon in maintaining activity in nickel anodes for electroplating.

VII. Physical Properties

1. General

(a) Atomic number, Atomic weight, Isotopes

Nickel is number 28 in the periodic listing of the elements. Its atomic weight is 58.69 and its stable isotopes, in order of abundance, have weights of 58, 60, 62, 61, and 64.

(b) Density

The density of nickle varies with its physical condition and prior treatment as well as with its composition. Determinations made at this Bureau [64] on high-purity (99.94-percent) nickel in the as-cast, cold-swaged, and annealed forms, showed that the highest density, 8.907 g/cm^3 at 23° C, was obtained from cast metal; cold-swaged and annealed metal yielded densities ranging from 8.900 to 8.903.

Calculations of the density of nickel from X-ray lattice parameter data were made by Jette and Foote [138] and by Owen, Yates, and Sully [168]. Their values were 8.902 and 8.898 g/cm^3, respectively. The latter workers also reported values of 8.829 g/cm^3 at 200° C, 8.739 at 400° C, and 8.647 at 600° C.

Commercial malleable nickel has a density of about 8.89 g/cm^3. The alloyed malleable nickels, for example, "D", "Z", and "Z–B" have densities, respectively, of 8.78, 8.26, and 8.75 g/cm^3.

2. Optical Properties

(a) Reflection, Absorption, Refraction

An important property of nickel is its ability to take and retain a high polish and to reflect a large percentage of the light incident upon it. The method of production and the subsequent treatment of the surface are of prime importance in determining optical behavior, whereas the presence of small amounts of impurities normally has little effect. Values for the reflectivity of various forms of nickel, reported by Hagen and Rubens [3], Coblentz and Stair [47], Sabine [218], and Kroller [139], increase with increasing wavelength of light, from about 10 percent reflectivity at wavelengths of about 1,000 A to about 90 percent for wavelengths of about 40,000 A.

TABLE 13. *Refractive index (n) and absorption coefficient (k) of nickel [8, 9, 120, 201]*

Wavelength	n	k
A		
4,200	1.42	1.79
4,358	1.41	2.56
4,600	1.40	2.77
5,000	1.54	1.93
5,400	1.54	3.25
5,400	1.63	1.97
5,461	1.66	3.39
5,780	1.70	3.51
5,800	1.73	1.98
6,200	1.82	1.99
6,200	1.72	3.67
6,600	1.95	1.98
7,000	2.03	1.97
7,000	1.84	4.07
7,500	2.19	1.99
7,800	2.13	4.43
8,600	2.24	4.69
8,700	2.45	1.96
9,400	2.45	4.92
10,000	2.63	2.00
12,500	2.92	2.11
15,000	3.21	2.18
17,500	3.45	2.25
20,000	3.70	2.31
22,500	3.95	2.33

Values for the refractive index and absorption coefficients of nickel, compiled from various sources, are shown in table 13.

(b) Spectrum

The spectrum of nickel is highly complex and contains thousands of individual lines. The most persistent, with a maximum intensity in both arc and spark sources, is at 3414.77 A; less sensitive persistent lines are at 3492.96, 3515.06, and 3524.54 A. A table of values for the spectral lines of nickel, ranging in intensity from one to ten, is found in the Handbook of Chemistry and Physics [354a].

Spectral lines of short wavelength are emitted from nickel cathodes in an X-ray tube operating at a sufficiently high potential. The most important of these are the K series, with wavelengths of the order of 1.5 A [275].

3. Magnetic Properties

(a) General

Nickel is ferromagnetic at ordinary temperatures; at moderately elevated temperatures, it becomes paramagnetic. The magnetic properties of nickel, as is the case with other ferromagnetic metals, are affected by many factors including composition of the metal, hardness, cold work, and heat treatment. In general, the magnetic properties of nickel itself are less important than those of its alloys, which are discussed in subsequent sections of this Circular.

(b) Curie Point

The Curie point, or temperature at which the magnetic transition occurs, is affected by the method of determination, prior thermal history, and the nature and amount of impurities present. The Curie point for high-purity nickel occurs in the range from 350° to 380° C. For soft "Z" nickel the transition occurs in the range from 16° to 49° C; for the same metal in the hardened condition the transition temperature is 93° C. For "Z–B" nickel the transition for the soft metal occurs at 315° C, and for the hardened metal at 295° C. Most alloying elements lower the Curie point of nickel, iron and cobalt being exceptions, as shown in figure 5.

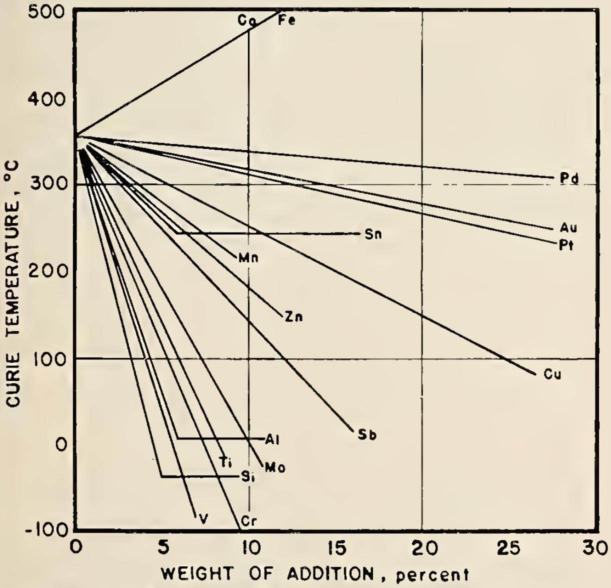

Figure 5. *Effect of single alloying additions on the Curie point of nickel.*
(Wise and Schaeffer [272]).

The heat effect accompanying the magnetic transition has been reported by various observers as 0.65, 1.33, and 2.01 calories per gram [150].

(c) Saturation Induction

The saturation induction value of nickel (99.94 percent) was determined by Sanford [66] to be 6,150 gausses. The physical condition of the metal, that is, the prior thermal and mechanical history, has a pronounced effect on induction values. The effect of cold work is illustrated in figure 6.

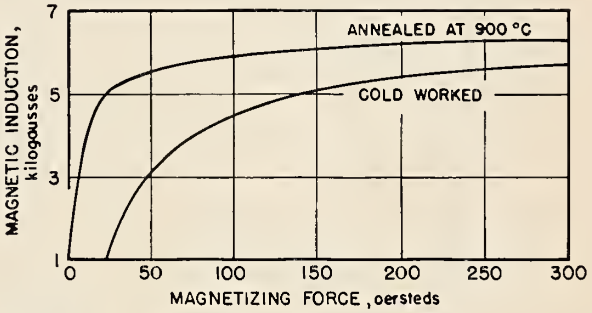

Figure 6. *Effect of cold work on the normal induction of nickel.*
(Sanford [66]).

(d) Magnetostriction

Nickel, "Z–B" nickel, and many alloys change in length under the influence of a magnetic field, resuming their original dimensions upon removal of the field. If an alternating field is used, the resultant vibrations of the metal produce sound waves within or above the audible range. This method has been used [357] in underwater detection devices, for inspection of metals, to produce emulsions, to accomplish pasteurization at room temperature, for more efficient nitriding of steel, and to chase pigeons from buildings.

4. Thermal Properties

(a) Melting Point: Heat of Fusion

The melting point of pure nickel is 1,453° C on the International Temperature Scale for 1948 [401]. The impurities normally present in commercial nickel lower its melting point to the range from 1,435° to 1,445° C. "D" and "E" nickels melt at about 1,427° C [346]. White [25] determined the latent heat of fusion of a specimen of nickel (99.1-percent Ni) as 73 calories per gram.

(b) Boiling Point

The boiling point of nickel is high enough to present serious experimental difficulties in its determination. Jones, Langmuir, and Mackay [35] measured the rate of evaporation and vapor pressure of nickel at various temperatures and concluded that the boiling point of nickel was 3,377° C. The recent compilation by Wise [399] gives 2,730° C as the boiling point for nickel.

(c) Specific Heat

Variations in the specific heat of nickel at temperatures from —200 to +800° C, determined by Klinkhardt [37] and by Grew [99], are shown in figure 7. The specific heat of nickel at any temperature represents a combination of four factors, the lattice vibrational specific heat, the dilatation effect, the electronic specific heat, and the magnetic specific heat, which reaches a maximum at the Curie point.

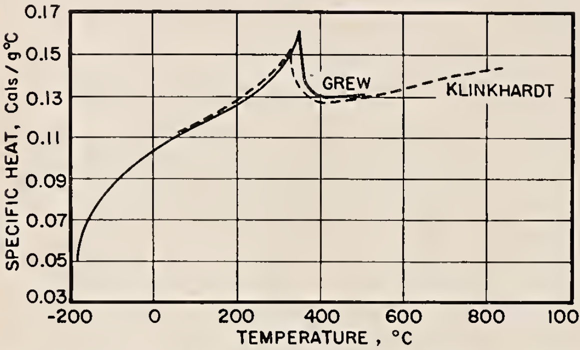

FIGURE 7. *Specific heat of 99.97-percent nickel (Grew [99]) and nickel with 0.5-percent manganese (Klinkhardt [37]).*

TABLE 14. *Specific heat of nickel*

Sykes and Wilkinson [197]

Temperature	Specific heat of nickel (cal/g per ° C$\times 10^4$)			
	Commercial	Mond	Powder	Cathode
° *C*				
60	1,060	1,055	-------	1,060
100	1,128	1,125	1,121	1,128
150	1,191	1,180	1,181	1,187
200	1,240	1,225	1,225	1,231
250	1,300	1,294	1,289	1,296
300	1,386	1,371	1,363	1,369
350	1,322	1,492	1,495	1,470
400	1,263	1,269	1,264	1,265
450	1,256	1,251	1,252	-------
500	1,263	1,270	1,259	-------
550	1,283	1,299	1,286	-------
600	1,306	1,328	1,324	-------

Values for the specific heat of commercial nickel (99.18 percent), Mond pellets (99.93 percent), powder (99.96 percent), and cathode nickel (99.54 percent), as determined by Sykes and Wilkinson [197], are given in table 14.

The specific heats of "Z" nickel and "Z–B" nickel are, respectively, 0.104 and 0.106 cal/g/°C, according to the International Nickel Co. [355]. These values presumably apply to temperatures in the vicinity of room temperature.

(d) Thermal Expansion

Nickel expands with increasing temperature at a regular rate except for a sharp maximum at the Curie temperature. Data reported by Hidnert [63], for 99.4-percent nickel, are presented in table 15, and results obtained by Nix and MacNair [259] for 99.9-percent nickel are shown in figure 8. Owen and Yates [144] worked with nickel 99.98-percent pure and obtained considerably higher values in the Curie region; their maximum value for the coefficient was 26.0 x 10^{-6}, at 370° C. Williams [106] had previously reported that impurities lower the maximum value of the coefficient of thermal expansion and the temperature at which the maximum occurs.

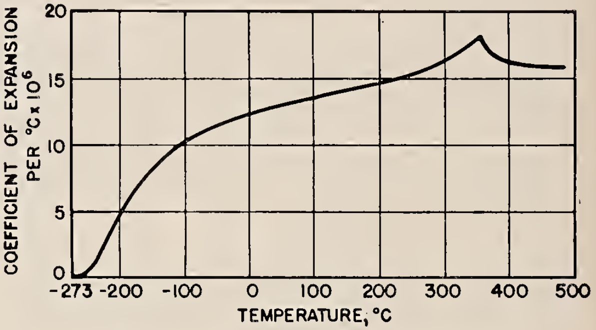

FIGURE 8. *Thermal expansion of nickel.*

(Nix and MacNair [259]).

TABLE 15. *Thermal expansion of nickel*

Hidnert [63]

Temperature range	Average coefficient per ° C $\times 10^6$	Temperature range	Average coefficient per ° C $\times 10^6$
° *C*		° *C*	
25 to 100	13.3	400 to 500	15.9
25 to 300	14.4	500 to 600	16.9
25 to 600	15.5	600 to 700	17.1
25 to 900	16.3	700 to 800	17.7
100 to 200	14.4	800 to 900	18.6
200 to 300	15.4	300 to 600	16.5
300 to 350	17.2	600 to 900	17.8
350 to 400	16.4		

(e) Thermal Conductivity

The thermal conductivity of nickel is lowered by the presence of impurities in the metal, and, as with other thermal properties, irregularities occur in the vicinity of the Curie point.

The results obtained by Van Dusen and Shelton [105] for the thermal conductivities of 99.94-percent nickel and commercially pure 99.17-percent nickel are shown in figure 9. Woldman [346] reported the thermal conductivity of "L" and "Z–B" nickel as 0.1445 cal $\mathrm{cm^{-1}\ sec^{-1}\ {}^\circ C^{-1}}$ and of "D" and "E" nickel as 0.1152. A recent bulletin of the International Nickel Co., Inc., gives 0.044 cal $\mathrm{cm^{-1}\ sec^{-1}\ {}^\circ C^{-1}}$ units for the thermal conductivity of soft "Z" nickel, for the range from 0° to 100° C, and 0.047 for the conductivity of age-hardened "Z" nickel.

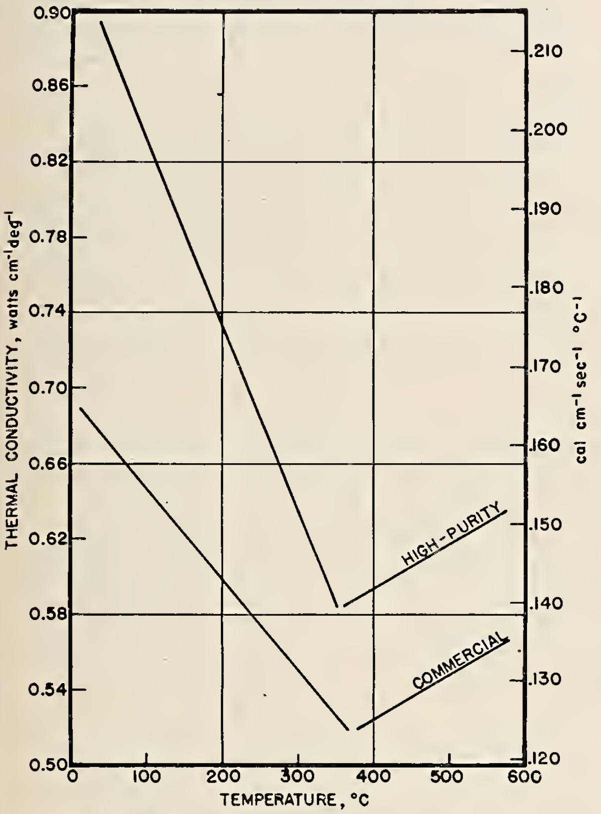

FIGURE 9. *Thermal conductivity of nickel.*

(VanDusen and Shelton [105]).

5. Electrical Properties

(a) Resistivity

The electrical resistivity of 99.99-percent nickel is 6.141 microhm-cm at 0° C, 6.844 at 20° C, and 10.327 at 100° C [207]. Equivalent conductivities in terms of the conductivity of copper are, respectively, 28.1, 25.2, and 16.7 percent. The resistivity of nickel increases with increasing temperature, with a decided change in direction of the curve in the vicinity of the magnetic transition. The presence of alloying elements, impurities, and other factors increases the resistivity of nickel; for example, the resistivities of wrought "D" and "E" nickels are reported [346], respectively, as 18.26 and 14.11 microhm-cm. Resistivities of "Z" nickel are reported [355] as 47 microhm-cm for soft metal and 43 for age-hardened metal, both at 0° C. For "Z–B" nickel, the effect of ageing is not so pronounced but, nevertheless, lowers the resistivity at 0° C from 16.6 to 15.7 microhm-cm.

The temperature coefficient of resistance of nickel in the range from 20° to 100° C was reported by Geiger [207] to be 0.00636 per °C for 99.99-percent nickel and 0.00474 per °C for "A" nickel and electrolytic nickel. A subsequent determination [272] made on 99.71-percent nickel, for the range 0° to 100° C, yielded a value of 0.00681. The temperature coefficients of "Z" and "Z–B" nickels for the range 20° to 100° C are, respectively, 0.001 and 0.0036 [355]. The values are not affected by age-hardening treatments.

Application of a longitudinal magnetic field initially causes an increase in the resistance, which continues rapidly up to a limited magnetic field strength after which the rate of increase depends upon the temperature. The initial rise grows less as the temperature increases and becomes negligible at temperatures near the Curie point. Some magneto-resistance curves at low, moderate, and high temperatures are shown in figure 10.

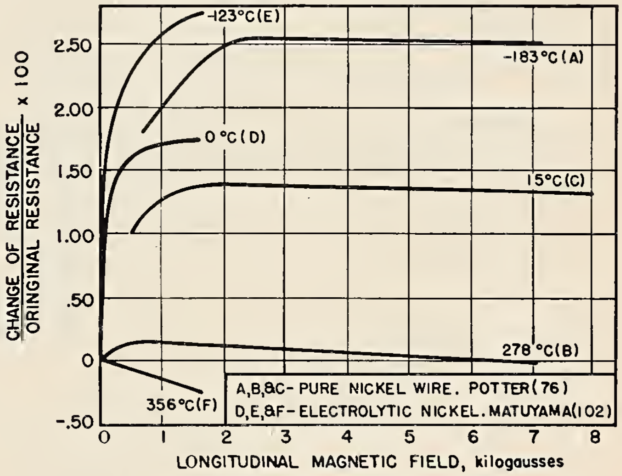

FIGURE 10. *Magneto-resistance curves for nickel.*

The elasto-resistance, the effect of tension on the resistance of nickel, differs from the magneto-resistance effect. With increasing tension the resistance decreases to a minimum and thereafter increases [246]. Bridgman [26] reported that a "seasoning" effect on the resistance of a nickel wire resulted from repeated applications and removals of a fixed load. According to Bittel

[177], cold working of a pure nickel wire increases the resistivity and reduces the temperature coefficient. These effects of cold work are destroyed by annealing, although Raines [192] reported that annealing at about 950° C produced somewhat higher resistances than were obtained by annealing at lower temperatures.

The formula KR/T, where $K=$ the thermal conductivity in cal cm^{-1} sec^{-1} $°\ C^{-1}$, $R=$electrical resistivity in microhm—cm, and $T=$absolute temperature, is known as the Lorenz function. Some values for this function for nickel are given in table 16.

Table 16. *Lorenz function for nickel*

Temperature	$\frac{KR}{T}$ for—	
	96.7% Ni [14]	99.2% Ni [32]
° *C*		
100	0.571×10^{-8}	0.545×10^{-8}
200	.605	.571
300	.644	.633
400	.639	.667
500	.645	.627
600	.653	.631
700	.655	.641
800	.657	----

(b) Thermal Electromotive Force

Values for the thermal emf of nickel against several metals, over a range of temperatures, are presented in figure 11. Irregularities in the thermal emf curves in the vicinity of the Curie point are intensified when results are plotted as thermoelectric power [83,91].

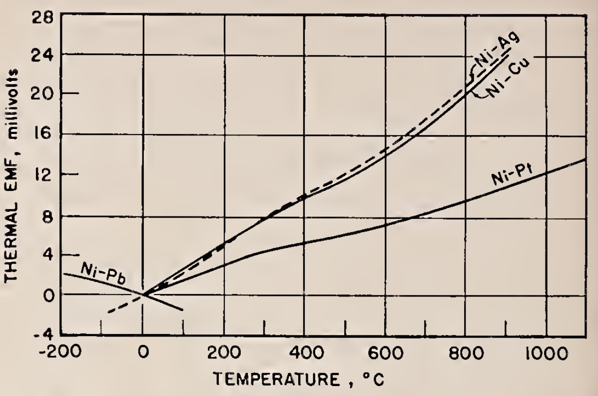

Figure 11. *Thermal electromotive force of nickel against silver (von Hevesy and Wolff [10]); copper (Pecheux [6]); platinum (Caldwell [61]); and lead (Dewar and Fleming [1]).*

Magnetic fields effect the thermoelectric behavior of nickel. For example, an emf can be developed in a nickel wire if one end of the wire is heated while a magnetic field is applied [49, 119]. The effect of magnetic fields of different intensity on the emf of a nickel thermocouple was studied by Yamanaka [173].

The contact potential for nickel and copper was reported as 0.25 volt [33]; for nickel and iron, 0.21±0.01 volt [72]; and for nickel and brass, 0.16 volt [92].

VIII. Mechanical Properties at Normal Temperatures

The mechanical properties of nickel are greatly influenced by the purity, previous thermal and mechanical history, and temperature. Furthermore, the values for mechanical properties of high-purity nickel and pure metals in general are lower than those of commercially pure or alloyed metals. Consequently, the values cited in the succeeding paragraphs are representative or indicative; more complete and specific information can be obtained from the references cited.

1. Tensile and Compressive Properties

The tensile strength of annealed nickel of the highest obtainable purity, 99.99 percent [272] and 99.94 percent [64], was reported as 46,000 lb/in.^{2}. For commercial grades of nickel the tensile strengths were summarized [272] as follows: By suitable choice of hot rolling, annealing, and cold drawing or cold rolling, tensile strengths ranging from 65,000 to 115,000 lb/in.^{2} can be had in rods and bars, as high as 130,000 lb/in.^{2} in strip and 160,000 in wire, whereas over 200,000 lb/in.^{2} can be had in the specially alloyed "Z" nickel wire.

The yield strength (0.2-percent offset) of high-purity nickel was reported [399] as 8,500 lb/in.^{2}. Corresponding values for "A" nickel (99.4 percent) range from 10,000 to 30,000 lb/in.^{2} for material in the annealed or as-cast condition to maximum values of 45,000 lb/in.^{2} for hot-rolled material, 80,000 for cold-drawn tubing, 115,000 for full-hard, cold-rolled sheet and strip, and 155,000 lb/in.^{2} for spring temper cold-drawn wire.

The yield strengths of nickel in compression, for 0.2-percent offset, are 23,000 lb/in.^{2} for hot-rolled material, 58,000 cold-drawn and stress-relieved, and 26,000 lb/in.^{2} cold-drawn and annealed. The compressive yield strength of "Z–B" nickel is considerably higher, reaching 51,000 lb/in.^{2} for hot-rolled, 103,000 for cold-drawn, 148,000 for hot-rolled and aged, and 166,000 for cold-drawn and aged, all for 0.2-percent offset [178].

Elongation of annealed high-purity nickel is about 30 percent in 2 in. Elongation of grade "A" nickel, and for the other commercial wrought nickels, is generally between 30 and 50 percent for annealed material; cold working reduces the elongation as it increases the tensile and yield strengths, for example, spring temper cold-drawn wire, which has a yield strength of 130,000 to 155,000 lb/in.^{2}, has elongation values of 10 percent or less.

2. Elastic Properties

An average value for Young's modulus for nickel is about 30,000,000 lb/in.^{2} [307]. For "A" nickel the modulus is reported [399] as 30,000,000 for annealed material and 21,500,000 lb/in.^{2} as sand-cast. Kenyon [287] reported average values of 31,200,000 lb/in.^{2} for cold-drawn nickel wire and 34,000,000 for "Z–B" wire. The effect of temperature and of imposed magnetic fields on Young's modulus for commercial cobalt-free nickel were reported by Siegel and Quimby [146].

The modulus of elasticity in compression is the same as in tension, 30,000,000 lb/in.^{2} [178], and practically identical values apply to all commercial forms of nickel [346].

The modulus of elasticity in torsion is also known as the modulus of rigidity and modulus of shear. Landon and Davies [188] obtained values of 11,995,000 lb/in.^{2} for annealed nickel (99.2 percent) and 11,603,200 lb/in.^{2} for an unannealed specimen. Mudge and Luff [40] reported 11,270,000 lb/in.^{2} for hot-rolled nickel and 11,340,000 lb/in.^{2} for "D" nickel in the same condition.

Poisson's ratio for nickel is reported [256] as 0.31.

3. Hardness

For the indentation hardness of annealed high-purity nickel, values as low as 35 Rockwell B, 7 Scleroscope, and 64 Vickers have been reported. Working and incomplete annealing raise these figures. The hardness of high-purity electrolytic nickel as electrodeposited has been reported to be as high as 282 Vickers. The effect of annealing at various temperatures on the Vickers hardness of electrolytic nickel is shown in figure 12. For grade "A" nickel, Brinell numbers range from 90 to 100 for annealed or as-cast material, to maxima of 200 for hot-rolled plate and 230 for cold-drawn rod and bar.

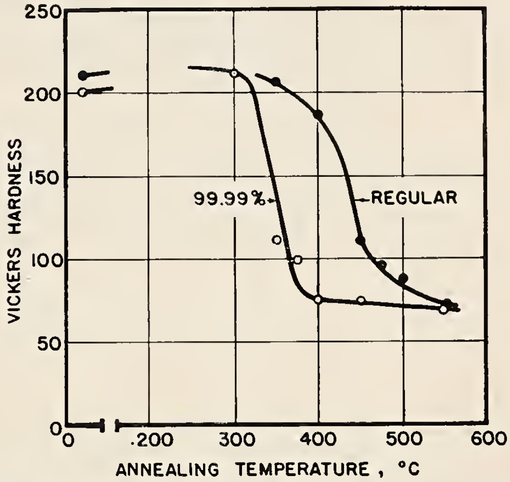

FIGURE 12. *Effect of annealing on the Vickers hardness of two types of electrolytic nickel.*

(Wise and Schaefer [272]).

4. Impact

Catlin and Mudge [178] reported values for the Izod, Charpy, Charpy torsion, and Charpy tension impact of nickel, as shown in table 17. "D" nickel yielded an Izod value of 1,100 ft-lb for a 7/8-in. rod hot-rolled and 69 ft-lb for the same material after annealing [307]. Izod tests on "Z" and "Z–B" nickel produced values of 120 ft-lb for hot-rolled or cold-drawn and stress-relieved material, and 25 ft-lb for material annealed after hot rolling or cold drawing [355].

TABLE 17. *Impact strength of nickel*

Catlin and Mudge [178]

Specimen	Izod	Charpy	Charpy torsion		Charpy tension		
	ft-lb	*ft-lb*	*ft-lb*	*Angle of twist, deg.*	*ft-lb*	*Elongation, percent*	*Reduction of area, percent*
Hot-rolled	120	200	29	103.5	98	20.0	83.1
Cold-drawn, stress relieved	120	204	35	102	88	19.5	71.2
Cold-drawn, annealed	120	228	29	103	113	33.0	75.1

5. Endurance Limit

The endurance limit for 100,000,000 cycles of "A" nickel is reported [399] as follows: annealed, 24,000 lb/in.^{2}; hot-rolled, 30,000 lb/in.^{2}; cold-drawn, 42,500 lb/in.^{2} Results reported [256] for "Z" or "Z–B" nickel are: annealed, 55,000 lb/in.^{2}; hot-rolled, 53,500 lb/in.^{2}; cold-drawn, 55,000 lb/in.^{2}; cold-drawn and aged, 59,000 lb/in.^{2}

The effect of rolling, in different directions and to different degrees of reduction, on the endurance limit of "A" nickel was investigated by Greenall and Gohn [157]. They found that rolling 24-gage sheet to a reduction of either 4 or 8 B & S numbers raised the endurance limit from about 25,000 lb/in.^{2} to about 40,000 lb/in.^{2}

According to Betty [276], the endurance limit of a cold-drawn specimen will be about 35 percent lower than the value obtained from a similar specimen with a polished surface.

The combined effects of corrosion and fatigue were studied by McAdam [36]. The endurance limit (10^8 cycles) for annealed "A" nickel was: in air, 33,000 lb/in.^{2}; in carbonated tap water, 21,000 to 24,000 lb/in.^{2}; in brackish water, 20,000 to 22,000 lb/in.^{2} The endurance ratio, the ratio of endurance limit to tensile or torsional strength, of this material was between 0.3 and 0.4.

6. Flexure

The flexure of nickel wire was determined [165] by cantilever bend tests in a Tour-Marshall tester with results shown in figure 13. All samples were straightened, before annealing, by stretching 1 percent.

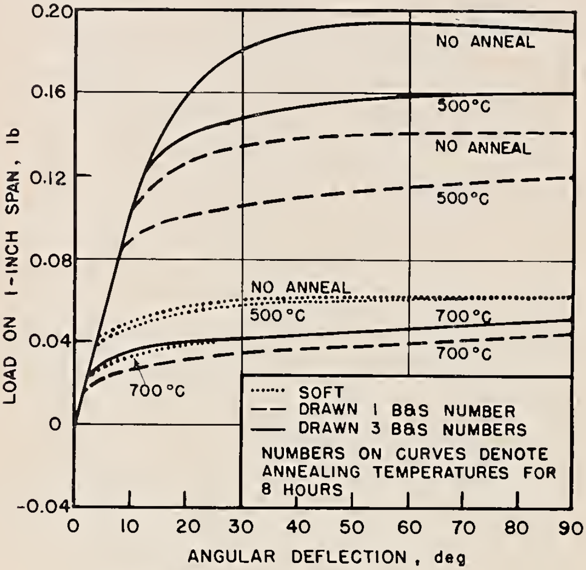

Figure 13. *Flexure of nickel wire.*

(MacBride [165]).

7. Friction

The coefficient of friction in rubbing contact of nickel against nickel was reported by Tichvinsky [222] as 0.53. With nickel as the moving contact, the coefficient for nickel and glass was 0.56, and for nickel and mild steel 0.66. With nickel stationary and mild steel moving, the coefficient was 0.49.

8. Shear

Results of double shear tests on 0.05-by 0.25-in. specimens are presented in table 18. Values for the ratio of shear strength to ultimate tensile strength were between 0.542 and 0.770 [256].

Table 18. *Shear properties of nickel*

International Nickel Co., Inc. [256]

Material	Condition	Rockwell hardness	Double shear properties	
			Maximum strength	Deflection at maximum strength
			lb/in.^{2}	
Nickel	Soft	46 B	52, 300	0. 09
	Half-hard	89 B	57, 550	.07
	Hard	100 B	75, 300	.05
"Z-B" Nickel	Soft	15 C	67, 500	.08
	Soft, age-hardened	40 C	116, 000	.04
	Half-hard	30 C	89, 000	.045
	Half-hard, age-hardened	41 C	104, 000	.03
	Full-hard	37 C	100, 000	.04
	Full-hard, age-hardened	45 C	111, 000	.03

9. Ductility

The amount of cold work that can be done without annealing may be determined by means of the Olsen (Erickson) test. The depth of cup in nickel at fracture is 0.60 in., when a ⅞-in. ball is used with a 1⅝ in. die [256]. The ductility of nickel is also indicated by the previously cited values for elongation and reduction in area.

IX. Mechanical Properties at High Temperatures

1. Creep

The resistance to creep of nickel is lower than that of steel and higher than that of copper, bronze, and brass. Somewhere within the range 425° to 540° C the resistance to creep begins to drop rapidly [69]. In a compilation of available information [278], the stress required to extend a hot-rolled nickel rod 0.25 percent in 1,000 hr is given as 20,000 lb/in.^{2} at 427° C. At 538° C, a stress of 10,000 lb/in.^{2} produced 0.28-percent extension in 1,000 hr. For "A" nickel, the stress necessary to produce a creep rate of 1 percent in 10,000 hr is reported [399] as 10,000 lb/in.^{2} for hot-rolled material at 400° C and 24,000 lb/in.^{2} for cold-drawn material at 425° C.

2. Tensile Properties

The effect of high temperatures on several of the tensile properties of "A" nickel and of "Z-B" nickel is shown in figure 14.

3. Elastic Properties

The modulus of elasticity of nickel generally decreases with increasing temperature. Zacharias [94a] observed a regular decrease or a pronounced minimum in the curve, depending upon the prior heat treatment for a single crystal of purified nickel (99.88 percent) and for annealed rods of commercial purity.

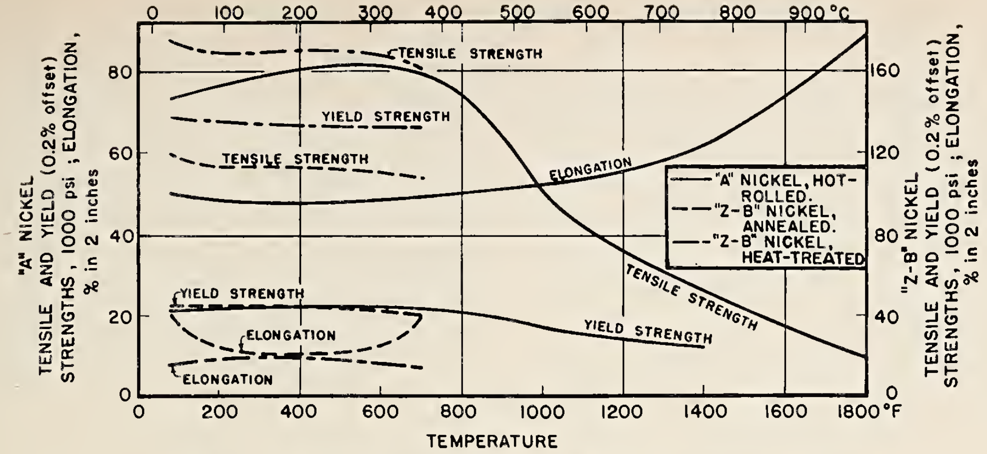

Figure 14. *Effect of temperature on some tensile properties of nickel.*

(International Nickel Co., Inc. [256, 355]).

4. Hardness

The values given in table 19, for dynamic hardness of nickel and "Z–B" nickel, were obtained by dividing the kinetic energy of a falling hammer, which carried a 10 mm carbide ball, by the volume of the resulting impression. The results are a combination of hardness and impact properties; the numbers are not similar to and cannot be converted to Brinell numbers [256].

Table 19.—*Dynamic hardness of nickel at high temperatures*

International Nickel Co., Inc. [256]

Material	Condition	Dynamic hardness at indicated temperatures, °F				
		Room	400	600	800	1, 000
Nickel	Annealed	202	174	156	149	148
	Cold-drawn	314	286	274	243	229
"Z–B" Nickel	Age-hardened	423	381	369	369	-----

Using a modified Brinell machine and a sintered carbide ball, Bolinger and Heilig [200] obtained Brinell hardness values for "Z–B" nickel at elevated temperatures. For hot-rolled specimens, the BHN of 192 at room temperature dropped to a minimum of 126 at 566° C; for hot-rolled and heat-treated material, the room temperature BHN was 336 and the minimum value at 593° C was 217.

5. Malleability

Ellis [98] determined the malleability of cold-drawn nickel rods at various temperatures by measuring the reduction in height caused by forging blows of known energy. His results are shown in figure 15. For "A" nickel the temperature range for hot working is reported [399] as 650° to 1,260° C.

In plant practice, different melts of the same type of nickel or high-nickel alloy may have almost identical mechanical properties at room temperature and be widely different in hot malleability. In the practice of the International Nickel Co., each melt is tested as described by Martin and Bieber [359] to select material for the most severe hot rolling and forging.

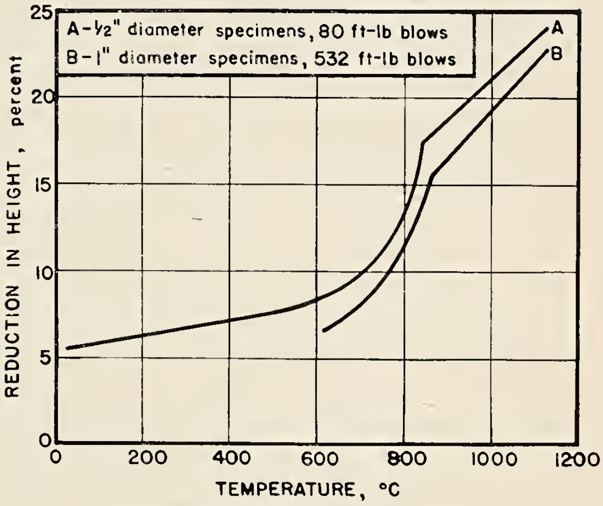

Figure 15. *Malleability of nickel.*

(Ellis [98]).

X. Mechanical Properties at Low Temperatures

Most of the mechanical properties of nickel improve at temperatures below room temperature. Improvement in the tensile strength and impact values is particularly evident; for example, the tensile strength of nickel (99.8 percent) was reported by Russell [77] as 133,000 lb/in.^{2} at 25° C and 155,000 lb/in.^{2} at −185° C. Charpy impact values for "pure nickel" increased from 135 ft-lb at room temperature to 236 at −80° C and 227 at −190° C, according to Foley [206]. For cold-drawn commercial nickel, a similar increase in Charpy impact values with decreasing temperature was reported by Rosenberg [240], but his values are lower than Foley's, 204 ft-lb at room temperature and 216 at −78° C. Less pronounced improvement is noted for yield strength, hardness, modulus of elasticity, elongation, and fatigue resistance. The yield strength of cold-drawn nickel increased from 97,000 lb/in.^{2} at room temperature to 112,000 at −76° C, and was accompanied by an increase in Rockwell C hardness from 19 at room temperature to 22 at −76° C [240]. Properties that are not consistently improved with decreasing temperature are reduction in area and compressibility.

XI. Effect of Minor Constituents on Properties

In general, impurities that are soluble in solid nickel increase the hardness, strength, and electrical resistivity, decrease the thermal expansion and thermal conductivity, and lower the Curie point (except iron and cobalt). Impurities that are insoluble in solid nickel affect, chiefly, the workability and particularly the hot working properties of nickel.

The effect of individual impurities commonly present in nickel is discussed in the ensuing paragraphs.

1. Carbon

Carbon exists in nickel in solid solution or as graphite formed by decomposition of the carbide. The solid solubility of carbon in nickel is reported [380] to be 0.65 percent at the eutectic temperature, 1,318° C, decreasing to about 0.03 percent at 500° C. The compound Ni_3C has been reported to exist at high temperatures, between 1,500° and 2,500° C, but is endothermic and very unstable.

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, the presence of carbon increases the difficulty of cold working, because of increased initial hardness and increased tendency to work harden. Carbon in excess of the solid solubility appears as graphite, which has an adverse effect on the malleability.

Kasé [29] reported that the magnetic transformation point of nickel was lowered by increasing carbon contents up to the limit of solid solubility, after which no further effect occurred. A recent survey [380] indicates that the Curie temperature of nickel is not affected appreciably by carbon.

2. Cobalt

Cobalt is soluble in all proportions in both liquid and solid nickel. It is invariably present in nickel produced in North America, in amounts up to 1 percent, averaging about 0.5 percent. Such quantities of cobalt raise the electrical resistivity and the magnetic transformation temperature slightly, but otherwise have no appreciable effect upon the properties of nickel. In the commercial forms of nickel and its alloys, the value for the cobalt content usually is combined with that of the nickel, that is, a single value is given for the content of nickel plus cobalt.

3. Copper

Copper and nickel are miscible in all proportions in both the solid and liquid states. Copper occurs in nickel in amounts usually less than 0.10 percent; in these amounts it has no noticeable effect upon the properties.

4. Iron

Iron is always present in commercial nickel, because of incomplete removal of the iron originally present in the ores and contamination from tools used in the roasting and refining operations. The amount of iron present in nickel, usually less than 1 percent, exists in solid solution and has no appreciable effect upon the properties of the metal.

5. Manganese

The equilibrium diagram of the manganese-nickel system [381] indicates solid solubility of 20 percent or more of manganese, with the established or probable existance of superstructures, for example, $MnNi_3$, in the 40 to 50 percent manganese area, and with the area beyond 50 percent manganese incompletely explored.

Small additions of manganese mildly increase the strength and hardness of nickel without materially decreasing the ductility. Additions of 10 to 20 percent of manganese markedly increase the electrical resistivity of cold-drawn and annealed nickel [15]. Additions of manganese decrease the

Curie temperature to less than 200° C for a 10-percent addition and to room temperature when 17 percent of manganese is added [216]. In the common commercial alloys, each percent of manganese up to 15 percent reduces the density of nickel by about 0.02.

In the production of malleable nickel, small amounts of manganese are added to combine with sulfur and thereby improve the malleability, and to facilitate the production of ingots with good surfaces, free from hot cracks and associated surface defects. Added in larger amounts, manganese increases the resistance of nickel to oxidation and decreases its susceptibility to sulfur from the fuels used in hot working operations.

6. Oxygen

According to Seybolt [145] the solubility of oxygen in solid nickel is exceptional; the amount dissolved increases with decreasing temperature, from 0.012 percent at 1,200° C to 0.020 at 600° C. Additions of oxygen lower the melting point of nickel, the melting point of the eutectic (0.22 percent oxygen) is 20° C below the melting point of nickel.

What little information is available on the effect of oxygen on the properties of nickel is concerned with the effect of nickel oxide, that is, with amounts of oxygen in excess of the solid solubility. The presence in nickel of the nickel oxide eutectic is readily detectible microscopically, but Merica and Waltenberg [31] showed that nickel may contain nickel oxide in amounts up to the eutectic composition (1.1 percent of NiO) and still be malleable, hot or cold. Nickel oxide may be encountered in nonmalleable forms, such as shot for alloy additions, but is generally eliminated in the preparation of malleable nickel.

7. Silicon

Silicon lowers the melting point of nickel; the eutectic composition (about 11.5 percent of Si) melts at 1,152° C. Silicon is soluble in solid nickel to the extent of 8.6 percent at the eutectic temperature, decreasing to about 6 percent at 600° C [391].

Silicon is always present in furnace-refined nickel in quantities under 0.25 percent, or for malleable nickels under 0.1 percent. In these amounts it has comparatively little effect on the properties of nickel, but larger amounts lower the Curie point [391] and the melting point, reduce the ductility and malleability, and increase the hardness.

8. Sulfur

Sulfur lowers the melting point of nickel; the eutectic occurs at 644° C and 21.5 percent of sulfur [377]. The solubility of sulfur in solid nickel is probably of the order of 0.005 percent [31], and any excess sulfur exists as nickel sulfide.

The presence of sulfide films along the grain boundaries and sulfide particles in the body of the grains seriously reduces the ductility, malleability, and other mechanical properties. Manganese is added to nickel to convert the sulfur to manganese sulfide, MnS, which does not have the objectionable effects of nickel sulfide. Magnesium is even more effective than manganese in the fixation of sulfur in relatively harmless forms in nickel.

A paper by Hall [280] describes methods for the microscopic identification of the various sulfides that are encountered in nickel.

XII. Casting, Fabrication, and Miscellaneous Processes

1. Casting

Nickel is cast from the furnaces into ingot molds for subsequent fabrication, open molds to produce blocks for remelting, sand molds for castings, and into water to form shot or spatter for use as alloying additions. Electrolytic nickel is used for most of the melting operations, alloying elements being added as desired for various uses. Melting is done in electric or fuel-fired furnaces; because of the possibility of sulfur contamination, low-sulfur fuels should be used, and the use of coke as a fuel is not recommended. According to Bieber [366], large melts are made in acid-lined open-hearth furnaces, and, according to Grubb [376], for smaller melts or for foundry operations neutral or basic linings are preferred.

In the preparation of ingots for subsequent fabrication, the furnace charge consists of up to 23,000 lb of electrolytic nickel and clean nickel scrap. No slag is intentionally added, but some is formed from the silica-alumina lining of the open-hearth furnace. The nickel heats are usually melted down with about 0.25 percent of carbon. After melting down, the carbon is reduced to 0.05 to 0.10 percent by additions of nickel oxide; the resulting boil carries out most of any hydrogen gas that may be present. After the carbon content has been adjusted, manganese is added and the metal is tapped into bottom-pour ladles where it is treated with small amounts of titanium, boron, and magnesium. The metal is cast in iron molds with copper bases; an electric arc hot top is used to eliminate pipes and center sponginess. The standard molds are 18 in. square and 40 in. long and produce ingots weighing about 4,600 lb each. Ingots weighing up to about 14,000 lb are cast for large forgings or heavy plates.

Ingots for the production of rolled anodes for electroplating are of two types: an oxidized type containing about 0.15 percent of oxygen combined as NiO and a type containing about 0.20 percent of carbon and 0.25 percent of silicon. The former is melted under mildly oxidizing conditions, the latter under reducing conditions. Small amounts of sulfur and copper are added to both types to improve their corrosion performance in the plating solutions. Ingots for rolling into anodes usually are 14 by 14 by 60 in. and weigh 3,300 lb each.

In making sand castings of nickel, the equipment, sand mixtures, and practice, in general, are similar to those for casting steel [376]. According to Wheeler [67], the composition of nickel castings should closely approximate: iron, 2.0 percent max; silicon, 0.75 to 2.0 percent; carbon,[2] 0.15 to 0.25 percent; manganese, 0.50 percent max; sulfur, 0.03 percent max (preferably as low as possible).

The metal is melted under a thin limestone slag, with additions of nickel oxide and carbon to cause a boil. The effectiveness of the boil in sweeping out gases is judged from the behavior of a test sample poured in a dry sand mold. If the top of the sample shrinks normally, the boil has been successful and the metal is killed with silicon. The heat is then finished as quickly as possible with final additions in the ladle of metallic silicon and approximately 0.10 percent of magnesium. Pouring temperatures range from 1,510° to 1,595° C (2,750° to 2,900° F) depending upon the size and section thickness of the casting.

In casting alloys, silicon is useful as a deoxidizer and to increase the fluidity of the molten metal and to reduce its cutting action on the sand. Manganese combines with sulfur and assists to some extent in deoxidizing the metal, but manganese also tends to make the molten metal sluggish and increases its tendency to cut the sand. Sulfur causes hot shortness and brittleness at normal temperatures. Final deoxidation is obtained by additions to the ladle of metallic silicon and about 0.10 percent of magnesium.

In casting practice, the pattern should provide for a linear shrinkage of ¼ in. per foot; gates and risers should be ample because of the volume shrinkage and small liquidus range of nickel. Mold washes or coatings and core binders should be chosen with consideration for the possibility of gas evolution.

The melting and casting of high-nickel alloys is similar to the practice for nickel, with necessary modifications because of the composition and melting points of the alloys.

2. Hot-Forming (Forging, Rolling, Bending, Extrusion)

Ingots of nickel and high-nickel alloys usually are milled, chipped, or otherwise treated to remove surface defects. They are then reheated in a low-sulfur or sulfur-free atmosphere and should not remain in the preheating furnace any longer than is necessary to heat the piece uniformly to the desired temperature. For forging nickel billets, the preheating temperature should be at least 1,100° C (2,000° F) and is usually close to 1,260° C (2,300° F); when rolled or extruded products are to be made, the forged blooms are inspected for surface defects, which may be removed by chipping or machining, and are then reheated to about 1,260° C (2,300° F) for the working operations. Heavy bending operations are started at the same temperatures as drop forging. The working temperatures and finishing temperatures of nickel alloys may be either higher or lower than those used for nickel, depending upon the composition and properties of the individual alloy.

For hot-rolling nickel bars and rods of the usual cross sections, the same designs of rolls as are used for steel are employed. Die blocks for forging or pressing to meet modern production requirements are usually made of alloy steel. Two widely used steels are (1) 1.25 to 2.0 percent of Ni, 0.5 to 0.8 percent of Cr, 0.25 to 0.35 percent of Mo, with 0.4 to 0.6 C, and (2) 5.0 to 5.25 percent of Cr, 1 to 1.75 percent of Mo, with 0.35 to 1.0 percent of carbon. Trimming dies may be of 18–4–1 high-speed steel [226, 256, 263, 289, 351, 355, 370].

Extrusion of nickel and high nickel alloys is made difficult by the high strength of the metal, its resistance to deformation at high temperatures, and the narrow range of temperature in which plastic deformation is possible. According to Barclay [109], pressures required for extrusion of nickel may be 30 to 50 percent greater than are used for copper alloys; the rate of extrusion should be faster than for commonly extruded alloys; and the container should be heated to maintain the temperatures of the billet at the desired level.

A 4,000-ton horizontal hydraulic press was installed recently at the Huntington, W. Va., plant of the International Nickel Co. for the extrusion of nickel and nickel alloy tubing from pierced billets. The largest tubes extruded up to March 1945 had an outside diameter of 8.9 in. with a wall thickness of 0.5 in. [304, 309]. Provision for heating the container, which Barclay considered mandatory, is not mentioned in the description of this press.

3. Cold-Forming (Shearing, Punching, Spinning, Deep-Drawing)

Shearing of nickel requires a shear load about 125 percent greater than is needed for mild steel of equal gage. Shear blades must be tight and sharp.

For punching, alloy steel punches and dies with a Rockwell C hardness of 58 to 61 are recommended. Sulfur-base oil is a good lubricant but must be completely removed prior to any subse-

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[2] Modern practice permits up to 0.75 percent of carbon in nickel castings.

quent heat treatment. Die and punch clearance should be the same as for neat steel punching, with a close clearance maintained between the punch and stripper plate. The minimum permissible punch hole diameter for nickel, Monel, or Inconel sheet varies with the sheet thickness, from 1.5 times the thickness for 0.018 to 0.034-in. sheet to one times the thickness for 5/32 in. and heavier sheet [256, 263].

Although nickel is quite ductile it is stronger and work-hardens faster than most of the nonferrous materials generally spun. Therefore, more power and more frequent annealing are required. Tools should be broader and flatter than those used for other metals. The most suitable tool material is highly polished, hard-alloyed bronze. Yellow laundry soap, beeswax, or tallow are satisfactory lubricants and should be removed prior to heat treating. "L" nickel may be spun more easily because it is softer and does not work-harden as fast. The "Z" nickels are more difficult to spin and require more frequent annealing [256].

Equipment and procedures similar to those used for deep-drawing steel may be applied to drawing nickel and its alloys. Grey cast iron or cast semisteel dies may be used for short runs, but for quantity production, hard bronzes, heat-treated nickel-chromium cast iron, or chromium-plated hard steel are preferred. For small work tungsten carbide dies are used. Carbon steel dies should not be used for drawing high nickel alloys because of danger of galling. Beef tallow, castor oil, and water or oil-soluble lubricants compounded from these two are excellent lubricants. White lead, graphite, and sulfur-bearing lubricants may be used but must be removed completely before any subsequent annealing treatment [289].

4. Annealing

The recrystallization temperature of highly purified nickel was determined by Ransley and Smithells [86] as 480° C (896° F), and by Fetz [182] as between 300° and 400° C (572° and 752° F). Both investigators found that small amounts of impurities raise the value considerably and that the recrystallization temperature for commercial nickel exceeds 600° C (1,112° F).

In all annealing treatments of nickel and its alloys, the furnace atmosphere should be free from sulfur compounds. Mildly oxidizing or reducing atmospheres may be used for annealing treatments but the atmosphere must not fluctuate between oxidizing and reducing conditions or severe intercrystalline attack will result.

According to Mudge [289, 382], the three annealing treatments commonly used for nickel and its alloys are:

(a) Soft annealing, usually to prepare the metal for further cold work. This operation may be either open or closed (box) annealing; figure 16 shows the effect of time and temperature in open annealing of nickel. Recommended practice for soft annealing of nickel is 6 to 1 min at 1,500° to 1,700° F for open annealing and 3 to 1 hr at 1,300° to 1,400° F for box annealing. Material may be furnace-cooled, aircooled, or quenched after either treatment. If a reducing atmosphere is maintained (carbon monoxide or hydrogen or mixtures of the two) the material can be bright-annealed, and the need for subsequent pickling and grinding may be avoided. Dead-soft annealing results from the use of higher temperatures and longer times than are used to produce the soft condition. Dead-soft annealing is accompanied by appreciable increase in the grain size of the metal.

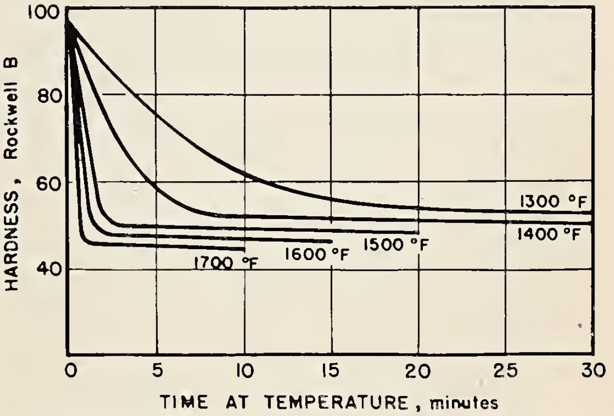

FIGURE 16. *Effect of annealing time and temperature on the hardness of nickel.*

(International Nickel Co., Inc. [256]).

(b) Temper annealing is partial annealing or stress-relief of work-hardened light sections and is usually applied only to strip and wire. The continuous method is preferred, but other procedures may be used. Recommended practice is 3 to 1 hr at 1,000° to 1,100° F, followed by furnace cooling, air cooling, or quenching. Bright annealing is possible in temper annealing, as in soft annealing.

(c) Stress-equalizing annealing, at temperatures too low to effect softening of the material, but sufficient to equalize stresses and thereby improve the mechanical properties and insure against distortion and warping in subsequent machining. Stress equalizing is accomplished by 3 to 1 hr at 525° to 600° F.

Some use is made of salt-bath annealing, in molten chlorides or carbonates of sodium, potassium, and barium, particularly for special work with small parts. Care must be exercised to remove all traces of sulfur from the salt bath to prevent embrittlement of the work. Another special method of annealing is by electric-resistance heating, but this method has seldom been satisfactory.

Recommended practices for annealing or heat treatment of nickel alloys, including age-hardening alloys, are given in publications of the International Nickel Co. [355, 382].

5. Pickling

Nickel and nickel alloys, in general, require pickling treatment different from that employed for iron, steel, and copper alloys. A light tarnish, such as is developed by thermal treatment at moderate temperatures, is easily removed, whereas a heavy oxide coating or scale is more difficult to remove. Before any pickling treatment is used the metal should be cleaned from oil, grease, drawing compounds, etc., by suitable treatment with soap and water, caustic solutions, or organic solvents. Molten salt baths have been used successfully for a combination of degreasing and removal of oxide and scale.

A bath recommended as a flash pickle for nickel contains—

Water	1 gal
Sulfuric acid (66° Be)	1½ gal
Nitric acid (38° Be)	2¼ gal

After the acid-water mixture has cooled, ¼ lb of salt (sodium chloride) is added. This solution at 70° to 100° F will flash pickle nickel in a few seconds.

Another flash pickle contains—

Water	1 gal
Sulfuric acid (66° Be)	¾ pt
Sodium nitrate (crude)	½ lb
Sodium chloride	1 lb

This bath is used at 180° to 190° F; the time of immersion to remove reduced nickel oxide is 30 to 90 min.

Nickel that has been hot-worked or annealed in an oxidizing atmosphere may be pickled by 1 to 2 hr immersion at 180° F in

Water	1 gal
Hydrochloric acid (20° Be)	½ gal
Cupric chloride	¼ lb

Pickling in this solution may be followed by a dip in one of the flash-pickling solutions to improve the appearance of the surface.

Additional pickling baths for nickel and its alloys are discussed in the references cited [263, 370].

6. Machining

Machining of nickel and its alloys is, in many respects, similar to that of steel. High-speed steel, cast cobalt-base alloys, and cemented carbides are used for cutting tools. Recommended lubricants include sulfurized oils with high-speed steel or cobalt-base tools, and water-soluble oil with cemented carbide tools. In drilling operations, high-speed steel drills are preferred, with turpentine or gasoline recommended as lubricants when small holes are being drilled.

Details of tool design and procedure for various machining operations, turning, boring, drilling, reaming, threading and thread chasing, planing, broaching, milling, etc., are given in the literature [256, 263, 289, 374].

7. Grinding, Polishing, Buffing

For heavy grinding, where the finish is not important, rubber or resinoid-bonded wheels of No. 14 or 24 grit should be used. Overheating in grinding should be avoided, particularly in grinding welds. When the appearance of the surface is important, finer wheels, for example No. 36 grit, should be used.

Various operations under the general head of polishing include roughing, dry finishing, greasing, and grease coloring, all accomplished with rollhead wheels or abrasive belts. Ordinarily there should be from 40 to 60 grit numbers between successive polishing operations, and the correct combination of abrasives and wheel speed must be maintained to achieve the best results.

Buffing operations from the removal of polishing scratches to the development of a mirror finish are conducted with high-count muslin, loose-disk wheels. Tripoli compounds are used for the removal of scratches and unfused alumina or green chromic acid for subsequent color buffing. Lime compounds are used for buffing nickel plate but do not have sufficient cutting and coloring characteristics for use with nickel alloys. For the highest mirror finish, Canton flannel and chromic oxide are used.

The work should be cleaned after any finishing operation, preferably by sprinkling with whiting and rubbing clean with a soft rag [289, 370].

8. Welding, Brazing, Soldering

Nickel may be welded to itself or to other metals by metallic arc, electric resistance, oxyacetylene, and atomic hydrogen processes. For some special purposes the inert gas-shielded arc or the submerged melt process may be used, but carbon-arc welding has been largely supplanted by metallic-arc welding with the improved electrodes that are now available. Nickel and the high-nickel alloys cannot be forge welded; the presence of a coating of nickel oxide prevents union unless the metal melts. When properly made, welded joints are equal to the parent metal in strength and resistance to corrosion, and no thermal or chemical treatment is needed. According to Spicer [392], arc-welded joints in nickel will have an average tensile strength of 70,000 lb/in.^{2} with an average elongation of 30 percent; for gas-welded joints in nickel the corresponding values are 60,000 lb/in.^{2} and 35 percent.

Electrodes for arc-welding nickel have been designed for use with direct current and reversed polarity. In use, the electrode should be inclined about 20 degrees in the direction of welding; the arc should be slightly shorter than would be used for a steel electrode of the same diameter; welds should never be wider than three times the diameter of the core wire.

Resistance welding of nickel, spot, seam, and flash is much the same as for steel, with allowance for the differences in electrical and thermal conductivity. Nickel cannot be spot welded to aluminum or magnesium and makes poor welds with tin, cadmium, and zinc. Copper-alloy electrodes with flat tips and with at least 25 percent of the conductivity of pure copper are desirable. Flash welding is employed when butt joints are required instead of lap seams. The jaws must move together more rapidly than for steel and with a continuous, uninterrupted motion.

In oxyacetylene, welding-filler rods should approximate the composition of the metal and should have a diameter equal to the sheet thickness up to 5/32 in. A flux is not needed in welding nickel, but mixtures of borax and boric acid are used for nickel alloys. Control of the flame size and characteristics is important; the torch tip should be large enough to produce a soft flame, that is, one size larger than would be used for steel, and the flame must be slightly reducing with a small excess of acetylene. To prevent oxidation, the tip of the welding rod should be kept within the flame envelope, the weld metal should be applied in a single layer, and puddling should be avoided. Properly made welds are ductile and can be cold-worked [243, 254, 256, 263, 298, 392].

Silver-brazing alloys that melt and flow at temperatures between 1,140° and 1,325° F are preferred for brazing nickel and nickel alloys. Bronze or brass-brazing alloys melt at higher temperatures and the joints usually are less resistant to corrosion than the silver-brazed joints. Alloys that contain phosphorous should not be used on nickel because of the embrittling action of the phosphorus.

Proprietary fluxes are used with the silver-brazing alloys; residual flux is removed from the finished joint by washing with hot or cold water. Borax and boric acid fluxes usually are not properly molten at temperatures used for silver brazing. It is, of course, desirable to complete the work at as low a temperature as possible, and silver brazing of nickel and its alloys can be done at temperatures so low that the annealing or softening effect is insignificant [243, 256, 289, 392].

Soft soldering of nickel and its alloys is employed only where corrosion resistance is not a factor and where a weak joint will suffice or where the solder is used merely to seal a strong joint made by other means. In soldering nickel, the surfaces should be pretinned. If an iron is used, it should be larger and hotter than for copper. Commercial acid or cut acid fluxes are preferred, and zinc chloride has been used with good results. The action of rosin flux is too mild to be satisfactory [243, 392].

Part 2. Ferrous Alloys

Accounts of the preparation of iron-nickel alloys were published by Stodart and Faraday as early as 1820, and iron-nickel alloys were exhibited at the New York Exposition in 1853. However, the results published by James Riley in 1889 first demonstrated the general merits of nickel steels and pointed out their commercial value.

Alloys of iron and nickel, with or without other alloying elements, constitute by far the largest use of nickel as evidenced in the tables for nickel consumption. The nickel content of these ferrous alloys ranges from 90 percent or more, in special-purpose alloys, down to the small percentages of nickel in structural and engineering steels. These compositions are so numerous and so important from a practical standpoint that attempts are often made to divide the field into nickel steels and nickel-iron or iron-nickel alloys, but a sharp dividing line between the two groups cannot be drawn. In the Alloys of Iron Monograph Series, Marsh [190] confined the first volume of the iron-nickel monograph to those iron-nickel alloys containing so much nickel (more than 6 percent) that, regardless of carbon content, they are not commonly used as structural or engineering steels, and to alloys of iron, nickel, and other elements, principally chromium, containing more than 6 percent of nickel and more nickel than chromium. The second volume of the iron-nickel monograph, now in preparation, will deal with engineering and structural steels, containing generally less than 6 percent of nickel, and with nickel cast irons. Discussion of the steels that contain more than 6 percent of nickel and more chromium than nickel, that is, the 18:8 and other stainless steels, is contained in another volume of the Monograph Series, volume 2 of the Alloys of Iron and Chromium. Sands [389] suggests another line of demarcation between nickel steels and iron-nickel alloys; iron-nickel alloys are those alloys that contain 30 percent or more nickel and are therefore wholly austenitic at room temperature under any conditions of cooling; steels are those alloys containing less than about 30 percent of nickel, which are not wholly austenitic at room temperature. The subdivisions of the subject in this circular do not always agree with the recommendations of either Marsh or Sands.

The amount of literature on the subject of ferrous alloys of nickel is tremendous, and the coverage permitted in the present publication is limited. Consequently, it has been possible only to touch upon selected topics and to indicate sources of more detailed information for the reader's convenience. In general, nickel is found only in the solid-solution phase; it is not a carbide former; excluding the austenitic alloys, the principal effects result from its influence on ferrite and on the manner of formation and distribution of the carbide phase.

I. Structure

The iron-nickel diagram is shown in figure 17. Accurate phase boundaries below about 600° C have not yet been established due to the sluggishness of structural changes at these temperatures. In the molten state, nickel and iron are soluble in all proportions and solidify as solid solutions. Nickel depresses the gamma to alpha transformation and the alloys with 6 to about 30 percent of nickel may contain the alpha phase (martensitic or ferritic) and the gamma phase, the amount of each present being governed by composition, heat treatment, and cold work. Below 6 percent of nickel the alloys are ferritic. Above 30 percent of nickel the alloys are predominantly austenitic, and their stability increases with increasing nickel content. The delta phase is present only in the iron-rich alloys within a small range of temperature and composition. There is some evidence of the formation of a superstructure on slow cooling in the alloys with about 76 percent of nickel [260a, 389].

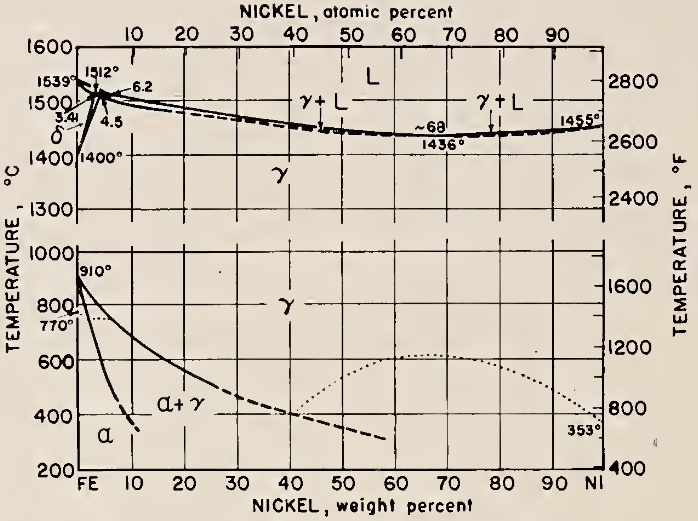

Figure 17. *Iron-nickel diagram* (*Sachs* [*388*]).

Note: On the International Temperature Scale for 1948 the melting point for nickel is 1,453° C and that for iron 1,536° C.

Nickel affects the temperatures of the A_3 transformation on heating as well as on cooling, and the effect is noticeable even with low nickel contents. Data reported by Scott [22] on the effect of 2 and 4 percent of nickel on the temperature of completion of Ac_3 are shown in figure 18. Scott's value for Ac_3 for iron is appreciably higher than the currently accepted value of 910° C for A_3 in high-purity iron, but the shape and relative positions of the curves should not be affected appreciably by this discrepancy.

Both the alpha and delta solid solutions have a body-centered cubic lattice, whereas the gamma phase is face-centered cubic. At room temperature the lattice constant of the alpha phase increases with increasing nickel content up to 6 or 8 percent; in the range from about 6- to 25-percent nickel, the mixture of alpha and gamma phases makes results uncertain and varying with the heat treatment; in the gamma phase alloys, the lattice constant increases with increasing nickel content from about 25 to 40 percent and decreases with further increase in the nickel content. At 300° and 600° C the parameters of the alpha alloys follow the same general trend as at room temperature. At 300° C the parameters of the gamma alloys continually decrease with increase in nickel content, except for a rise in the 40-percent-nickel region, and at 600° C the parameters of the gamma alloys decrease constantly with increased nickel. Values reported by Owen, Yates, and Sully [168] for three different temperatures are shown in table 20. Similar results for room temperatures were obtained by Bradley, Jay, and Taylor [152] and by Jette and Foote [138].

Table 20. *Lattice parameters of iron-nickel alloys*

Owen, Yates, and Sully [168]

Ni	Angstroms at—		
	15° C	300° C	600° C
Percent, atomic			
0	2.8605	2.8712	2.8855
3.1	2.8621	2.8723	2.8857
8.8	2.8634	2.8730	2.8845
16.4	2.8630	2.8725	2.8844
23.4 (alpha)	2.8630	2.8721	------
23.4 (gamma)	3.5733	3.5934	3.6122
31.2	3.5813	3.5917	3.6106
34.3	3.5856	3.5915	3.6100
41.75	3.5883	3.5927	3.6067
44.3	3.5856	3.5929	3.6061
57.0	3.5691	3.5816	3.5950
72.8	3.5492	3.5626	3.5787
82.2	3.5378	3.5518	3.5691
90.8	3.5278	3.5418	3.5602
93.8	3.5241	3.5382	3.5562
96.6	3.5207	3.5347	3.5527
100	3.5171	3.5318	3.5509

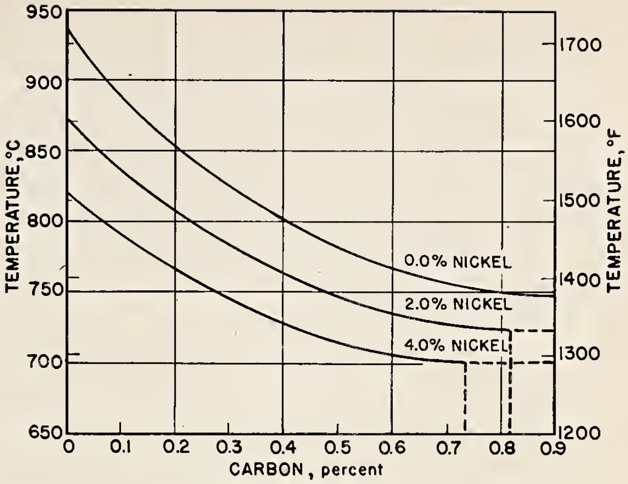

Figure 18. *Effect of carbon and nickel on the end of* Ac_3 *range of steels.*

(Scott [22]).

II. Thermal Expansion and Magnetic Properties

Discussion of these properties is incorporated in the subsequent section on high-nickel alloys, to which these properties particularly apply.

III. Density

The density at 15° C of iron-nickel alloys increases gradually with increasing nickel content throughout the alpha phase, from about 7.87 g/cm^3 for iron to about 7.94 for the 23.4-percent nickel alloy. The alpha-gamma transformation is accompanied by an abrupt increase in density. The density of the gamma alloys decreases with increasing nickel content up to about 37.5 percent, and thereafter increases with increasing nickel until the density of pure nickel is reached. With increasing temperature, the density of all compositions decreases, and the minimum in the 15° C curve at 37.5-percent nickel flattens out and eventually disappears. The effects of composition and temperature on the density of iron-nickel alloys, as determined by Owen, Yates, and Sully [168] from lattice parameter data, are shown in figure 19. Values obtained by Jette and Foote [138] are in good agreement with those of Owen, Yates, and Sully. Earlier determinations of densities by direct methods, for example, by Nishiyama in 1929 and by Chevenard in 1914, are in general agreement with the more precise lattice parameter data.

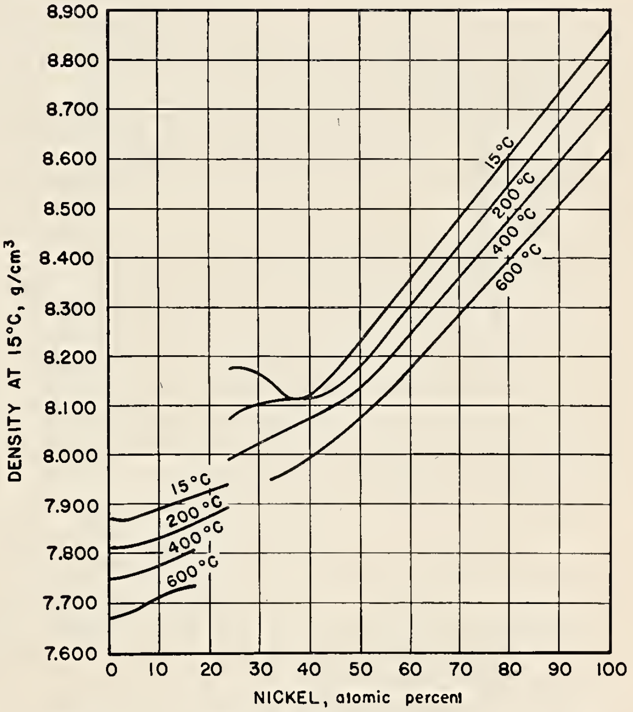

Figure 19. *Densities of iron-nickel alloys at various temperatures.*

(Owen, Yates, and Sully [168]).

IV. Specific Heat

The specific heat of iron-nickel alloys remains fairly constant until the nickel content reaches about 20 percent, then rises sharply to a maximum at about the Invar composition. Further increase in the nickel content is accompanied by a decrease in specific heat. Data obtained by Ingersoll [21] for alloys that he prepared from electrolytic iron and electrolytic nickel are given in table 21.

TABLE 21. *Specific heats of pure iron-nickel alloys*

Ingersoll [21]

Nickel content	Specific heat 25 to 100° C	Nickel content	Specific heat 25 to 100° C
Percent	*cal* g^{-1} °C^{-1}	*Percent*	*cal* g^{-1} °C^{-1}
1.07	0.1162	22.11	0.1163
1.93	.1170	25.20	.1181
7.05	.1163	28.42	.1191
10.20	.1168	35.09	.1228
13.11	.1160	47.08	.1196
19.21	.1163	75.06	.1181

V. Thermal Conductivity

The thermal conductivity of iron-nickel alloys reaches a minimum at about 30-percent nickel, according to Ingersoll [21] and Honda [18], whose results are shown in figure 20. The values obtained by Ingersoll were for the range 20° to 100° C, and those of Honda were for 30° C. The lower values obtained by Honda apparently resulted from the test temperature and from his use of less pure metals than were used by Ingersoll.

The thermal conductivity increases with increasing temperature; for example, the conductivity of a 28-percent-nickel steel increased from 0.033 at 50° C to 0.044 cal cm^{-1} $°C^{-1}$ sec^{-1} at 350° C [220].

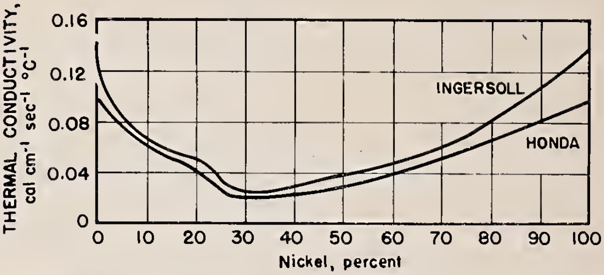

FIGURE 20. *Thermal conductivity of iron-nickel alloys.*

(Ingersoll [21], Honda [18]).

VI. Electrical Resistivity

The electrical resistivity of iron-nickel alloys is of interest primarily in connection with the magnetic properties. Direct use of the resistivity of iron-nickel alloys, for example, as resistance elements in rheostats and electric heaters, has been largely supplanted by the use of copper-nickel and nickel-chromium alloys.

Data reported by Burgess and Aston [7], Yensen [23], Ingersoll [21], and Sizoo and Zwikker [56] show that the resistivity of annealed iron-nickel alloys increases with increasing nickel, slowly at first and then rapidly, to a maximum at 30- to 35-percent nickel. With further increase in the nickel content, up to about 50 percent [21, 23] or about 75 percent [7], the resistivity decreases rapidly at first, then gradually.

Dahl [133] studied the effect of heat treatment and cold work on the resistivity of alloys containing more than 30 percent of nickel. He found a pronounced minimum in the resistivity of the annealed metal at 73-percent nickel and maxima at the same point, that is, 73-percent nickel in the resistivities of the quenched and the cold-drawn alloys. According to Bozorth [323], the resistivity of iron-nickel alloys is increased by exposure to a magnetic field. Tension increases the resistivity of those alloys with positive magnetostriction and decreases it for alloys with negative magnetostriction. Yamanaka [246] found similar effects in the alloys he studied.

VII. Corrosion Resistance

In general, in those media where nickel is more resistant to corrosion than iron, the beneficial effects of nickel in iron-nickel alloys increase with increasing nickel content.

Iron-nickel alloys are more resistant than carbon steel to atmospheric exposure but are not equal to some of the corrosion-resistant steels commonly referred to as stainless steels [185]. The iron-nickel alloys are not immune to corrosion, particularly in moist climates, and the protection of instruments and tapes by a suitable grease or vaseline is recommended. Strauss [195] recommended a 28-percent-nickel steel for resistance to both marine and industrial atmospheres. Additional data on resistance to atmospheric corrosion are included in the subsequent sections on low-nickel and high-nickel steels.

The resistance of iron-nickel alloys to corrosion in aqueous solutions of all kinds, including solutions of the common mineral acids, has been widely studied. Pilling and Ackerman [55] reported results of an extended study of the resistance of a wide variety of iron-nickel alloys to a number of solutions. Strauss [195] claimed almost unlimited serviceability in sea water for a 28-percent-nickel alloy. Studies of the behavior of iron-nickel alloys in dilute hydrochloric acid, by Utida and Saito [34], Pilling and Ackerman [55], and Schmidt and Wetternik [170], showed that nickel improves the resistance of iron, and the improvement is great for nickel contents above about 25 percent. Some of Schmidt and Wetternik's results are shown in figure 21. Nickel is attacked by either dilute or concentrated solutions of nitric acid and the iron-nickel alloys are not so resistant as pure nickel to nitric acid [34, 55]. The effect of different concentrations of sulfuric acid on different compositions of iron-nickel alloys was studied by Fink and DeCroly [48], Utida and Saito [34], Pilling and Ackerman [55], and Schmidt and Wetternik [170]. In general, the rate of corrosion in sulfuric acid decreases with increasing nickel content, as is indicated for the 20-percent acid in figure 21. The relation is not always regular; minima in the corrosion rates at about 50-percent nickel have been reported.

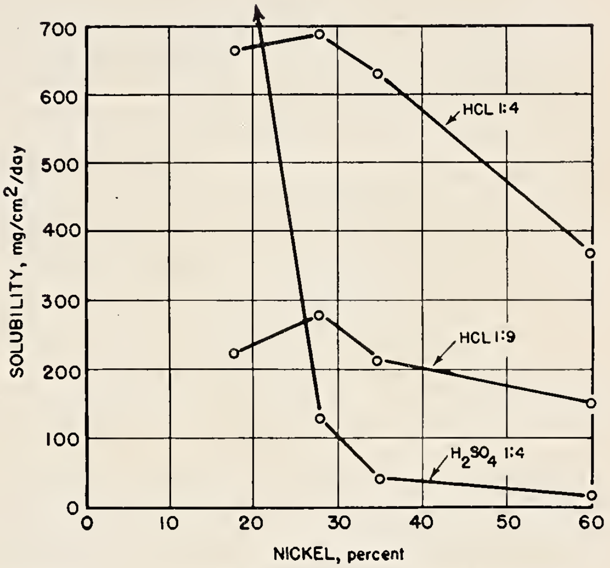

FIGURE 21. *Solubility of iron-nickel alloys in hydrochloric and sulfuric acids.*

(Schmidt and Wetternick [170]).

VIII. Mechanical Properties

As the nickel content increases, the tensile and yield strengths of annealed iron-nickel alloys rise to maximum values at about 18-percent nickel, accompanied by minimum values of reduction of area and elongation. With increasing nickel between 18 and about 30 percent, the tensile and yield strengths are progressively reduced, whereas elongation and reduction of area are increased. Above 30-percent nickel, all four properties increase to flat maxima at about 70-percent nickel. Data for alloys containing 30 percent or more of nickel are shown in figure 22.

Hardness values increase with increasing nickel up to about 17 percent, then fall to a low at 25 percent. Between 25- and 50-percent nickel the hardness remains fairly constant.

The effect of nickel on the impact resistance is particularly important for the low-nickel steels and is further discussed in the section devoted to low-nickel steels. Iron-nickel alloys, which contain more than about 42 percent of nickel, have as good or better resistance to impact at liquid air temperatures as at room temperature [185], but the impact resistance at liquid air temperatures falls off rapidly with decreasing nickel below 42 percent.

Data on the elastic constants of iron-nickel alloys were reported by Nishiyama [54], Davis and Thomas [154], Marsh [190], and Eskin and Fritze [230]. The temperature coefficient of the elastic modulus is positive in alloys containing 28 to 44 percent of nickel and has a maximum value at 35 percent.

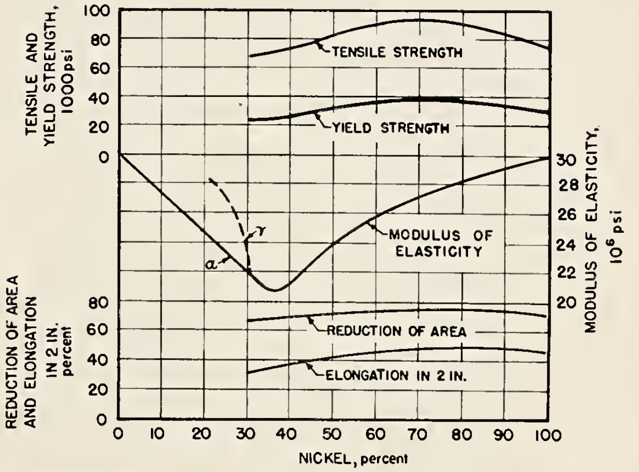

FIGURE 22. *Approximate mechanical properties of annealed iron-nickel alloys.*

(Sands [389]).

IX. Low-Nickel Steels

Low-nickel steels are popular principally for their mechanical properties; for example, a higher yield strength than is usual in carbon steels permits smaller sections to be used in structures. The effect of nickel on the tensile properties of annealed low-carbon steel is shown in figure 23. A secondary but still an important consideration is the generally better resistance to corrosion, at least for the milder forms of corrosive attack, as compared with unalloyed steels [401].

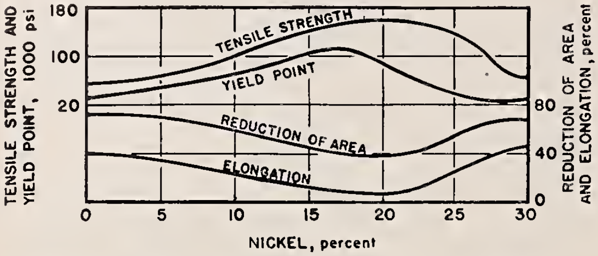

Figure 23. *Effect of nickel on the tensile properties of annealed low-carbon (0.05-percent C) steels.*

(Sands [389]).

Nickel lowers the A_{c_3} range in steels (figure 18). This factor, combined with the somewhat deeper hardening characteristics nickel imparts, permits the steels to be cooled at slower rates and from lower temperatures, thereby reducing the tendency of the steel to warp and crack. The presence of nickel tends to produce a stronger ferrite and a finer pearlite, and it reduces the eutectoid carbon ratio about four points of carbon per 1 percent of nickel [389]. These effects, together with the improved strength, toughness, and fatigue resistance, make the nickel steels with low carbon contents (up to 0.20-percent carbon) especially adaptable to carburizing treatments. The carburized case of nickel steels hardens completely with an oil quench. The carburized zone is more uniform and the mechanical properties of the core after heat treatment are superior to those of plain carbon steel, as is shown in figure 24. However, the resistance to wear by dry-rolling friction and dry abrasion, for carburized nickel steels, is reported [80] to be inferior to that of carburized carbon steels. Nickel is sometimes added to nitriding steels to help produce a somewhat harder core and a strong, tough case, although some lessening in the hardness of the case is involved [82, 377a].

Nickel is effective, even in the amounts present in the low-nickel steels, in reducing the deterioration in toughness that ferritic steels undergo at low temperatures. Aldridge and Shepherd [130] found that a 2.4-percent-nickel steel was superior to a plain carbon steel in resistance to impact at temperatures down to −100° F. Egan, Crafts, and Kinzel [90] found that the resistance, to impact at low temperatures, of a 3.5-percent-nickel steel was superior to some plain carbon steels, although not as good in this respect as some complex alloy steels that were included in the tests. Malcolm [189] recommended low-carbon, 2.5- to 3-percent-nickel steel for impact resistance down to −100° F. Rosenberg [240] also reported the superior resistance to impact, at temperatures down to −78° C, of 3.3-percent-nickel steel as compared to carbon steels. The influence of nickel on the impact strength of low-carbon steels at low temperatures is summarized in figure 25.

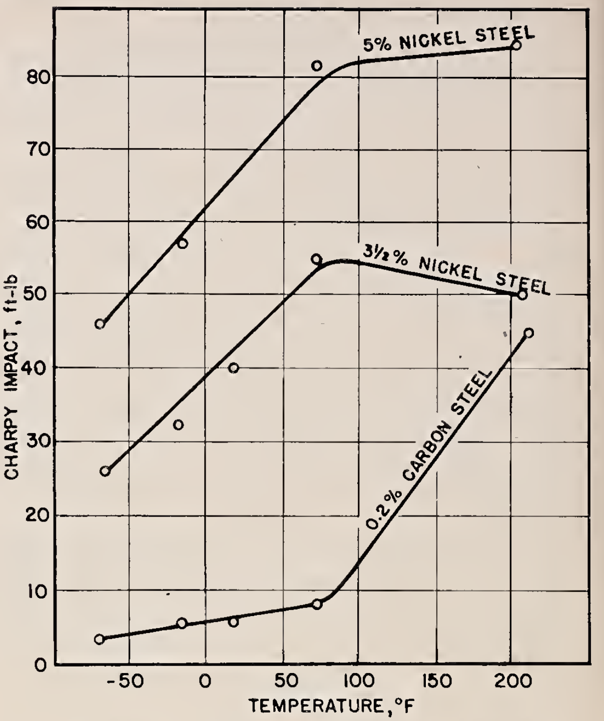

Figure 24. *Charpy impact values from unnotched case-hardened steels.*

(Sergeson [87]).

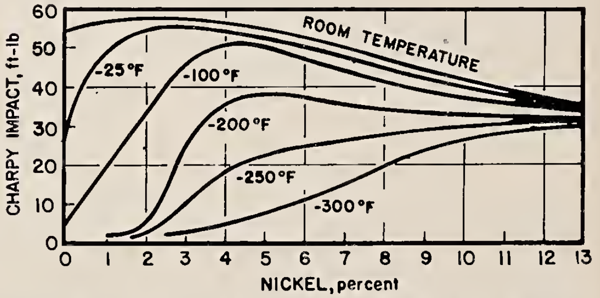

Figure 25. *Influence of nickel on the impact strength (keyhole notch) of normalized low-carbon (0.1- to 0.2-percent C) steel at low temperatures.*

(Sands [389]).

McAdam [52] found that the fatigue resistance of a 3.7-percent-nickel steel was decidedly superior to that of a nickel-free steel of similar carbon content for both the quenched-and-tempered and the annealed conditions. Additional information on the mechanical properties of nickel steels is found in NBS Circular C447 [278].

Nickel improves the resistance of steels to corrosion by industrial and marine atmospheres and by alkalies. Dixon and Gross [114] and Friend [183] reported the results of exposure tests up to 15 years' duration, in which a 3.75-percent-nickel steel had markedly greater resistance to atmospheric and fresh water corrosion than a plain carbon steel of the same carbon content. Pilling and Wesley [239] found that, in the atmosphere of Bayonne, N. J., the corrosion rate of 2-percent-nickel steel was definitely less than that of ingot iron and was roughly comparable to that of nickel-copper and copper-molybdenum steels. Larrabee [314] recorded the results of 3.5 years' exposure of low nickel steels in an industrial and a marine atmosphere, as shown in figure 26.

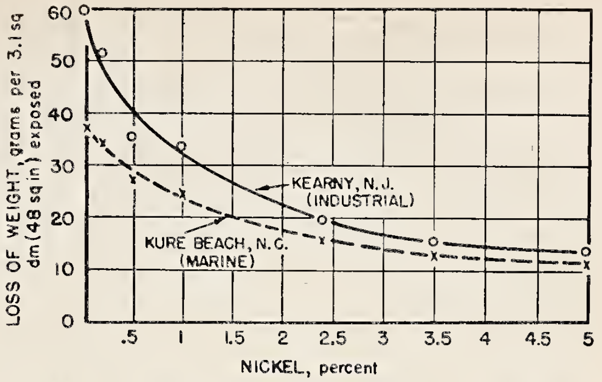

FIGURE 26. *Effect of nickel content on the atmospheric corrosion rate of low-nickel steels.*
(Larrabee [314]).

1. 3.5-Percent-Nickel Steels

The 3.5-percent-nickel steel is the oldest and probably the best known of the nickel steels. Compositions of the various members of the series, as established by the Society of Automotive Engineers, and the American Iron and Steel Institute, are given in table 22.

TABLE 22. *Compositions of 3.5-percent-nickel steels*

AISI No.	SAE No.	C	Mn	Si	P	S	Ni
		Percent	*Percent*	*Percent*	*Percent* (max.)	*Percent* (max.)	*Percent*
2317	2317	0.15 to 0.20	0.40 to 0.60	0.20 to 0.35	0.040	0.040	3.25 to 3.75
2330	2330	.28 to .33	.60 to .80	.20 to .35	.040	.040	3.25 to 3.75
2335	------	.33 to .38	.60 to .80	.20 to .35	.040	.040	3.25 to 3.75
2340	2340	.38 to .43	.70 to .90	.20 to .35	.040	.040	3.25 to 3.75
2345	2345	.43 to .48	.70 to .90	.20 to .35	.040	.040	3.25 to 3.75

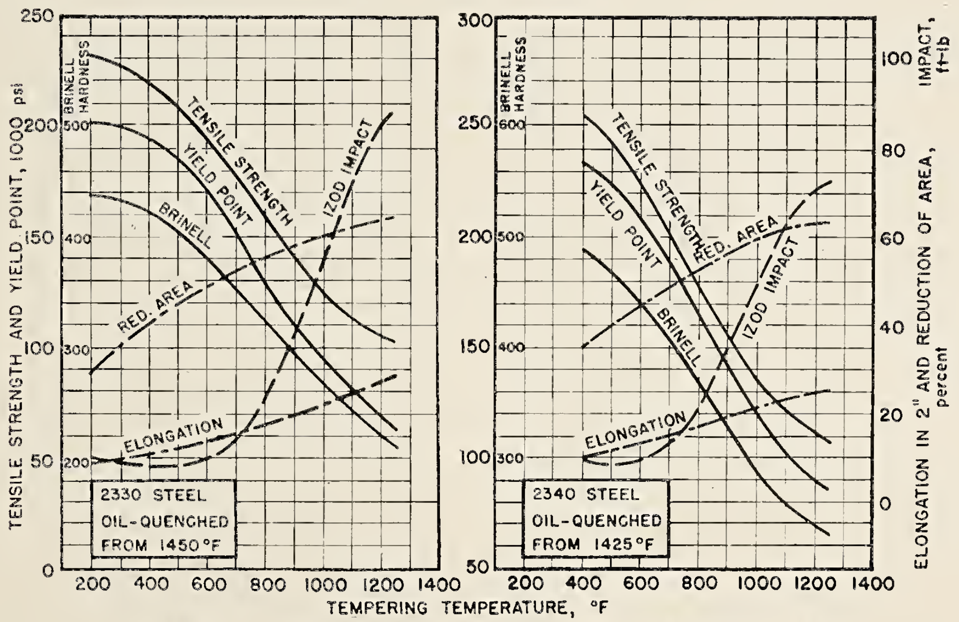

FIGURE 27. *Mechanical properties of nickel steels, SAE 2330 and 2340.*
(International Nickel Co., Inc. [332]).

Steels of the 2300 series find a variety of uses. The 2317 steel is popular for case hardening, cyaniding, etc.; 2330 is used in automotive, aviation, and agriculture parts where considerable strength and toughness are required, for example, screws, studs, nuts, bolts, levers, keys, and propeller-shaft tubes. Its good machinability, strength, and ductility make it a valuable cold-drawn stock. The 2335 composition provides somewhat greater strength and hardness because of the increased carbon content. The 2340 steel is still stronger and is tough; it is used for propeller shafts, spline shafts, axle shafts, chisels, and for cold-drawn bar stock. 2345 has the highest strength and hardness obtainable in this series and is used for structural shapes, eyebars, and plates as well as transmission gears, oil-hardened axles, shafting, bolts, screw drivers, etc.

Data on the properties of two of the steels of the 2300 series are shown in figure 27.

2. 5-Percent-Nickel Steels

Compositions of the 5-percent-nickel steels according to SAE and AISI standards are given in table 23. These steels are used for case-hardened applications in which a high degree of core toughness is desired. Their low quenching temperature reduces scaling and distortion. Applications of these steels include wrist pins, king pins, transmission gears, rock drill parts, engine cams, and riveting tools. Data on the properties of steels of the 2500 series are presented in figures 24, 26, and 28.

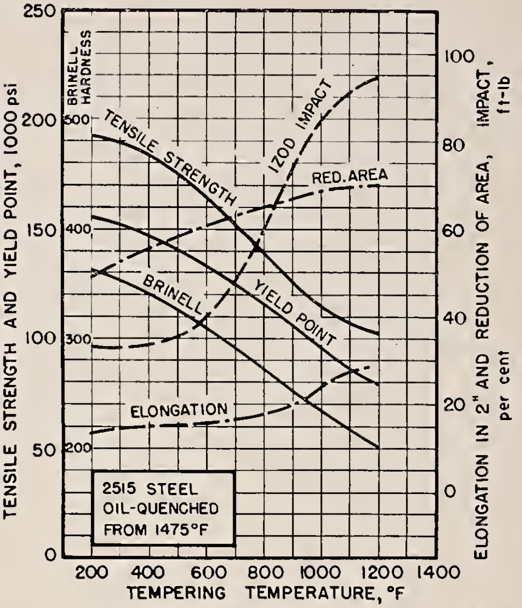

Figure 28. *Mechanical properties of nickel steel SAE 2515.*

(International Nickel Co., Inc. [332]).

Table 23. *Compositions of 5-percent nickel steels*

AISI No.	SAE No.	C	Mn	Si	P	S	Ni
		Percent	*Percent*	*Percent*	*Percent* (maximum)	*Percent* (maximum)	*Percent*
2512 [a]	[a] E2512	0.09 to 0.14	0.45 to 0.60	0.20 to 0.35	0.025	0.025	4.75 to 5.25
2515	2515	.12 to .17	.40 to .60	.20 to .35	.040	.040	4.75 to 5.25
2517 [a]	[a] E2517	.15 to .20	.45 to .60	.20 to .35	.025	.025	4.75 to 5.25

[a] Electric-furnace steel.

3. Miscellaneous Low-Nickel Steels

Water-hardened 0.5-percent-nickel steels with low carbon contents have been used in differential gears. The 1.5-percent-nickel steel with about 0.15 percent of carbon is widely used for bolts and for case-hardened valve motion parts of locomotives. It is also used for high shear-strength rivets. Two-percent-nickel steels with 0.06 to 0.20 percent of carbon are used in locomotive boiler tubes, firebox plates, and boiler plates. Low-carbon 2.75-percent-nickel steel is used considerably for heavy locomotive forgings, for example, piston rods, main rods, and driving axles.

It has been reported [256] that a 1-percent-nickel steel with about 0.40 percent of carbon has been used in England as low-cost, oil-hardening, forging material. A 7-percent-nickel steel, with characteristics similar to those of the 2500 series, has been used abroad as an air-hardening carburizing steel.

Nickel-steel tubing with 9 percent of nickel and approximately 0.07 percent of carbon was developed recently [361] for use in handling alkaline solutions and mildly acidic solutions, such as paper mill black liquor, as evaporator tubes handling caustic soda solutions, as sucker rods handling corrosive fluids, and for low-temperature uses as in handling liquefied gases.

X. High-Nickel Alloys

Alloys of iron and nickel, containing 20 to 90 percent of nickel, are widely used for their low thermal expansion, high or low magnetic permeability, and a positive coefficient of the elastic modulus (increased stiffness with an increase in temperature) [389].

The thermal expansion characteristics of the iron-nickel alloys are useful in two fields: (1) where very little change in size with change in temperature is desirable, and (2) where a low-expansion alloy is used in combination with a high-expansion alloy to produce movement. The first class includes length standards, measuring tapes, instrument parts such as balance wheels in watches, variable condensers, struts in light-alloy pistons for internal combustion engines, tuning forks, Bourdon tubes, special springs, glass to metal seals, and some electronic devices. The second class includes thermostatic bimetals, thermoswitches, and other temperature regulating devices.

1. Thermal-Expansion Alloys

The fact that many iron-nickel alloys have low coefficients of thermal expansion, reaching a minimum at 36-percent nickel, was reported by Guillaume [2] in 1897. His name for the alloy, Invar, meaning invariable, and his diagram showing the variation of the coefficient with composition, are in use at the present time. Subsequent work has expanded Guillaume's results to include temperatures other than room temperature, as is shown in figure 29. These subsequent investigations confirmed the conclusions of Scott [43] that, as the nickel content is increased above 36 percent, the coefficients of expansion gradually increase, but simultaneously the maximum temperature over which the alloys maintain a low rate of expansion also increases. This characteristic is of practical importance where a low-expansion material, although not as low as Invar, is needed at temperatures in excess of that at which the 36-percent alloy is effective. The thermal expansion, over a range of temperature, of Invar and other nickel alloys in comparison with that of a 0.25-carbon steel is shown in figure 30.

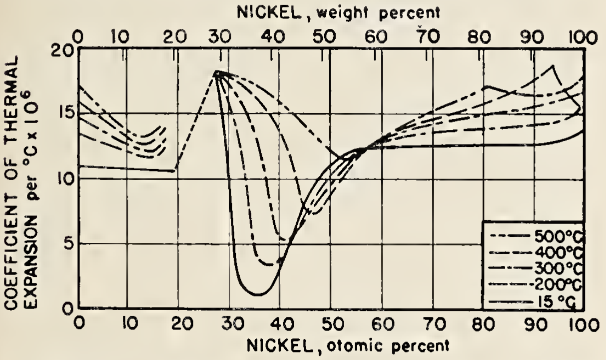

FIGURE 29. *Coefficient of thermal expansion of iron-nickel alloys at different temperatures as determined by X-ray measurements.*

(Owen, Yates, and Sully [168]).

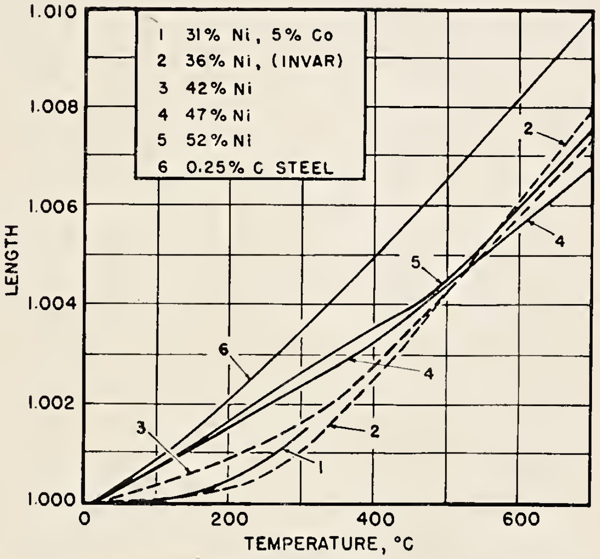

FIGURE 30. *Thermal expansion of iron-nickel alloys.*

(Hunter [378]).

Heat treatment or cold work affects the expansivity of Invar appreciably. The expansivity is greatest in completely annealed material and least in quenched samples. Cold work after a quenching operation may produce a zero coefficient of expansion or even a negative one, and such a negative coefficient may be raised to zero by careful annealing at low temperatures. These artificial methods of producing a low coefficient produce instability in the metal and make it susceptible to aging. Consequently, in applications where extreme reliability and stability are required, in geodetic tapes, for example, a prolonged stabilizing and aging treatment is essential [378].

The effect of minor additions of chromium, manganese, silicon, tungsten, or molybdenum is to shift the minimum coefficient towards a higher nickel content, but the minimum expansivity for any of these ternary alloys is usually less than that of Invar. On the other hand, copper and carbon move the minimum expansivity in the direction of lower nickel contents, and carbon is also believed to reduce the stability of the alloy [378]. Cobalt lowers the coefficient of Invar type alloys at ordinary temperatures, according to Scott [43] and Masumoto [73]. Titanium raises the minimum value of the expansion coefficient and shifts the minimum towards higher nickel contents [336].

Guillaume found that two alloys, at 29- and 45-percent nickel, have zero thermoelastic coefficient; that is, the modulus of elasticity does not change with variations in temperature. However, these two alloys are sensitive to minor changes in composition, and Guillaume found that the addition of 12 percent of chromium to a 36-percent-nickel alloy (Invar) produced an alloy with zero thermoelastic coefficient and without sensitivity to minor changes in composition. The composition of this alloy has been modified from the original values; modern Elinvar contains about 34 percent of nickel, 4.5 chromium, 2 tungsten, and small amounts of manganese, silicon, and carbon, and is used for hairsprings and balance wheels in clocks and watches and in tuning forks used in radio synchronization.

A series of age-hardening alloys, each containing about 2.5 percent of titanium was reported by Mudge and Talbot [336]. Three of these alloys are called Ni-Span Lo with appropriate numbers, 42, 45, and 52 to indicate the nickel contents. They have high tensile strengths; with proper cold working and heat treatment, Ni-Span Lo 42 may develop a tensile strength of 195,000 lb/in.^{2} Other members of the series are Ni-Span Hi, which contains 8.0 to 9.0 percent of chromium and has a relatively high thermal expansion, and Ni-Span C, which contains about 5.5 percent of chromium, has a thermal expansion of 3.8 to 4×10^{-6} per °F at room temperature and has a relatively constant modulus. Several iron-nickel-cobalt alloys find use as glass-to-metal seals, because of their expansion characteristics. The alloys called "Kovar" and "Fernico" contain approximately 54 percent of iron, 28 nickel, and 18 cobalt. "Fernichrome" contains 37 percent of iron, 30 nickel, 25 cobalt, and 8 chromium [101, 283].

Alloys containing 68 percent of iron, 27 nickel, and 5 molybdenum, or 53 percent of iron, 42 nickel, and 5 molybdenum are used as the high expansion side of thermostatic bimetals [283].

2. Magnetic Alloys

Binary iron-nickel alloys containing 30 to 90 percent of nickel have high initial permeabilities at small field strengths, the maximum permeability being exhibited by the alloy that contains 78.5 percent of nickel [27]. Maximum permeabilities as high as 100,000 are readily obtained with the 78.5-percent-nickel alloy and are accompanied by low hysteresis losses, low saturation values, and low electrical resistivity [225]. Because of the magnetic characteristics, several alloys in the 30- to 90-percent-nickel range are termed Permalloy, individual alloys being identified by a number that represents the nickel content. Those Permalloys that contain an additional major alloying element are identified by two numbers and the chemical symbol of the additional element, all preceding the word Permalloy.

Heat treatment greatly affects the magnetic properties of the alloys with more than 50 percent of nickel, as indicated by the data compiled by Marsh [190] and shown in figure 31. Magnetic treatments and mechanical working also affect the magnetic properties of iron-nickel alloys. Webb [198] investigated the effect of heat treatment on the 78.5 Permalloy and found that the special air-quench procedure produced maximum permeability of 100,000 with coercivity of 0.05 oersted, but annealing and slow cooling reduced the permeability and increased coercivity, both by a factor of 10. The addition of 3.8 percent of chromium to this alloy eliminates the necessity of the above critical heat treatment. The 3.8-78.5 Cr-Permalloy has high initial permeability and resistivity of about 65 microhm-cm after annealing and slow cooling, but the maximum permeability and the saturation flux density are appreciably less than for the chromium-free alloy. The 3.8-78.5 Mo-Permalloy has essentially the same characteristics as the Cr-Permalloy [198, 349]. Use is made of the properties of Permalloy, particularly the 78.5-percent-nickel alloy, in such applications as wrapping for undersea cables, loading coils for land lines, telephone and radio mechanisms, and high-frequency transformer coils [185].

A magnetically soft alloy, called "Supermalloy," contains 79 percent of nickel, 15 percent of iron, 5 percent of molybdenum, 0.5 percent of manganese, and low contents of the usual impurities. This alloy has initial permeabilities of 50,000 to 120,000 and a resistivity of about 65 microhm-cm [349]. Magnetic properties of a number of magnetically soft alloys, some with nickel and some without, were reported by Yensen [225]. "Mumetal" contains 76 percent of nickel, 17 iron, 5 copper, and small amounts of other elements. It has magnetic properties similar to Permalloy but is less affected by mechanical work and requires only a simple heat treatment to obtain optimum magnetic properties [198, 349].

The 50-percent-nickel alloy frequently called Hipernik has high saturation values and its magnetic properties are not as sensitive to heat treatment and other factors, but its permeability is about one-half that of the 78.5 percent-nickel alloy. The magnetic properties of Hipernik are improved by annealing in hydrogen at 1,000° to 1,200° C, which treatment reduces the carbon, sulfur, and oxygen contents [198, 225]. According to Marsh [190], the saturation values of the iron-nickel alloys are at a maximum for the 50-percent alloy. Alloys of the Hipernik type are cheaper than the 78.5 Permalloy and are used where maximum initial

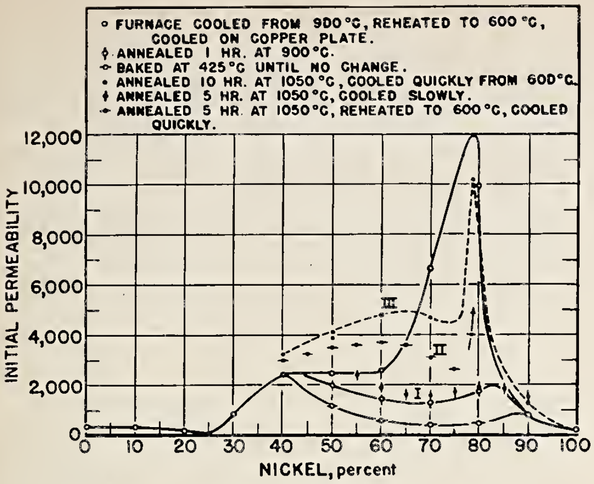

Figure 31. *Effect of heat-treatment on the initial permeability of iron-nickel alloys.*

(Marsh [190]).

permeability is not necessary and higher saturation and resistance values are desired, as in the bushing type of current transformer. For this use the Hipernik alloy is in competition with a 4-percent silicon-iron, which is lower-priced but which has higher energy losses [185].

Some iron-nickel-cobalt alloys with 20- to 75-percent nickel, 5 to 40 cobalt, and sometimes molybdenum have constant permeability, and are usually termed "Perminvar". The alloy "45 Perminvar" contains 45 percent of nickel, 30 percent of iron, 25 percent of cobalt, and, after proper heat treatment, has a constant permeability of about 300 for field strengths up to about 3 oersteds, with a resistivity of about 18 microhm-cm. Additions of molybdenum raise the resistivity but reduce the range of field strengths for which the permeability is constant [190, 198].

The iron-aluminum-nickel-cobalt permanent-magnet alloys, commonly called "Alnico", contain 15 to 30 percent of nickel and have outstanding magnetic properties. Formerly these alloys were available only in cast forms, but the development of powder metallurgy techniques now permits many of the alloys to be made by pressing and sintering processes. The sintered alloys are more homogeneous magnetically and have greater mechanical strength than their cast counterparts. Proper heat treatment is essential to develop optimum properties. The alloys cannot be machined and are finished by grinding. They have many uses including vital parts of motors, generators, radio speakers, telephone receivers, microphones, magnetos, and galvanometers [202,360].

The compositions and some of the properties of prominent numbers of the Alnico group are shown in table 24. Type 1 is the general purpose grade of magnet alloy and is used in sections of 1 in. by 1 in. or larger, and in smaller sizes where type 3 would be liable to crack. Type 2 has better permanent magnet properties than type 1, at slightly higher cost. Type 3 is the lowest cost grade of the cast alloys. Type 4 has high coercive force and is used where space limitations require the use of short magnets. Type 5 has very high external energy and residual induction but has strong directional properties. Type 5E (VE) was developed to overcome a weakness of type 5, which made the latter unsatisfactory for use in airgap devices, that is, type 5 showed a sudden decrease in the demagnetization curve for flux densities less than 8,000 gausses. Type 6 is the most suitable of these alloys for motor and generator use and will probably supplant the 5E variety. Type 12 has the highest coercive force of the Alnico alloys.

Table 24. *Alnico magnet alloys [269, 360]*

Type	Nominal composition						Magnetic properties				
	Al	Ni	Co	Cu	Ti	Fe	H maximum	B maximum	B_r	H_c	B_dH_d maximum
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Oersteds*	*Gausses*	*Gausses*	*Oersteds*	
1. Cast	12	20	5	-------	------	Balance	2,000	12,350	7,300	440	1.40×10^{6}
2. Do	10	17	12.5	6	------	do	2,000	12,600	7,350	560	1.60
2. Sintered	10	17	12.5	6	------	do	2,000	12,300	6,900	520	1.43
3. Cast	12	25	------	-------	------	do	2,000	12,000	6,900	475	1.38
4. Do	12	28	5	-------	------	do	3,000	11,850	5,300	730	1.30
5. Do	8	14	24	3	------	do	3,000	17,200	12,500	550	4.50
6. Do	8	14	24	3	1.75	do	-------	------	10,500	800	3.90
12. Do	6	18	35	-------	8	do	-------	------	6,500	1,000	2.00
5E. Do	8	14	24	3	0.75	do	-------	------	12,000	740	5.00

Other useful magnetic alloys include the 15- to 36-percent cobalt, 10 to 25 nickel, 8 to 25 titanium, balance iron and the 60 copper, 20 nickel, 20 iron alloy known as "Cunife," [190], and the 50 copper, 21 nickel, 29 cobalt alloy, "Cunico".

Magnetostriction is negative in nickel; in iron it is positive in weak fields and negative in stronger fields. In iron-nickel alloys, magnetostriction is positive for alloys containing 30 to 81 percent of nickel and becomes negative when the nickel content exceeds 81 percent. Volume magnetostriction reaches a sharp maximum at about 30-percent nickel [190].

The nonmagnetic 20- to 30-percent-nickel alloys find some applications where nonmagnetic materials with good strength, toughness, and corrosion resistance are required, but the usual practice is to improve austenitic stability by additions of chromium and manganese. Exceptions to this generalization are the alloys that have their magnetic transformation points in the vicinity of room temperature, that is, the alloys of about 30-percent nickel. These alloys find important use in compensating for ambient temperature changes affecting the behavior of electrical and magnetic equipment. In the usual procedure the compensating material is employed as a shunt that bypasses decreasing amounts of flux as the temperature rises and the magnetic field weakens. A typical application of this principle includes compensating for change resulting from temperature variations, in the strength of permanent magnets in watt-hour meters and speedometer magnets [324].

XI. Cast Steel and Cast Iron

The beneficial effects of nickel on the properties and heat treatment of steel apply to cast as well as to wrought products. Nickel does not oxidize readily in the molten bath and, consequently, is an easy metal to use in foundry practice.

Castings containing 2 percent of nickel and not more than 0.20 percent of carbon are in general use for locomotive frames because of their superior elastic and impact properties as compared to carbon steel of equal strength. When higher strength and hardness are required, a carbon range of 0.25 to 0.35 percent is used.

The 2-percent nickel, 0.2-percent-carbon steel is also used in castings for mining, excavating, and steel mill machinery, and ship castings. With slightly higher carbon, 0.2 to 0.3 percent, it is used in large gears not subjected to severe abrasion and in the frames for crushers, tractors, and power shovels. Cast steel containing 2.25 percent of nickel is used [347] for truck frames in railroad passenger cars.

Low-carbon 2.75-percent-nickel cast steel is used in low-temperature service, for refrigerating machinery and pump parts, and in dewaxing equipment. 3-percent-nickel steel is used in castings where a full anneal is required, and in gears and pinions that operate under high loads. It has been used in pintle castings in lock and dam construction.

Cast steels containing about 1.5 percent of nickel 0.1 vanadium, and not more than 0.25 carbon are fine-grained, resistant to impact and fatigue stresses, have yield points between 45,000 and 55,000 lb/in.^{2} when fully annealed, and are readily welded. They are used in heavy machinery and in locomotive and railway passenger car castings. With a higher carbon content (0.30 percent) and about 1-percent of manganese, the mechanical properties are unusually high for such low alloy steel. When normalized from the temperature range 1,600° to 1,650° F and subsequently tempered in the range 1,000° to 1,225° F, this steel develops yield-point values up to 70,000 lb/in.^{2}, tensile strengths up to 100,000 lb/in.^{2}, elongations up to 29 percent in 2 in, reductions of area up to 60 percent, and Izod impact values up to 60 ft-lb. Typical applications include engine frames, driving wheel cutters, driving boxes, rolling mill gears and pinions, hammer rams, and forging dies [94, 186].

Pearlitic nickel-manganese steel castings, containing 0.75- to 2-percent nickel, 1.0- to 1.5-percent manganese, and 0.2- to 0.4-percent carbon are used in place of carbon steels where improvement in properties at only slightly increased cost is desired. These steels respond to full annealing, quenching, normalizing, and tempering, although normalizing large sections of the higher manganese types is not recommended. Castings of these steels are used in tractor shoes, road-building machinery, freight-car frames, yokes, and couplers [99, 176, 186].

Data on the mechanical properties of some cast nickel steels from several sources have been assembled in table 25.

As an alloying element for cast iron, nick ranks first in total quantity used, although the amount of nickel in nonaustenitic cast iron seldom exceeds 5 percent [153]. Nickel may be the only alloying element in the cast iron, but it is frequently added along with other elements, particularly chromium. There is no universal formula for nickel cast iron and several authorities warn that each problem of alloy cast iron must be considered individually and carefully to insure that the alloy additions are suitable and economically proper for the particular conditions involved [315].

Many of the beneficial effects of nickel in steel are also evident in cast iron. It depresses the

Table 25. *Mechanical properties of some cast nickel steels*

No.	Composition	Heat treatment	Yield strength	Tensile strength	Elongation in 2 in.	Reduction of area	Izod impact resistance	Brinell hardness number
	Percent		*lb/in.*²	*lb/in.*²	*Percent*	*Percent*	*ft-lb*	
1	Ni 0.08 to 1.25, Mn 0.90 to 1.25, C 0.30 to 0.45.	Water-quenched, tempered 900° to 1,250° F.	96,000	120,000	17	40	-------	262
2	Ni 0.08 to 1.25, Mn 0.90 to 1.25, C 0.25 to 0.40.	Normalized, tempered, 900° to 1,250° F.	58,000	88,000	[b] 23	45	-------	180
3	Ni 1.0 to 1.5, Mn 1.0 to 1.5, C 0.25 to 0.35, Si 0.45 max.	Normalized 850° C, air-cooled, tempered 550 to 600° C.	56,000	89,600	[b] 22	45	-------	-------
4	Ni 1.20 to 1.50, Mn 1.35 to 1.65, C 0.26 to 0.33.	Normalized, tempered, 1,000° to 1,225° F.	65,000	95,000	26	50	-------	197
5	Ni 1.40, Mn 0.62, C 0.26, S 0.23, P 0.039, S 0.034.	Tempered 4 hr at 930° F	40,300	75,000	15	28	9	-------
6	Ni 1.75 to 2.25, Mn 0.80 to 1.10, C 0.25 to 0.35.	Normalized, tempered 1,050° to 1,225° F.	62,000	95,000	25	50	-------	197
7	Ni 2.0 min., Mn 0.6 to 0.9, C 0.2 max, Si 0.15 min.	Annealed 940° C, normalized 820° to 850° C, air-cooled, tempered 600° to 675° C.	44,800 to 53,800	73,900 to 85,100	[b] 32 to 25	65 to 45	80 to 40	-------
8	Ni 2.0 min., Mn 0.60 to 0.90, C 0.2 max.	Double normalized, tempered 1,200° F.	50,000	80,000	28	55	-------	163
9	Ni 2.0 min., Mn 0.7 to 1.0, C 0.2 to 0.3, Si 0.25 to 0.4.	Normalized 900° C, air-cooled, tempered 650° C.	49,300 to 65,000	98,600 to 105,300	[b] 28 to 22	55 to 42	-------	-------
10	Ni 2.00 to 2.25, Mn 0.80 to 1.00, C 0.20 to 0.30, Si 0.25 to 0.40, P + S 0.05 max.	Normalized 1,650° F, tempered 1,200° F.	[a] 55,000 to 65,000	90,000 to 105,000	[b] 28 to 22	55 to 42	-------	-------
11	Ni 2.11, Mn 0.81, C 0.20, Si 0.33, P 0.011, S 0.024.	Normalized and tempered	48,500	81,500	[b] 32	60	-------	-------
12	Ni 3.29, Mn 0.59, C 0.30	Fully annealed	61,100	95,500	22	48	-------	-------
13	Ni 3.00 to 3.50, Mn 0.60 to 0.90, C 0.30 to 0.40.	do	60,000	90,000	22	40	-------	185
14	Ni 3.00 to 3.50, Mn 0.50 to 0.80, C 0.30 to 0.40.	Water-quenched, tempered 1,050° to 1,225° F.	125,000	135,000	[b] 17	40	-------	290

[a] Elastic limit.

[b] Gage length not stated.

critical temperature ranges and refines the grain. With increasing nickel content the matrix is rendered successively sorbitic, martensitic, and austenitic. The phase relations in nickel cast iron and steel are shown in figure 32.

Nickel is a graphitizer, breaking down combined carbon into free carbon or graphite, but its effectiveness in this respect is less than that of silicon. Nickel largely eliminates hard and chill spots and thus improves machinability. It also produces improved uniformity in castings that have thick and thin portions and thus permits employment of a single heat treatment for castings of variable section. According to Sands and Nemser [219], if a casting is sufficiently strong, sound, and has a suitable composition but is difficult to machine, all that is required is a sufficient addition of nickel to reduce chill and increase machinability. However, if the castings are unsound and shrinkage and porosity are high, the silicon content should be reduced and sufficient nickel added to compensate, in point of chill, for the reduction in silicon.

The effects of nickel on the hardness and structure of grey and white cast irons were reported by Everest [181], and some of his results are given in table 26. Additions of nickel, plus suitable heat treatment, convert the normal white structure more or less completely to martensite or austenite, plus graphite. With rapid chilling, high-tensile strengths and hardness values can be developed, usually in the form of a hard, white, chilled surface on a less hard gray iron backing.

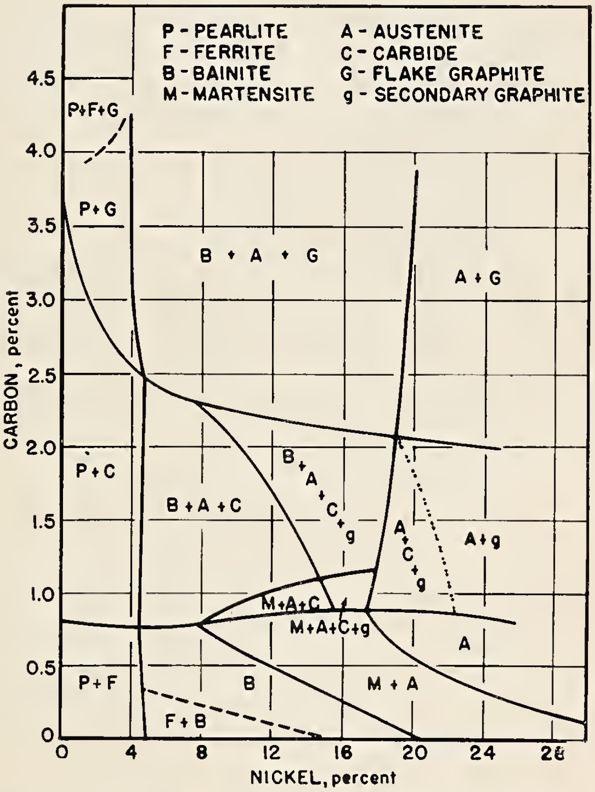

Figure 32. *Phase relations in 1.2-in.-diam nickel cast irons and steels.*

(Eash and Pilling [265]).

Table 26. *Structure, properties, and machinability of various types of nickel cast iron*

Everest [181]

Nickel	Structure	Properties	Machinability
Percent			
1 to 2	Grey pearlitic	Improved machinability, density, pressure-tightness, strength, wearing quality.	Excellent.
2 to 4	Grey sorbitic	High machinable hardness, excellent wearing quality	Moderate.
2 to 4	Grey martensitic	Heat-treated to give high-strength, hardness and wearing quality	Good as cast.
4 to 5	Grey martensitic	Very high hardness and wearing quality	Requires special equipment.
1 to 2	Grey pearlitic	Inoculated alloy cast iron for high strength (Ni Tensyliron)	Excellent.
1 to 2	White pearlitic	Improved hardness and strength	Requires special equipment.
2 to 5	White martensitic	Maximum hardness and strength (Ni Hard)	Do.
6 to 10	Grey martensitic-austenitic	Toughness and abrasion resistance	Do.
14 to 22	Grey austenitic	Tough, corrosion and heat resistant, nonmagnetic, high expansion	Good.
30 to 36	Grey austenitic	Low expansion, superior corrosion resistance, magnetic	Do.

High-nickel austenitic gray irons, such as the last two items in table 26, are valued for their special characteristics including controlled thermal expansion, and magnetic response, and corrosion and heat resistance. An example of this type of alloy is the low expansion variety of Invar known as Minvar or, more recently Minovar, which contains 34 to 36 percent of nickel and is used in precision equipment [316].

Various combinations of nickel with other elements are incorporated in cast iron, usually to refine the structure and harden and strengthen it without sacrifice of machinability. For example, cast iron of high tensile strength (up to 63,000 lb/in.^{2} as cast and 78,000 after heat treatment), high impact resistance, high modulus of elasticity, and excellent machinability is produced in many foundries and is known as Ni Tensyliron. To prepare this iron, suitable quantities of the alloying elements are added while the metal is being tapped into the ladle. The graphite precipitates in fine uniformly distributed particles in a matrix resembling alloy steel. The composition range of this iron is generally 2.5- to 3.15-percent total carbon, 0.5 to 0.9 manganese, 0.15 max phosphorus, 0.12 max sulfur, 1.2 to 2.75 silicon, 1.0 to 4.0 nickel, 0.0 to 0.5 chromium, and 0.0 to 0.75 molybdenum. This iron is used for flywheels, dies for pressing steel, crusher frames, gears, hydraulic castings, etc. [219].

The high tensile strengths and surface hardness, previously mentioned as obtainable in nickel irons, are also obtained in more complicated compositions. For example, the chilled white iron known as Ni Hard contains about 4.5 percent of nickel and 1.5 percent of chromium and develops surface hardnesses in the range of 600 to 800 Brinell.

Vanadium stabilizes the carbides and reduces the grain size in cast iron. Nickel-vanadium irons have been used as steel mill rolls.

An austenitic cast iron, known as Ni Resist, contains 14 percent of nickel, 7 copper, 2 chromium, 3 total carbon, 1.5 silicon, 1 manganese, 0.2 phosphorus, and 0.1 sulfur. This iron is characterized by resistance to wear, erosion, and corrosive attack of many types, and resistance to growth and oxidation when heated. It is nonmagnetic and has a high electrical resistance. Variations in the composition include an increase in the chromium content, for increased resistance to heat, and an increase in the nickel content to compensate for a reduction in the copper content when the latter is not wanted.

For additional and more detailed information on nickel irons and cast irons in general, the reader is referred to appropriate sections of the 1948 edition of Metals Handbook (ASM), and the 1944 editions of Alloy Cast Iron Handbook, and Cast Metals Handbook of the American Foundrymen's Society.

XII. Complex Low-Alloy Steels

The merits of nickel-iron alloys frequently are further improved by additions of small amounts of other alloying elements, as has been discussed in preceding sections of this circular, and this improvement continues when the amounts of the other elements are great enough to warrant their designation as alloying elements rather than as minor additions.

1. Nickel-Chromium Steels

Nickel-chromium steels containing 0.55 to 1.75 percent of chromium, together with about twice as much nickel as chromium, are classed as SAE and AISI series 3100, 3200, and 3300, and are recorded in table 27.

Table 27. *Compositions of low nickel-chromium steels* [*319*]

AISI No.	SAE No.	C	Mn	Si	P max	S max	Ni	Cr
		Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
3115	3115	0.13 to 0.18	0.40 to 0.60	0.20 to 0.35	0.040	0.040	1.10 to 1.40	0.55 to 0.75
3120	3120	.17 to .22	.60 to .80	.20 to .35	.040	.040	1.10 to 1.40	.55 to .75
3130	3130	.28 to .33	.60 to .80	.20 to .35	.040	.040	1.10 to 1.40	.55 to .75
3135	3135	.33 to .38	.60 to .80	.20 to .35	.040	.040	1.10 to 1.40	.55 to .75
3140	3140	.38 to .43	.70 to .90	.20 to .35	.040	.040	1.10 to 1.40	.55 to .75
3141	3141	.38 to .43	.70 to .90	.20 to .35	.040	.040	1.10 to 1.40	.70 to .90
3145	3145	.43 to .48	.70 to .90	.20 to .35	.040	.040	1.10 to 1.40	.70 to .90
3150	3150	.48 to .53	.70 to .90	.20 to .35	.040	.040	1.10 to 1.40	.70 to .90
(a)	3240	.38 to .45	.40 to .60	.20 to .35	.040	.040	1.65 to 2.00	.90 to 1.20
3310	3310	.08 to .13	.45 to .60	.20 to .35	.025	.025	3.25 to 3.75	1.40 to 1.75
3316	----	.14 to .19	.45 to .60	.20 to .35	.025	.025	3.25 to 3.75	1.40 to 1.75

[a] Eliminated from AISI Standards, July 1, 1946.

The 3115 and 3120 steels are used for structural purposes and for carburized parts including ring gears and pinions, spline and countershafts, transmission gears, piston pins, etc. [342]. The 3130 steel in the annealed condition can be cold-pressed into desirable shapes. It has good creep-resistant qualities up to 1,000° F and accordingly is used for valves and other applications at medium high temperatures. Its properties, shown in figure 33, lead to its use for axles, drive shafts, stressed bolts, drill collars, steering knuckles, etc. The 3140 steel has somewhat higher strength and elastic properties than the 3130 and is used for automobile engine intake valves and in wear-resistant parts of road building, excavating, and farm machinery. Steels in the higher carbon ranges, 3145 and 3150, are forged and heat-treated for use in large structural parts and in heavy duty machine tool gears [332, 342].

SAE 3240 contains more nickel and chromium than the 3100 series and consequently is stronger and better able to withstand severe service. Its ability to deep-harden makes it suitable for large sections. This steel is no longer included in the AISI classification.

The 3300 steels are air-hardening and frequently should be quenched from the tempering temperature to avoid temper brittleness. They are used for carburized parts with tough, high strength cores such as rear axle and transmission gears for busses and trucks. Data for the mechanical properties of the 3310 steel are shown in figure 33.

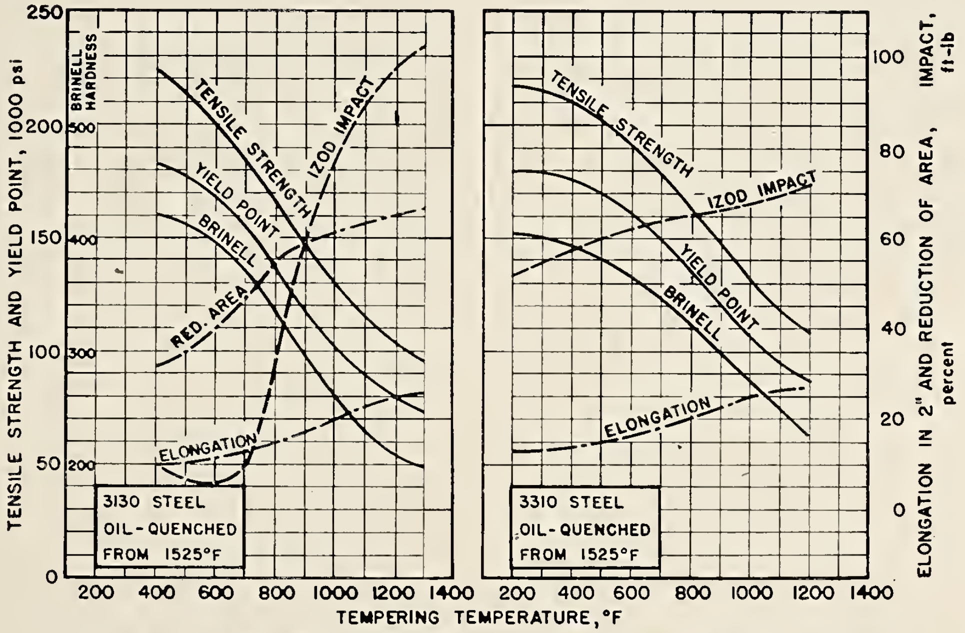

Figure 33. *Mechanical properties of nickel-chromium steels, SAE 3130 and 3310.*

(International Nickel Co., Inc. [332]).

Compositions similar to those of the wrought steels of the 3100 and 3300 series are also used in the form of castings [186].

2. Nickel-Molybdenum Steels

The nickel-molybdenum wrought steels, containing 0.15 to 0.30 percent of molybdenum, represented by SAE classification 46xx (1.75 Ni) and 48xx (3.50 Ni), are characterized by their ability to resist distortion when quenched, uniformity of mechanical properties, and excellent toughness combined with relatively high hardness. SAE steels 4615 and 4620 are carburizing grades that are used extensively for gears, cams, and shafts, where high fatigue resistance, toughness, and tensile properties are necessary. The 4620 steel is used for heavier sections. Mechanical properties of 4620, for 1-in. sections, are illustrated in figure 34. A higher carbon variety designated 4640 is also considerably used in transmission gears. SAE 4815 and 4820 are higher nickel carburizing grades used for gears, steering knuckle pins, etc. [342].

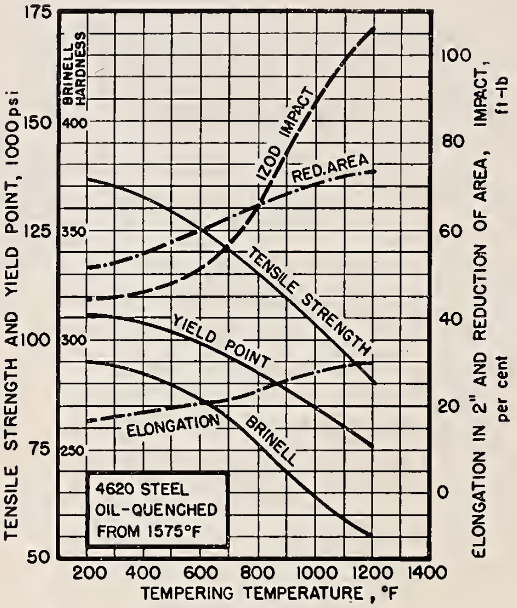

Figure 34. *Mechanical properties of nickel-molybdenum steel SAE 4620.*

(International Nickel Co., Inc. [332]).

Nickel-molybdenum cast steel is used in some large heavy duty parts subjected to severe loads, such as mill rolls, mining machinery, and large pinions [95].

3. Nickel-Chromium-Molybdenum Steels

The nickel-chromium-molybdenum steels containing 1.75 percent of nickel, 0.40 to 0.90 chromium, and 0.20 to 0.30 molybdenum, represented by SAE numbers 4320 and 4340, are air-hardening steels that offer the highest combination of ductility and strength in large sections and the best fatigue-tensile ratio of any of the SAE 4xxx steels. SAE 4320 is a carburizing grade that gives a harder and stronger core than is normally obtained with 4620. SAE 4340 is suitable for oil-hardening gears, Diesel engine crankshafts, and heavy duty shafting over 2 in. in diameter. Its mechanical properties are shown in figure 35.

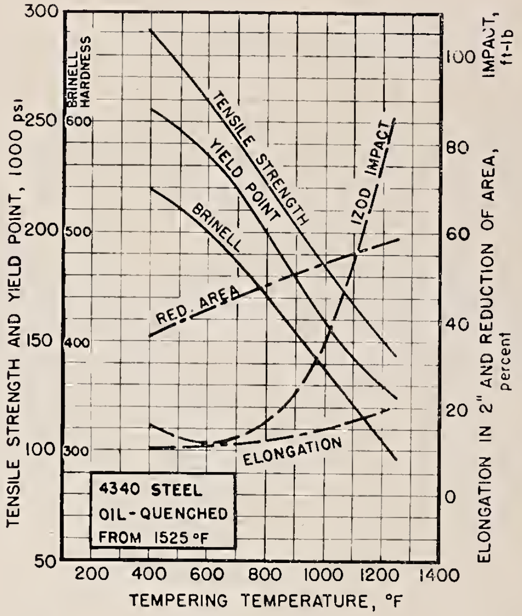

Figure 35. *Mechanical properties of nickel-chromium-molybdenum steel, SAE 4340.*

(International Nickel Co., Inc. [332]).

As with nickel-molybdenum types, some nickel-chromium-molybdenum steel is used in the cast form in mill rolls. A wide range of properties is obtainable through variations in heat treatment, which lead to such diversified uses as tractor shoes, power-shovel bucket lips, large gears, high-strength structural castings, sheaves, abrasive-resistant castings, and moderately heat-resistant castings [95].

The nickel-chromium-molybdenum National Emergency steels now considered as standard by the Society of Automotive Engineers and the American Iron and Steel Institute are the NE 8600, 8700, 9400, 9700, and 9800 series [362, 391a]. They were adopted because of the large tonnages produced, their good mechanical properties and performance, and their favorable response to various methods of fabrication and heat treatment. The group compositions of these steels are shown in table 28.

TABLE 28. *Compositions of nickel-chromium-molybdenum NE steels adopted as SAE and AISI standards [362, 391a]*

NE Type [a]	C	Mn	Ni	Cr	Mo
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
86XX	From 0.13 to 0.18 in 8615 to 0.55 to 0.65 in 8660	0.70 to 0.90 or 0.75 to 1.00	0. 40 to 0. 70	0. 40 to 0. 60	0. 15 to 0. 25
87XX	From 0.18 to 0.23 in 8720 to 0.48 to 0.53 in 8750	0.70 to 0.90 or 0.75 to 1.00	. 40 to . 70	. 40 to . 60	. 20 to . 30
94XX	From 0.35 to 0.40 in 9437 to 0.43 to 0.48 in 9445	0.90 to 1.20 or 1.00 to 1.30	. 30 to . 60	. 30 to . 50	. 08 to . 15
97XX	From 0.45 to 0.50 in 9747 to 0.60 to 0.67 in 9763	0.50 to 0.80	. 40 to . 70	. 10 to . 25	. 15 to . 25
98XX	From 0.38 to 0.43 in 9840 to 0.48 to 0.53 in 9850	0.70 to 0.90	. 85 to 1. 15	. 70 to . 90	. 20 to . 30

[a] All types except 8641 contain 0.20 to 0.35 Si, 0.040 P (max), 0.040 S (max).

4. Nickel-Copper Steels

Copper added to structural steel in amounts less than 1 percent has been found effective in considerably reducing atmospheric and other types of corrosion. However, copper also causes steel to surface crack during hot-working unless additional materials are introduced. Nickel up to 2.00 percent is added to copper steel to improve hot-working characteristics and further increase resistance to corrosion. This provides a steel that is more effective than carbon steel in resisting corrosion, though not as good as austenitic steels, and at a cost considerably less than the high-alloy product.

Nickel is also an essential material in the proprietary high-strength steels containing copper-molybdenum, copper-chromium, and copper-manganese, all with or without phosphorus. These steels have high yield points, ranging upward from 45,000 lb/in.^{2} in 2-in. sections to 50,000 lb/in.^{2} in ½-in. or smaller sections. The substantial savings in weight afforded by this high-strength steel have lead to its usage in railroad rolling stock, mine cars, excavating equipment, truck and bus frames, bodies, and in tanks. Resistance welding may be carried out on these steels when the carbon content is less than 0.2 percent [116, 175, 356].

XIII. Austenitic Chromium-Nickel Steels

The austenitic chromium-nickel steels, together with the ferritic and pearlitic (or martensitic) straight-chromium steels, are widely known as corrosion-resisting or stainless steels. Chromium is the element primarily responsible for the corrosion resistance of these steels. The nickel acts as an austenite stabilizer; increases of nickel tend to lower the tensile strength and hardness, and decrease the tendency of the material to harden with cold work. The austenitic alloys find applications in castings as well as in the wrought form. Since nickel is not primarily or solely responsible for their desirable properties, the discussion of stainless steels in this publication does not attempt to be complete and all-inclusive.

The 18 chromium-8 nickel steels and the modifications of this basic composition constitute about two-thirds of all the production of wrought stainless steels. Aborn and Bain [59] have shown that the 18 : 8 composition is close to the maximum amount of chromium and the minimum amount of nickel that will produce an austenitic structure in the quenched alloy. Magnetic measurements can be used to indicate the amount of ferrite in these metastable steels.

The austenitic stainless steels as a class are highly resistant to corrosive conditions. They are subject to oxidation at high temperatures; the formation of scale on 18:8 steel limits its use to temperatures below about 1,600° F. These steels are tough at normal and low temperatures and retain high creep strengths at moderately elevated temperatures. Although they work-harden readily, they are nevertheless fabricated by a variety of hot- and cold-working processes. The tendency to work-harden decreases with increasing nickel content. The steels have high coefficients of thermal expansion, as much as 50 percent greater than carbon steels in the lower temperature ranges, and low thermal conductivities. The austenitic alloys cannot be hardened by heat treatment [128, 189, 236, 262, 384].

The compositions of the austenitic wrought chromium-nickel steels, according to AISI designations, are shown in table 29. Type 301 is used for trim and structural purposes. It is not as stable as the higher alloy steels and welding or similar heating operations may result in carbide precipitation. Type 302 is the wrought, general purpose, corrosion-resistant steel, which finds applications too numerous to itemize. Accepted modifications of the basic 302 composition are 302B, in which silicon is added to improve resistance to scaling at high temperatures, and 303, which is a free machining 18:8. The restricted carbon content and slightly higher chromium and nickel contents make type 304 weldable with less danger of carbide precipitation. In types 308, 309, and 310, increasing alloy contents improve the strength, corrosion-resistance and resistance to scaling at high temperatures. The low carbon content of 309S facilitates welding. The higher nickel content of type 310 promotes stability at welding temperatures. Types 316 and 317 have superior resistance to corrosion, especially of the pitting type. The addition of titanium and columbium in types

321 and 347, respectively, prevents carbide precipitation at high temperatures or as the result of welding.

Table 29. *Compositions of wrought austenitic chromium-nickel steels*

Parmiter [384]

AISI No.	C	Cr	Ni	Other elements
	Percent	*Percent*	*Percent*	*Percent*
301	0.08 to 0.20	16.0 to 18.0	6.0 to 8.0	Mn 2.0 max
302	.08 to .20	17.0 to 19.0	8.0 to 10.0	Mn 2.0 max
302B	.08 to .20	17.0 to 19.0	8.0 to 10.0	Si 2.0–3.0; Mn 2.0 max
303	.15 max	17.0 to 19.0	8.0 to 10.0	P, S, Se 0.07 min; Zr, Mo 0.60 max
304	.08 max	18.0 to 20.0	8.0 to 11.0	Mn 2.0 max
308	.08 max	19.0 to 21.0	10.0 to 12.0	Mn 2.0 max
309	.20 max	22.0 to 24.0	12.0 to 15.0	Mn 2.0 max
309S	.08 max	22.0 to 24.0	12.0 to 15.0	Mn 2.0 max
310	.25 max	24.0 to 26.0	19.0 to 22.0	Mn 2.0 max
316	.10 max	16.0 to 18.0	10.0 to 14.0	Mo 2.0 to 3.0
317	.10 max	18.0 to 20.0	11.0 to 14.0	Mo 3.0 to 4.0
321	.08 max	17.0 to 19.0	8.0 to 11.0	Ti at least 5 times C
347	.08 max	17.0 to 19.0	9.0 to 12.0	Cb at least 10 times C

Mechanical and physical properties of the basic type 302 alloy include:

Brinell hardness number, annealed, 135 to 185.
Brinell hardness number, cold-rolled, 190 to 330.
Yield strength, 1,000 lb/in.^{2}, annealed, 0.2-percent offset, 34 to 36.
Yield strength, 1,000 lb/in.^{2}, cold-rolled, 0.2-percent offset, 50 to 148.
Tensile strength, 1,000 lb/in.^{2}, annealed, 80 to 90.
Tensile strength, 1,000 lb/in.^{2}, cold-rolled, 100 to 180.
Elongation in 2 in., percent, annealed, 60 to 55.
Elongation in 2 in., percent, cold-rolled, 50 to 10.
Reduction of area, percent, annealed, 65 to 55.
Izod Impact, ft lb, annealed, 110 to 70.
Modulus of elasticity, million lb/in.^{2}, 28.
Specific heat, cal/g at 100° C, 0.118.
Thermal conductivity cal/cm/sec/°C at 100° C, 0.050.
Coefficient of linear expansion, microinches per inch per °F, 0 to 200° F, 9.0.
Density, g/cm^3, 7.93.

For information on the properties of other types of wrought austenitic steels, the reader is referred to appropriate sections of Metals Handbook (ASM).

The chromium-nickel steels containing more than 18 percent of chromium are extremely resistant to rural, industrial, and marine atmospheres. At high temperatures, the resistance to oxidation and scaling increases with increasing chromium content; when 25 percent of chromium is present, the steels resist scaling at temperatures as high as 2,000° F, and the presence of such amounts of chromium minimizes the effect of sulfur in hot oxidizing atmospheres.

The austenitic stainless steels are resistant to corrosion by natural waters, steam, fruit juices, food products, and many other substances. Under most conditions they are highly resistant to nitric acid and cold acetic acid, but are badly attacked by all concentrations of hydrochloric acid. Other mineral and organic acids, salt solutions, nonaqueous liquids, etc., may or may not attack these steels depending on a multitude of conditions that include the type of corrodent, concentration, composition of the steel, condition of the steel surface, dissolved oxygen, impurities, and temperature [74, 128, 141, 234, 324a, 343, 367, 375]. Detailed information may be obtained from the references cited and from stainless steel manufacturers.

XIV. Heat-Resistant and Corrosion-Resistant Ferrous Alloys

Alloys classified under these headings include iron-chromium-nickel alloys, which contain more chromium than nickel, and iron-nickel-chromium alloys, which contain more nickel than chromium. Heat-resistant and corrosion-resistant alloys, which contain little or no iron, are discussed in subsequent sections devoted to nonferrous alloys.

The dividing line between heat-resistant and corrosion-resistant castings is rather vague. Heat-resistant castings have been defined as those capable of sustained operation at temperatures in excess of 900° F; corrosion-resistant castings as those capable of sustained operation at temperatures lower than 900° F [371, 390]. The Alloy Casting Institute, however, uses 1,200° F as the dividing line. The standard alloys in these two classes, as given by the Alloy Casting Institute are listed in table 30.

The alloys classed as corrosion resistant find many applications in the chemical, paper, and other industries, for example, as valves, pump parts, and containers for nitric acid, acid mine waters, sulfite liquor, etc. The alloys may be exposed to five types of corrosive attack: (1) general, (2) intergranular, (3) contact corrosion, (4) pitting, and (5) erosion—corrosion. The choice of composition and heat treatment of the alloy for a particular type of service requires consideration of the physical, mechanical, structural, and corrosion-resistant requirements. All of these alloys are readily welded but usually should be heat-treated after welding.

TABLE 30. *Alloy Casting Institute standard designations and chemical composition ranges for heat and corrosion resistant castings*

Designation	Composition							
	C	Mn	Si	P	S	Cr	Ni	Other elements
	Percent	*Percent (max)*	*Percent*	*Percent (max)*	*Percent (max)*	*Percent*	*Percent*	*Percent*
CA-15	0.15 max	1.00	1.50	0.04	0.04	11.5 to 14	1 max	Mo 0.5 max
CA-40	.20 to 0.40	1.00	1.50	.04	.04	11.5 to 14	1 max	Mo .5 max
CB-30	.30 max	1.00	1.00	.04	.04	18 to 22	2 max	
CC-50	.50 max	1.00	1.00	.04	.04	26 to 30	4 max	
CE-30	.30 max	1.50	2.00	.04	.04	26 to 30	8 to 11	
CF-8	.08 max	1.50	2.00	.04	.04	18 to 21	8 to 11	
CF-20	.20 max	1.50	2.00	.04	.04	18 to 21	8 to 11	
CF-8M	.08 max	1.50	1.50	.04	.04	18 to 21	9 to 12	Mo 2.0 to 3.0
CF-12M	.12 max	1.50	1.50	.04	.04	18 to 21	9 to 12	Mo 2.0 to 3.0
CF-8C	.08 max	1.50	2.00	.04	.04	18 to 21	9 to 12	Cb 8 x C min, 1.0 max
CF-16F	.16 max	1.50	2.00	.17	.04	18 to 21	9 to 12	Mo 1.5 max, Se 0.20 to 0.35
CF-16Fa	.16 max	1.50	2.00	.04	.20 to 0.40	18 to 21	9 to 12	Mo 0.40 to 0.80
CG-12	.12 max	1.50	2.00	.04	.04	20 to 23	10 to 13	
CH-10	.10 max	1.50	2.00	.04	.04	22 to 26	12 to 15	
CH-20	.20 max	1.50	2.00	.04	.04	22 to 26	12 to 15	
CK-20	.20 max	1.50	2.00	.04	.04	23 to 27	19 to 22	
HC	.50 max	1.00	2.00	.04	.04	26 to 30	4 max	Mo 0.5 max
HD	.50 max	1.50	2.00	.04	.04	26 to 30	4 to 7	Mo .5 max
HE	.20 to 0.50	2.00	2.00	.04	.04	26 to 30	8 to 11	Mo .5 max
HF	.20 to .40	2.00	2.00	.04	.04	18 to 23	8 to 12	Mo .5 max
HH	.20 to .50	2.00	2.00	.04	.04	24 to 28	11 to 14	Mo .5 max, N 0.2 max
HI	.20 to .50	2.00	2.00	.04	.04	26 to 30	14 to 18	Mo .5 max
HK	.20 to .60	2.00	3.00	.04	.04	24 to 28	18 to 22	Mo. 5 max
HL	.20 to .60	2.00	3.00	.04	.04	28 to 32	18 to 22	Mo .5 max
HT	.35 to .75	2.00	2.50	.04	.04	13 to 17	33 to 37	Mo .5 max
HU	.35 to .75	2.00	2.50	.04	.04	17 to 21	37 to 41	Mo .5 max
HW	.35 to .75	2.00	2.50	.04	.04	10 to 14	58 to 62	Mo .5 max
HX	.35 to .75	2.00	2.50	.04	.04	15 to 19	64 to 68	Mo .5 max

The 19 chromium-9 nickel alloys, types CF in table 30, are the most widely used of the group and constituted better than 60 percent of the total production of corrosion-resistant castings in 1945, according to the Alloy Casting Institute. These alloys are austenitic and nonmagnetic, although proper balance of the nickel, manganese, and nitrogen contents must be maintained to insure nonmagnetic performance in the low carbon grades, which show the best resistance to corrosion. Molybdenum is added to type CF alloys for improved service in contact with dilute sulfuric acid. Columbium may be added as a carbide stabilizer to prevent intergranular corrosion and selenium to improve machinability.

The heat-resistant castings are used in metallurgical furnaces, oil refinery furnaces, cement mill furnaces, power plant equipment, turbo superchargers, gas turbines, and the manufacture of synthetic rubber [371]. Figures reported by the Alloy Casting Institute show that the 1945 production of heat-resistant alloys was divided almost equally between the Fe-Cr-Ni and Fe-Ni-Cr alloys, which together accounted for 97 percent of the production.

The Fe-Cr-Ni alloys, containing more chromium than nickel, are resistant to oxidizing and reducing conditions in the presence of sulfur and are used in preference to iron-chromium alloys where greater strength and ductility is desired. The Fe-Ni-Cr alloys are resistant to oxidizing and reducing conditions in the absence of sulfur; they have useful electrical properties and are frequently used in resistance heating elements; they are slow to carburize and do not absorb nitrogen in nitriding operations, making them useful as fixtures for case-hardening processes. In general the resistance of both groups to severe conditions in various media increases with increasing alloy content.

During World War II the need arose for new materials for service at previously impossible temperatures in gas turbines and jet propulsion engines. One of the first steps to meet this need was to modify the compositions of the 19:9 and other austenitic stainless steels to extend the range of temperatures at which they could be used. Table 31 lists the compositions of five varieties, as reported by the American Society for Metals Subcommittee on Wrought Heat-Resisting Alloys [396].

Most of these alloys are age hardenable. In the results reported by the Subcommittee, the 19:9 DL alloy, forged bar stock reduced 21 percent by rolling at 2,100° F, produced the best stress rupture results at 1,200° F and 1,350° F; the stress for rupture in 1,000 hr was 50,000 lb/in.^{2} at 1,200° F and 20,500 lb/in.^{2} at 1,350° F. At 1,500° F the S-495 alloy, water-quenched from 2,250° F and aged at 1,400° F, required a stress of 14,000 lb/in.^{2} to produce rupture in 1,000 hr. These results are materially better than were previously available but do not satisfy the requirements of the design engineers who want materials for extended service at 1,800°, 2,000°, and 2,500° F, and even higher temperatures.

Table 31. *Some newly developed heat-resisting steels*

Subcommittee on Wrought Heat-Resisting Alloys [396]

Designation	Composition (balance iron)						
	C	Mn	Si	Cr	Ni	Mo	Others
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
19:9 W-Mo	0.12 max	0.5	0.6	19	8.5	0.35	W, 1.25; Cb, 0.5; Ti, 0.35
19:9 D-L	.25	.5	.6	19	9	1.25	W, 1.2; Cb, 0.3; Ti, 0.2
234 A-5	.38	4.2	.3	18.5	4.6	1.35	W, 1.35; Cb, 0.6
Timken 16-25-6	.10	1.4	.7	16.7	25.2	6.25	N_2, 0.15
S-495	.45	1.0 max	1.0 max	14	20	4	W, 4; Cb, 4

Part 3. Nonferrous Alloys

I. Nickel-Copper Alloys

1. General

The phase diagram for the copper-nickel system was determined by Guertler and Tammann [4], and has been confirmed by other investigators. As shown in figure 36, the two metals form a continuous series of solid solutions. The alloys are face-centered cubic and the lattice parameter varies linearly with atomic concentration from 3.60 A for copper to 3.54 A for nickel. The Curie temperature varies linearly with the nickel content from 353° C for pure nickel to −170° C at 50-percent nickel, so that alloys of more than 30-percent copper are paramagnetic at room temperature [387]. The metallographic structure of the wrought or annealed commercial alloys consists of grains of the solid solution with or without sulfide inclusions. Cast alloys commonly show a dendritic structure that can be relieved by hot working or by cold working and annealing.

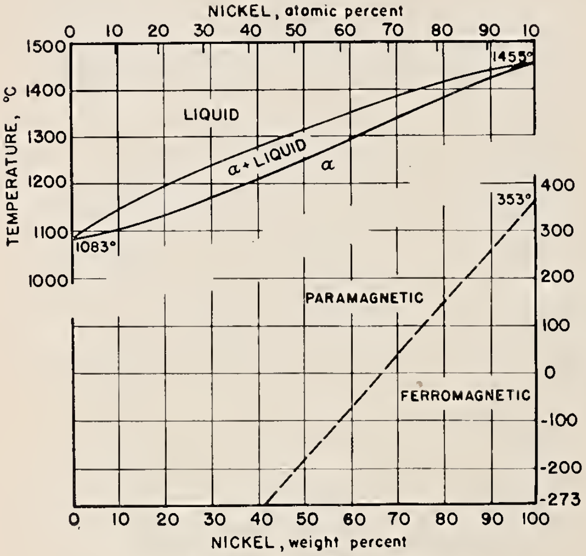

Figure 36. *Copper-nickel system.*

(Guertler and Tammann [4], Pilling and Kihlgren [387]).

Note: On the International Temperature Scale for 1948, the melting point of nickel is 1,453° C.

Metallographic techniques for the nickel-rich alloys are similar to those described for nickel, while for the copper-rich alloys, the American Society for Testing Materials procedures for copper alloys are recommended [320]. Monel, the important nickel-rich alloy, which contains 30 percent of copper with small amounts of iron and manganese, has been electropolished at this Bureau, using an electrolyte of two parts methyl alcohol and one part concentrated nitric acid, cautiously mixed. The recommended voltage is 2.4 to 2.6, with a current density of 125 to 150 ma/cm^2.

Impurities affect these alloys in much the same manner as they do nickel. Carbon content must be kept low in order to avoid precipitation of free graphite, which causes intercrystalline brittleness. For example, precipitation occurs at a carbon content of about 0.35 percent in Monel and with amounts as low as 0.04 percent in the alloy containing 80 percent of copper. Tests on coinage metal (75-percent Cu, 25-percent Ni) by Bose [151] disclosed that the annealing brittleness caused by this graphite precipitation could be prevented by the addition of about 1 percent of manganese when 0.1-percent carbon is present.

Reduction of graphite precipitation has also been accomplished by titanium additions [155]. Sulfur is extremely harmful in these alloys and must be kept low. Lead in the presence of silicon coarsens the structure, causes cracking and produces a detrimental effect on the high-temperature properties of sand-cast material. Controlled quantities of silicon, manganese, magnesium, and zinc are beneficial in most of the alloys.

2. Monel

(a) Types, Forms, Applications

Monel was introduced by the International Nickel Company about 1905, deriving its name from Ambrose Monell, who was at that time president of the company. It is obtained by roasting copper-nickel converter matte, reducing the resulting oxide to metal with charcoal, and refining in basic electric furnaces [178]. Monel is widely used because of its excellent resistance to corrosion and to erosion by steam and water, and because of its white color and good strength and hardness over a wide range of temperature. Since its introduction several modifications have appeared that possess special properties while retaining the essential corrosion-resistant properties of the original alloy. Nominal compositions and some physical constants of the various grades of Monel are given in table 32.

TABLE 32. *Nominal compositions and physical constants of cast and wrought Monels [149, 237, 256, 263, 278, 307, 331, 373, 382, 385]*

	Composition								Density	Melting range	Magnetic transformation temperature	Specific heat	Coefficient of thermal expansion, 25 to 100° C per ° C	Electrical resistivity at 20° C
	Ni	Cu	S	Si	Mn	C	Fe	Al						
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*g/cm³*	*° C*	*° C*	*cal/g*		*Microhm-cm*
Wrought Monel	67	30	0.01	0.1	1.0	0.15	1.4	--------	8.84	1,300 to 1,350	27 to 95	0.127	14.0×10^{-6}	46.8
Cast Monel	63	32	--------	1.6	--------	.15	1.5	--------	8.63	1,315 to 1,345	−8	--------	12.9	53.3
"R" Monel	67	30	.035	.05	1.1	.10	1.7	--------	8.84	1,300 to 1,350	43 to 60	.130	14.0	------
"K" Monel	66	29	.005	.5	.85	.15	.9	2.75	8.47	1,315 to 1,350	below −101	.127	14.0	58.3
"KR" Monel	66	29	.005	.5	.85	.3	.9	2.75	8.47	1,315 to 1,350	below −101	.127	14.0	58.2
"H" Monel	63	31	--------	3.0	.75	.1	2.0	--------	8.48	1,290 to 1,315	−54	--------	------------	61.6
"S" Monel	63	30	--------	4.0	.75	.1	2.0	--------	8.36	1,260 to 1,290	−54	.13	12.2	63.3

Regular Monel is available in all commercial forms and is used in equipment where a high strength and corrosion-resistant material is required. Typical applications include valve and pump parts, turbine blades, and equipment for the food, chemical, oil refinery, pulp and paper, textile, and pharmaceutical industries. It is also used in household and architectural applications where appearance is a factor.

"R" Monel is available only in hot-rolled or cold-drawn rod and possesses substantially the same properties as the regular grade, but is more readily machinable and is therefore used for automatic screw machine products such as bolts, screws, and precision parts.

"K" Monel is supplied in cold-drawn rods and bars, tube and pipe, forged billets and shapes, and hot-rolled rods and bars. It is an agehardenable alloy and in the heat-treated condition has mechanical properties superior to those of the regular alloy. It is nonmagnetic at room temperature. Applications include nonmagnetic parts for aircraft, springs, shafts, and valve stems. "KR" Monel is a more readily machinable form of the "K" alloy and is available in hot-rolled and cold-drawn rods.

"H" Monel, produced in both centrifugal and sand-castings, is utilized in highly stressed, corrosion-resistant parts, such as cast turbine nozzles.

"S" Monel is the hardest of the cast Monels and retains its hardness and resists galling at elevated temperatures. Applications include nongalling valve seats, bushings, pump liners and sleeves [248, 273, 319].

"A" Monel, used in foundries as a raw material, is supplied in blocks approximately 2×2×4 in. that weigh 6 to 8 lb [256].

(b) Physical and Mechanical Properties

Physical constants of the various Monels are included in table 32. Monel is slightly magnetic at temperatures below the Curie point; its permeability varies slightly with composition, working, and heat treatment. Reflectivity values for rolled Monel, as determined by Coblentz [20], vary from 54 percent for a wavelength of 4,358 A to 91 percent for 40,000 A. The reflectivity, absorption coefficient, and refractive index of Monel approximate the corresponding values for nickel [20, 120].

Mechanical properties of the Monels vary with shape and size of the product, method of fabrication, and with heat treatment. Table 33 shows the range in mechanical properties that may be expected for the different Monels, and table 34 shows the variations in tensile properties and hardness of regular Monel in various fabricated forms. Temperature affects the mechanical properties of Monel in a manner similar to the effect on nickel. Some data on the effect of both high and low temperatures on the tensile properties of

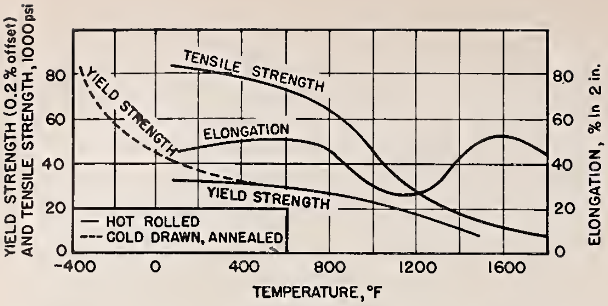

Figure 37. *Tensile properties of Monel at high and low temperatures.*

(International Nickel Co., Inc. [256], McAdam and Mebs [288]).

Monel are shown in figure 37. According to Betty, Eiselstein, and Huston [306], the creep strength of Monel permits its use up to 480° C, at which temperature a working stress of 6,300 lb/in.^{2} is recommended for the cold-worked, annealed alloy, based on 80 percent of the stress to produce a minimum creep rate of 0.01 percent per 1,000 hr. The stress and temperature for certain creep rates, as determined by Bennett and McAdam [264], are plotted in figure 38. The tensile properties of "K" Monel at elevated temperatures are shown in figure 39. Much attention has been devoted to the desirable mechanical properties of Monel at temperatures down to −190° C and even to −253° C, but the reported results are difficult to tabulate satisfactorily and the reader is referred to the original reports of the investigations [77, 129, 171, 240, 301, 373]. In general, both Monel and "K" Monel have good mechanical properties at low temperatures; strength and hardness increase with decreasing temperature without appreciable loss in ductility or impact values.

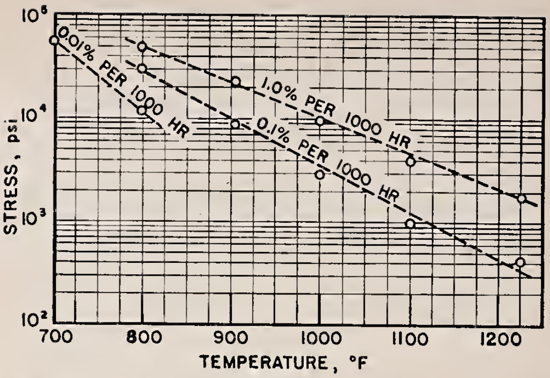

Figure 38. *Relationship between temperature and stress required to produce indicated creep rates in cold-drawn Monel.*

(Bennett and McAdam [264].

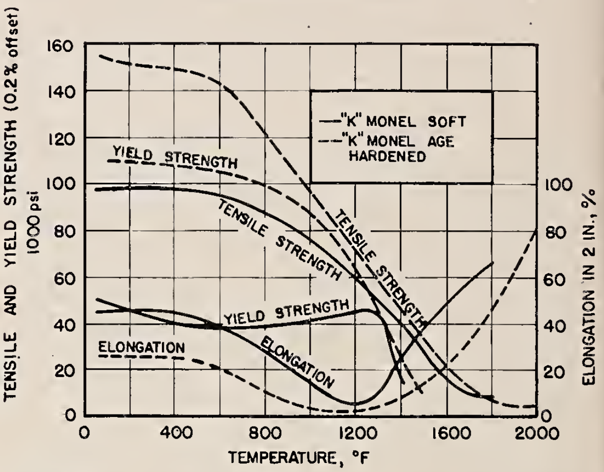

Figure 39. *Tensile properties of "K" Monel at elevated temperatures.*

(Eash [373], International Nickel Co., Inc. [256]).

Table 33. *Range of mechanical properties of Monels at normal temperatures [157, 169, 178, 237, 248, 256, 307, 319, 382, 386]*

	Tensile strength	Yield strength	Elongation in 2 in.	Reduction of area	Modulus of elasticity	Brinell hardness number	Compressive yield strength (0.1% offset)	Torsional yield strength (0.0% offset)	Charpy impact	Endurance limit 10^8 reversals
	1,000 lb/in.^{2}	*1,000 lb/in.^{2}*	*Percent*	*Percent*	*1,000 lb/in.^{2}*		*1,000 lb/in.^{2}*	*1,000 lb/in.^{2}*	*ft-lb*	*1,000 lb/in ^{2}*
Wrought Monel	70 to 170	25 to 160	50 to 2	75 to 50	26,000	120 to 140	26 to 70	19 to 58	151 to 232	24 to 50
Cast Monel	65 to 90	32 to 40	45 to 25	42	23,000	125 to 150	19	--------	35 to 130	--------
"R" Monel	70 to 140	25 to 130	50 to 4	70 to 50	26,000	130 to 240	25 to 65	--------	140 to 196	--------
"K" Monel	90 to 200	40 to 175	45 to 2	70 to 25	26,000	140 to 320	38 to 119	27 to 62	42 to 170	27 to 59
"KR" Monel	90 to 200	40 to 175	45 to 2	70 to 25	------	140 to 320	---------	--------	25 to 50	--------
"H" Monel	90 to 115	60 to 80	20 to 10	19	23,800	175 to 250	---------	--------	30 to 75	--------
"S" Monel	110 to 145	80 to 115	10 to 1	11 to 8	24,000	275 to 375	30 to 67	--------	5 to 13	--------

TABLE 34. *Tensile and hardness ranges of Monel standard forms*

Patton [385]

Form and condition	Tensile properties					Hardness number	
	Yield strength (0.01% offset)[a]	Yield strength (0.2% offset)	Tensile strength	Elongation in 2 in.	Reduction of area	Brinell 3,000 kg.	Rockwell B
Rod and Bar (cold-drawn):	*1,000 lb/in.*^{2}	*1,000 lb/in.*^{2}	*1,000 lb/in.*^{2}	*Percent*	*Percent*		
Annealed	20 to 30	25 to 40	70 to 85	50 to 35	75 to 60	110 to 140	60 to 75
As-drawn	45 to 95	55 to 120	85 to 125	35 to 10	70 to 50	160 to 250	85B to 23C
No. 1 temper (less than ½ in. diameter)	--------	50 to 85	95 to 110	20 to 5	--------	--------	--------
Hot-rolled	30 to 55	40 to 65	80 to 95	45 to 30	75 to 60	140 to 185	75 to 90
Forged	25 to 65	40 to 85	75 to 110	40 to 20	70 to 60	140 to 220	75 to 98
Wire (cold-drawn):							
Annealed	--------	25 to 40	70 to 85	50 to 30	--------	--------	--------
No. 1 temper	--------	50 to 85	95 to 110	20 to 5	--------	--------	--------
Regular temper	--------	85 to 130	110 to 140	15 to 4	--------	--------	--------
Spring (less than 5/16 in. diameter)	--------	130 to 160	140 to 170	10 to 2	--------	--------	--------
Plate (hot-rolled):							
Annealed	20 to 30	25 to 45	70 to 85	50 to 30	--------	110 to 140	60 to 75
As-rolled	25 to 70	40 to 90	80 to 110	45 to 20	--------	140 to 220	75 to 98
Sheet and Strip:							
Annealed	--------	25 to 45	70 to 85	50 to 30	--------	--------	61 to 73
No. 35 sheet	--------	45 to 65	78 to 85	40 to 20	--------	--------	74 to 89
¼ hard strip	--------	45 to 65	78 to 85	40 to 20	--------	--------	74 to 82
Hard sheet	--------	90 to 110	100 to 120	15 to 2	--------	--------	94 min
Full-hard strip	--------	90 to 130	100 to 140	15 to 2	--------	--------	98 min
Tubing (cold-drawn):							
Annealed	--------	25 to 45	70 to 85	50 to 30	--------	--------	60 to 75
As-drawn	--------	60 to 120	90 to 125	20 to 10	--------	--------	8C to 23C

[a] Proof stress.

(c) Corrosion Resistance

The ensuing discussion of corrosion resistance in various media applies to all grades of Monel and has been assembled from various sources [140, 169, 256, 321, 375]. Broadly speaking, the Monels are more resistant to acids than commercial nickel, less resistant to alkalis, and equally resistant to salts. Being solid-solution alloys, they are free from local galvanic corrosion.

Atmosphere. The rate of atmospheric corrosion of Monel is less than that of nickel in most localities. Recent tests in Pittsburgh, Pa., show a corrosion rate of 0.000038 in./yr for Monel compared to 0.00013 for nickel. When a section of Monel roofing on the Pennsylvania Terminal in New York City was examined after 25 years of service, no determinable decrease in gage thickness was found. Colored tarnish films are formed in industrial and humid atmospheres; slow fogging occurs indoors.

Waters. Monel is highly resistant to the corrosive action of both fresh and salt water, and especially to the effects of impingement and cavitation in sea water under conditions of high velocity. In stagnant sea water, accumulations of marine organisms and other solids may result with subsequent pitting underneath, for the alloy is nontoxic to these organisms.

Salt Solutions. Neutral and alkaline salts, including chlorides, carbonates, sulfates, nitrates, acetates, and others, rarely attack Monel at a rate greater than 0.005 in./yr, making it a useful material for handling refrigerating brines, laundry solutions, dye solutions, alkaline peroxide bleaching solutions, and the brines and wet salts of salt-producing plants. Nonoxidizing acid solutions, such as zinc chloride, ammonium sulfate, and aluminum sulfate, usually attack Monel at rates of less than 0.02 in./yr.

Oxidizing acid salts, such as ferric chloride, ferric sulfate, and cupric chloride, are severely corrosive. However, the dilute acids containing chromates encountered in textile dyeing and leather tanning are not highly corrosive and Monel is used in these processes. The oxidizing alkaline hypochlorites are highly corrosive when the available chlorine concentration exceeds 3 g/liter. Monel is used satisfactorily as wire cloth for filter and cylinder molds employed in washing chlorine-bleached paper pulp.

Mineral Acids. Corrosion of Monel by mineral acids is largely dependent on the oxidizing characteristics of the acid, degree of concentration, amount of aeration, and temperature. Monel is superior to nickel in handling sulfuric acid, corrosion being practically nonexistent in air-free room-temperature solutions with concentrations up to 80 percent. In air-saturated solutions the maximum rate of corrosion occurs at 5-percent concentration. Boiling sulfuric acid may be handled in concentrations less than 20 percent. Monel is widely used in the construction of acid-pickling tanks for steel. In hydrochloric acid the rate of corrosion varies with concentration and air content from 0.005 in./yr in 1-percent air-free cold acid to 0.25 in./yr in air-saturated 30-percent cold acid. At higher temperatures, Monel has been used with aerated hydrochloric acid in 2-percent concentrations at 50° C and 1-percent concentrations at 80° C in apparatus such as pickling baskets and fruit-washing machines. Other mineral acids that are not severely corrosive are hydrofluoric, throughout a wide range of concentrations and temperatures, and pure phosphoric acid in low concentrations. Nitric and other oxidizing acids are severely corrosive and are used only under limited circumstances with concentrations less than 1 percent and temperatures lower than 27° C.

Organic Acids. Organic acids are moderately corrosive toward Monel and may become appreciably so when saturated with air. Tests with acid fruit juices show Monel to be slightly more resistant to these acids than nickel. Monel is extensively used in canning and soap making machinery.

Gases. All common dry gases have little effect on Monel at normal temperatures. Chlorine, bromine, sulfur dioxide, nitric oxide, and ammonia are detrimental when water is present. As with nickel, the mixture of nitrogen, hydrogen, and ammonia used in ammonia synthesis is destructive under the conditions of temperature and pressure used. Monel resists atmospheric oxidation at temperatures up to about 540° C.

Molten Metals. Molten metals, such as aluminum, tin, lead, solder, bismuth, antimony, zinc, and brass, attack Monel quite rapidly. Amalgamation by mercury is resisted up to 375° C.

Galvanic corrosion and the methods for its prevention are essentially the same as for nickel.

3. Cupro-Nickels

The copper-rich copper-nickel alloys are undoubtedly among the earliest alloys known to man. As previously mentioned, coins containing 78 percent of copper and 20 percent of nickel, approximately the composition of the present United States five cent coinage, were used in Bactria as early as 235 B. C. The term *cupro-nickel* is commonly applied to alloys of copper and nickel containing less than 50 percent of Ni. Their color varies from pink in the low-nickel alloys to nickel-white when nickel is present in amounts of 20 to 25 percent or more.

The alloys containing about 2 percent of nickel are corrosion resistant and have a combination of strength, ductility, and toughness that makes them useful for boiler parts of locomotives. Alloys containing from 2½ to 22 percent of nickel are used as electrical resistors where moderate resistivity and an intermediate temperature coefficient are desired. The present United States five cent coinage contains 25 percent of Ni. The 20- and 30-percent nickel alloys are widely used in condenser tubes and plates and heat exchanger tubes in ships and oil refineries, the 30-percent alloy is also used for resistance wire and in pipe for handling salt water and some chemicals. When the nickel content is less than 40 percent, the alloys are toxic to marine life and prevent the accumulation of these organisms in sea water. At a composition of about 45-percent nickel the cupro-nickels have a silver color combined with good corrosion resistance and are sometimes used in food service equipment [257, 315, 365]. The alloy containing 45 percent of nickel, commonly known as Constantan, has an electrical resistivity near the maximum of the alloy series and a temperature coefficient near zero, making it valuable for use in electrical resistors. It also has a high thermoelectric force against copper, iron, and chromium-nickel and is used for high-sensitivity thermocouples at low and medium temperatures [44, 393]. Data for Constantan couples are included in the subsequent discussion of nickel-chromium thermocouple alloys.

Some of the trade names under which copper-nickel are marketed are given in table 35, together with their compositions, manufacturers, and applications. Data on the mechanical properties of some of these alloys, at various temperatures, are given in tables 36 and 37. Data reported by Lowry, Bor, and Wilkinson [120] for the reflectivity, refractive index and absorption coefficient of copper-nickel alloys, for wavelengths of 4358, 5461, and 5780 angstroms are shown in table 38. The effect of composition on the thermal conductivity of copper-nickel alloys is shown in figure 40.

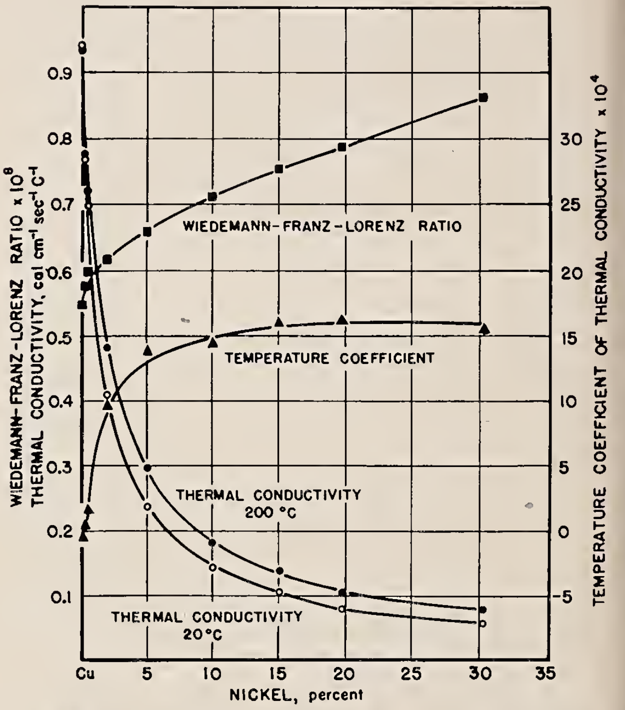

Figure 40. *Effect of composition on thermal conductivity of copper-nickel alloys, annealed at 800° C.*

(Smith and Palmer [126]).

Table 35. *Some commercial cupro-nickel alloys*

Woldman and Metzler [317]

Alloy	Composition	Manufacturer	Uses and remarks
	Percent		
Advance	55 to 54 Cu, 44 to 45 Ni	Driver Harris Co	Similar to Constantan.
Benedict Nickel	79 Cu, 20 Ni, 0.36 Fe	American Brass Co	Corrosion resistant sheets, tubes, extrusions.
Berthier's Alloy	68 Cu, 32 Ni		Evaporaters, stills.
Chase Cupro-Nickel 70–30	70 Cu, 30 Ni	Chase Brass and Copper Co., Inc	Condenser tubes.
Chase Cupro-Nickel 80–20	80 Cu, 20 Ni	do	Do.
Constantan	60 to 45 Cu, 40 to 55 Ni, 0 to 1.4 Mn, 0.1 C, balance Fe.		Electrical resistances, thermocouples.
Constantan	54 Cu, 44 to 46 Ni, 0 to 0.4 Fe, 0 to 1.34 Mn.		Resistance alloy.
Copel	55 Cu, 45 Ni	Hoskins Mfg. Co	Hot resistances, rheostats, electrical instruments.
Copper-Nickel 10%	90 Cu, 10 Ni	Henry Wiggin & Co	Dynamo rings.
Copper-Nickel 15%	85 Cu, 15 Ni	do	Bullet jackets, coinage, condenser tubes.
Copper-Nickel 20%	80 Cu, 20 Ni	do	Condenser tubes.
Cunic	55 Cu, 45 Ni	Geo. W. Prentiss & Co	Rheostats, shunts, thermocouples.
Cupro-Nickel Sheet	81 to 79 Cu, 19 to 21 Ni		Condenser tubes, turbine blades.
Cupro-Nickel No. 300 alloy	89 Cu, 11 Ni		Corrosion resisting parts.
Cupro-Nickel, Locomotive tubes	97 Cu, 3 Ni		Locomotive tubes.
Cupro-Nickel, Driving bands	97.5 to 95 Cu, 2.5 to 5 Ni		Driving bands.
Cupro-Nickel, Commercial	98 to 60 Cu, 2 to 40 Ni		Hardware.
Cupro-Nickel, Bullet Jackets	85 Cu, 15 Ni, <0.04 C		Bullet jackets.
Cupro-Nickel	93.2 Cu, 6.8 Ni	Western Cartridge Co	Corrosion resistant.
Cupron	55 Cu, 45 Ni	Wilbur B. Driver Co	Similar to Constantan.
Eureka	60 Cu, 40 Ni		Do.
Excelsior	53 Cu, 45 Ni, 0.3 Fe	Alloy Metal Wire Co	Resistance Alloy.
Ferry	56 to 55 Cu, 44 to 45 Ni	Henry Wiggin & Co	Similar to Constantan.
Guillaume's Metal	64.3 Cu, 35.7 Ni		Tape, chemical equipment.
Ia-Ia	58 to 60 Cu, 42 to 40 Ni, 1.0 Fe+Mn	H. Boker & Co	Resistances, thermocouples.
Ideal	58 to 53 Cu, 40 to 45 Ni, 0.6 to 1.0 Fe, 0.5 to 1.0 Mn.	Driver Harris Co	Heating elements, electrical resistors.
Imperial	80 Cu, 20 Ni	Empire Metal Co	Condenser tubes.
Jelliff Alloy 45	55 Cu, 45 Ni	C. O. Jelliff Mfg. Corp	Thermocouples, resistance coils.
Lechesne	90 to 60 Cu, 10 to 40 Ni, 0.2 to 0.05 Al		Chemical engineering equipment.
Midohm	78 to 77 Cu, 22 to 23 Ni	Driver Harris Co	Electrical resistances and rheostats, below 200° C.
Nickelin "B"	68 Cu, 32 Ni		Resistance alloy.
Nickeloid	60 to 55 Cu, 40 to 45 Ni	Barker & Allen Ltd	Nonrusting, corrosion resisting parts.
Radio Alloy 60	95 Cu, 5 Ni	Wilbur B. Driver Co	Electrical instruments, resistors.
Radio Alloy 90	88 Cu, 12 Ni	do	Do.
Seventy-Thirty	70 Cu, 30 Ni		Condenser tubes, turbine blades.
Silveroid	54 Cu, 45 Ni, 1 Mn	Henry Wiggin & Co	Corrosion resistant, cutlery.
Super Nickel—701	70 Cu, 30 Ni	American Brass Co	Condenser tubes.
Turbine Blading	78 to 81 Cu, 22 to 19 Ni, 0.75 max Fe		Turbine blades.

Table 36. *Mechanical properties of copper-nickel alloys at normal temperatures*

Everhart and Associates [278]

Composition					Condition	Tensile strength	Yield strength (0.01% extension)	Modulus of elasticity	Proportional limit	Elongation in 2 in.	Reduction of area	Endurance limit 10^8 cycles	Hardness No.	
Ni	Fe	Mn	C	Others									Brinell	Rockwell B
Percent	*Percent*	*Percent*	*Percent*	*Percent*		*lb/in.^{2}*	*lb/in.^{2}*	*1,000 lb/in.^{2}*	*lb/in.^{2}*	*Percent*	*Percent*	*lb/in.^{2}*		
2.16				P, 0.013	Cold-drawn; annealed 700°C	33,400			3,600					
					Cold-drawn, 44% reduction	51,700			19,700					
2.72	0.04	0.04		S, .011	1-in. rod, cold-drawn	47,000	34,500		23,300	20				
19.23	.27	.12	0.03		1-in. rod, annealed 760° C	44,400	9,000			49	71	16,000	61	
					1-in. rod, cold-rolled	49,900	30,000	22,000		36	68	[a]18,000	86	
20.24					0.058-in. sheet, annealed 600° C	45,300	[b]18,900			27				
20.55				Ag, .11	0.058-in. sheet, annealed 600° C	51,000	[b]30,200			25				
21.24	.51	.29	.03	Si, .005	1-in. rod, annealed 760° C	48,000	10,200		6,200	48	74	17,800		
					1-in. rod, annealed 205° C	62,500	45,000		25,000	23	68	25,500		
30.48	.07	.22		Mg, .03	0.75-in. rod, cold-drawn 15%	67,300	[c]63,800	21,600		23	71			
					0.75-in. rod, annealed 450° C	65,800	[c]53,700	22,100		30	72			
45.0					Sand-cast	56,000	[b]21,000			32	34		80	
45.0	.27	1.0	.05	Si, .02 S, .006	Rod, annealed 760° C	66,600	[d]27,100	24,800	20,200	46	78			54
					Rod, hot-rolled	67,800	[d]35,000	24,900	21,200	42	76			62
44.68	.52	1.14	.11		1-in. rod, hot-rolled	70,500	28,000	25,000	14,500	48	78	34,500	100	
44.77	.66	.89	.078		Rod, annealed 790° C	69,400	25,400		21,000	48	79	28,000	86	
					Rod, cold-rolled	103,000	54,700			15	70	[e]43,000	159	
45.0	.38	1.03	.04	Si, .02	Rod, annealed 400° C	95,500	65,000		38,500	23	11	40,500		

[a] 5x10^7 cycles.

[b] 0.2% extension.

[c] 0.5% extension.

[d] Yield point.

[e] 4x10^7 cycles.

Table 37. *Mechanical properties of copper-nickel alloys at high and low temperatures [278, 373]*

Composition					Condition	Temperature	Tensile strength	Yield strength, 0.1 extension	Elongation in 2 in.	Reduction of area	Izod impact	Charpy impact	Stress for creep rates per thousand hours of—		
Ni	Fe	Mn	Si	Others									0.001%	0.01%	0.1%
Percent	*Percent*	*Percent*	*Percent*	*Percent*		° *C*	*lb/in.²*	*lb/in.²*	*Percent*	*Percent*	*ft-lb*	*ft-lb*	*lb/in.²*	*lb/in.²*	*lb/in.²*
9. 64	0. 85	0. 27	0. 08	P, 0. 05	Hot-rolled	Room	49, 000	[a]29, 000	34	64	------	42	------	------	------
						−134	60, 000	[a]33, 000	43	65	------	56	------	------	------
						−196	66, 600	[a]33, 500	50	62	------	68	------	------	------
20. 58	------	. 11	. 03	------	1-in. rod annealed	Room	51, 500	27, 700	26	78	77	------	------	------	------
						−40	59, 600	29, 000	29	77	81	------	------	------	------
						−80	61, 600	28, 900	29	76	79	------	------	------	------
						−114	66, 100	29, 200	28	75	84	------	------	------	------
						−180	73, 700	32, 500	36	72	85	------	------	------	------
29. 54	------	. 57	------	Zn, . 62	Annealed	Room	57, 600	[a]34, 200	54	------	------	66	------	------	------
						−31	------	------	------	------	------	59	------	------	------
						−115	------	------	------	------	------	60	------	------	------
30. 06	. 03	. 8	------	Pb, . 005	0.125 wire, annealed	Room	59, 000	[a]21, 000	40	------	------		------	------	------
						149	------	------	------	------	------	------	24, 000	35, 000	------
						260	------	------	------	------	------	------	16, 000	30, 000	------
30. 06	. 03	. 8	------	Pb, . 005	0.125 wire, drawn 84%	Room	90, 500	[a]80, 000	9	------	------	------	------	------	------
						260	------	------	------	------	------	------	8, 000	------	------
30. 32	------	. 65	------	Zn, . 15	0.75-in. rod, annealed 550° C	30	64, 700	[a]48, 300	37	65	------	------	------	------	------
						399	47, 600	------	22	48	------	------	9, 100	18, 800	------
45. 78	. 07	. 39	. 15	Co, . 26	1-in. rod, annealed	Room	60, 000	19, 600	40	77	80	------	------	------	------
						−40	67, 600	21, 000	43	78	85	------	------	------	------
						−80	72, 200	22, 100	48	75	81	------	------	------	------
						−120	77, 100	24, 100	48	74	83	------	------	------	------
						−180	89, 600	26, 300	57	76	86	------	------	------	------

[a] 0.5 extension.

Table 38. *Optical properties of copper-nickel alloys*

Lowrey, Bor, and Wilkinson [120]

Nickel	Wavelength=4,358 A			Wavelength=5,461 A			Wavelength=5,780 A		
	Reflectivity	Refractive index	Absorption coefficient	Reflectivity	Refractive index	Absorption coefficient	Reflectivity	Refractive index	Absorption coefficient
Percent	*Percent*			*Percent*			*Percent*		
0	51. 6	0. 964	2. 03	61. 3	0. 817	2. 27	77. 8	0. 431	2. 39
8. 2	51. 7	1. 04	2. 11	64. 1	. 940	2. 59	70. 4	. 800	2. 75
17. 2	57. 7	1. 12	2. 47	66. 5	1. 15	3. 02	70. 3	1. 14	3. 28
23. 2	53. 6	1. 23	2. 37	62. 8	1. 38	3. 03	65. 0	1. 44	3. 25
33. 4	54. 4	1. 33	2. 50	61. 8	1. 56	3. 13	63. 2	1. 68	3. 33
43. 1	56. 1	1. 46	2. 69	59. 9	1. 86	3. 22	60. 2	2. 00	3. 33

4. Ternary and Complex Copper-Nickel Alloys

(a) Nickel Brasses

The copper-nickel-zinc alloys are of very old origin, being known in ancient China as Paktong. In 1824, the Henniger brothers of Berlin and Dr. Geitner of Schneeberg, Germany, invented almost simultaneously an alloy of copper, nickel, and zinc similar in appearance to silver and suitable for table and culinary purposes. The Henniger alloy was termed "Neusilber" and the Geitner alloy "Argentan" [5]. In England the name German Silver was in general use until after World War I. Since then the trade has largely adopted the name nickel silver but a more logical designation for these alloys is nickel brass, and they are so named in this Circular.

The liquidus temperature and the section of the ternary diagram at 25° C are shown in figure 41. These are taken from the work of Schramm consolidated with the work of other investigators by Kihlgren [379]. The cold-working alloys contain only the alpha phase, whereas the hot-working or extruding alloys may contain both alpha and beta. Alpha has a face centered cubic structure, whereas beta is body-centered cubic. Metallographic procedures are similar to those for copper alloys [320].

Frequently, lead, tin, manganese, magnesium, aluminum, and phosphorus are added to nickel brass, particularly castings, to impart special characteristics. Iron, antimony, arsenic, carbon, sulfur, and nonmetallic oxides are often present unintentionally. The following discussion of the effect of these minor constituents is condensed from a summary by Draper [251].

Lead, in quantities up to 6 percent, is added to nickel brass to increase machinability. It decreases tensile strength and ductility, making cold-work more difficult, while the tendency toward fire cracking and water cracking is increased. Corrosion resistance and color are little affected. Tin in castings refines the grain, reduces porosity, and increases fluidity, hardness, and strength. In the presence of lead it reduces the danger of lead sweat, but it increases the tend-

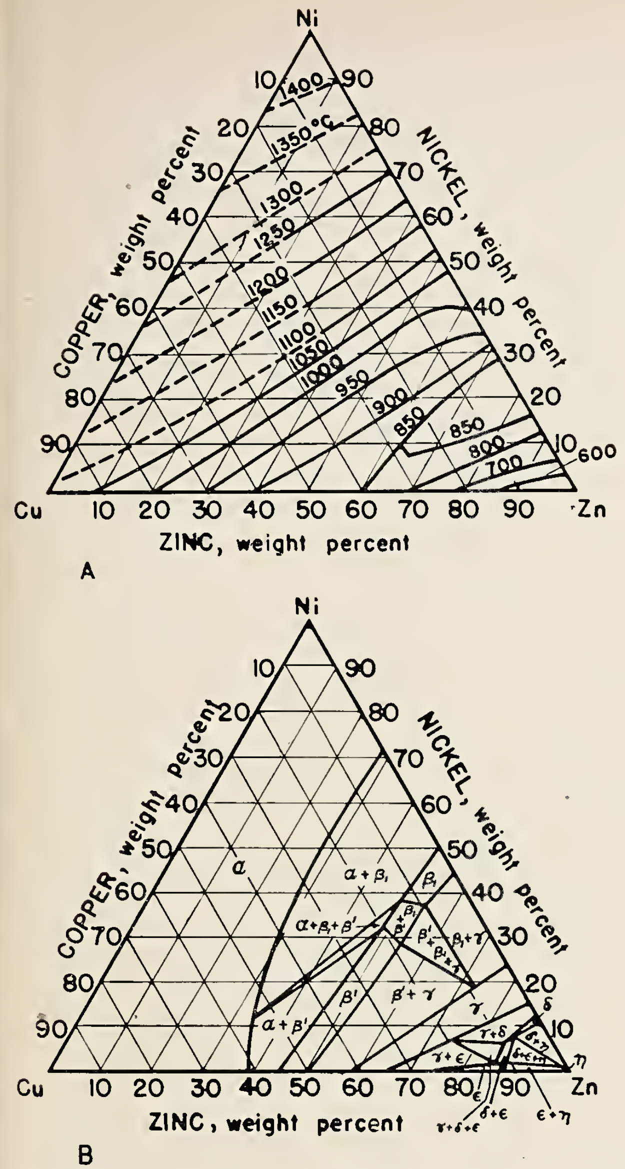

FIGURE 41. *Copper-nickel-zinc system* (*Kihlgren* [*379*]).
A, Liquidus temperatures; B, constitution of alloys at 25° C.

ency to crack during rolling. Both manganese and magnesium are excellent deoxidizers and desulfurizers and are usually used together. They give castings increased soundness and tensile strength with subsequent improvement in the working properties. Aluminum in small amounts is sometimes used as a deoxidizer, but in amounts greater than 0.25 percent it produces a troublesome oxide film and causes considerable shrinkage in castings. Alloys containing more than 3 percent of Al are susceptible to heat treatment. Phosphorus in amounts up to 0.02 percent is useful as a deoxidizer and to clean the surface of a melt, but in excess of 0.025 percent this element is detrimental to ductility. Iron in small amounts increases strength and ductility, but it is usually kept as low as possible, for it promotes cracking during cold-working and at a content of about 2 percent reduces strength and ducility. Although silicon under certain conditions has been found useful as a deoxidizer, it is harmful, particularly if lead is present, for it lowers the pressure tightness of castings and makes the alloy susceptible to hot tears. Carbon may cause porosity in castings, and in wrought alloys that are annealed between 700° and 900° C it may precipitate as free graphite along the grain boundaries and cause brittleness. Arsenic and antimony are seldom present in sufficient quantity to be harmful, but an excess of either may cause brittleness.

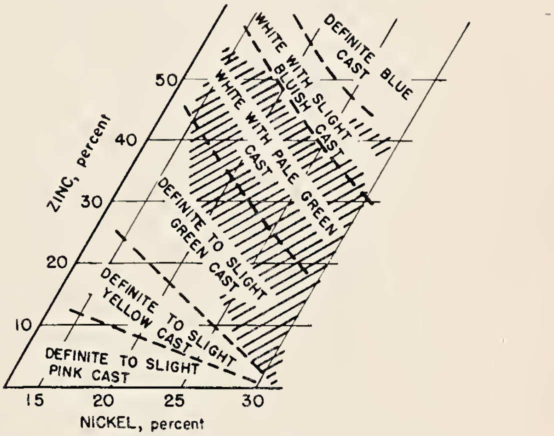

FIGURE 42. *Color trends in copper-nickel-zinc alloys.*
Shaded area indicates sensibly white alloys. (Kihlgren, Pilling, and Wise [118]).

Both nickel and zinc have a whitening effect in these brasses; of the two, nickel is the more influential. The color of the alloys varies with the amount of these two elements present, from a slightly pinkish cast at low zinc, through a sensibly white shade at medium zinc and into a blue cast at high zinc. Kihlgren, Pilling, and Wise [118] prepared a schematic diagram showing the effect of varying amounts of copper, nickel, and zinc on color, which is reproduced in figure 42.

The high-nickel brasses are largely used as the base metal for plated silverware and rolled gold plate jewelry, for architectural purposes and for ornamental metal work. Other applications include food handling equipment, marine fittings, drafting and musical instruments, dental instruments, slide fasteners, and many others where a silvery color and corrosion-resistant properties are required. They are also used extensively for spring elements in electrical relays. Leaded nickel brass is used for machined parts as in cigarette lighters, fishing reel parts, grills and keys.

Table 39.—*Physical constants of some copper-nickel-zinc alloys* [*126, 131, 285*]

Composition						Condition	Density	Specific resistance at 20° C	Temperature coefficient of electrical resistivity (20° to 200° C) at 20° C	Electrical conductivity		Electrical conductivity 20° C	Thermal conductivity		Coefficient of thermal expansion		
Cu	Ni	Zn	Pb	Fe	Miscellaneous					20° C	200° C		20° C	200° C	0° to 100° C	0° to 200° C	0° to 400° C
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*		*g/cm³*	*Microhm-cm*		*(Ohm-cm)⁻¹ ×10⁻⁴*	*(Ohm-cm)⁻¹ ×10⁻⁴*	*IACS units*	*cal cm⁻¹ sec⁻¹° C⁻¹*	*cal cm⁻¹ sec⁻¹° C⁻¹*			
56.1	1.0	42.3		0.49					0.001872	14.40	10.77	24.84	0.272	0.310			
64.0	5.4	30.5		.05		Annealed 750° C			.000721	7.278	6.440	12.55	.140	.185			
62.6	10.0	27.1	0.005	.04	0.149	Annealed 800° C	8.608	20.71					.089	.108	15.0	15.8	17.0
59.8	10.1	29.9		.04	.19	Annealed 750° C			.000495	4.938	4.532	8.51	.101	.135			
65.5	10.4	23.9		.08	.191	Annealed 750° C			.000430	4.947	4.590	8.53	.110	.146			
65.0	11.0	22.0		1.5	.5	½-in. drawn rod									16.5 (20 to 100° C)	17.4 (20 to 300° C)	19.7 (20 to 800° C)
63.2	12.3	24.3	.005	.04	.149	Annealed 800° C	8.648	22.32					.072	.090	14.8	15.4	16.8
63.6	13.2	21.4	.05	1.72		½-in. drawn rod									17.2 (20 to 100° C)	17.5 (20 to 200° C)	18.0 (20 to 300° C)
62.4	15.3	22.1	.003	.04	.121	Annealed 800° C	8.685	24.79					.064	.081	15.0	15.6	16.8
58.4	15.7	25.5		.22	.15	³⁄₁₆-in. tube									17.4 (20 to 100° C)	17.8 (20 to 300° C)	18.9 (20 to 500° C)
63.8	16.3	19.8		.14	.18	Annealed 750° C			.000352	3.633	3.417	6.26	.081	.107			
56.0	18.0	25.9		.08	.20	Annealed 750° C			.000306	3.251	3.080	5.60	.071	.098			
62.0	18.4	19.4	.004	.07	.135	Annealed 800° C	8.724	27.55					.054	.065	14.8	15.4	16.8
64.1	18.4	17.1		.19	.53	Annealed 750° C			.000257	3.399	3.249	5.860	.080	.100			
63.4	19.9	8.2	5.4	.14	3.54	Sand-cast			.000350	2.916	2.742	5.03	.066	.088			
74.1	20.0	5.3		.09	.57	Annealed 750° C			.000230	3.575	3.431	6.16	.092	.116			
62.2	20.2	17.4	.005	.05	.130	Annealed 800° C	8.752	29.03					.052	.063	15.4	16.2	17.4
62.0	25.6	12.3	.004	.07	.129	Annealed 800° C	8.819	33.65					.049	.060	15.8	16.4	17.6
64.1	29.4	5.7		.07	.52	Annealed 750° C			.000128	2.642	2.581	4.56	.068	.086			
62.0	29.8	7.9	.003	.19	.168	Annealed 800° C	8.872	37.89					.046	.056	16.2	16.6	17.8

The nickel brasses are available commercially under a great variety of trade names and compositions. Campbell [62] in 1930 listed the trade names of 210 such alloys; current alloys were listed by Woldman and Metzler [317]. The usual composition ranges [118] are:

For cold-working:

Zinc	5 to 30 percent
Lead	1 to 3 percent
Nickel	10 to 30 percent
Copper	Remainder.

For hot-working: Some of the cold-working alloys with less than 10 percent of zinc and with added manganese are suitable for hot-working. Other alloys adapted to hot-working or extruding are in the range: Zinc, 38 to 45 percent; nickel, 8 to 18 percent, copper, remainder.

For casting:

Zinc	5 to 15 percent
Nickel	12 to 30 percent
Lead	2 to 10 percent
Tin	0 to 6 percent
Copper	Remainder.

The properties of the nickel brasses vary with composition and treatment and can best be shown by charts and graphs. Table 39 contains physical constants and table 40 the mechanical properties of some of the alloys in this series.

TABLE 40. *Mechanical properties of some copper-nickel-zinc alloys* [*301, 179, 261*]

Composition				Condition	Tensile strength	Elongation in 2 in.	Vickers hardness number
Cu	Ni	Zn	Others				
Percent	*Percent*	*Percent*	*Percent*		*lb./in.²*	*Percent*	
60.2	4.8	35.0	------	Chill-cast	43,900	50.0	95
				Hot-forged	53,800	37.0	92
49.5	5.3	45.2	------	Chill-cast	67,200	15.5	163
				Hot-forged	60,000	9.0	153
50.1	9.9	40.0	------	Chill-cast	54,400	37.5	130
				Hot-forged	68,300	55.0	120
59.5	10.1	30.4	------	Chill-cast	40,300	45.5	79
				Hot-forged	61,100	56.0	114
40.2	14.7	45.1	------	Chill-cast	62,300	5.0	208
				Hot-forged	80,600	7.0	159
54.4	15.7	29.9	------	Chill-cast	41,600	25.0	105
				Hot-forged	66,300	47.5	126
65.3	17.6	17.1	Fe, 0.2	Cold-drawn	62,400	28.0	------
74.3	19.5	5.4	Mn, .8	Annealed	54,700	43.0	------
74.0	19.8	5.2	Fe, .3 Mn, .7	Hot-rolled	57,100	36.0	------
74.2	20.2	5.3	------	Cold-drawn	61,200	25.0	------
				Annealed 450° C	58,300	32.0	------
				Annealed 0.06 grain size	49,000	50.0	------
44.0	21.5	34.5	------	Chill-cast	58,500	9.0	165
				Hot-forged	76,000	34.5	139
39.8	26.1	34.1	------	Chill-cast	69,400	5.5	181
				Hot-forged	79,500	11.5	162

(b) Nickel Bronzes

Eash [372] correlated the data of several investigations of the copper-nickel-tin system. The liquidus surface, and a section at 300° C of the copper-rich alloys is shown in figure 43. The solid phases are isometric in structure with the exception of the Eta phase, which is probably derived from the hexagonal phase of the copper-tin system. Figure 44 is a section from the diagram at 3 percent of Ni, as determined by Eash and Upthegrove [89]; their paper also contains similar diagrams for 5-, 10-, and 20-percent nickel alloys.

The copper-nickel-tin alloys are largely used as castings. The commercial alloys, many of which contain considerable amounts of lead and zinc, may be grouped into five arbitrary classes:

1. Low-nickel bronze, containing up to 3 percent of nickel.
2. Medium-nickel bronze, containing 3 to 10 percent of nickel.
3. Medium-high-nickel bronze, containing up to 30 percent of nickel.
4. High-nickel bronze, containing 40 to 70 percent of nickel.
5. Bearing bronze with nickel (contains lead).

The first class has received the most attention in the literature and is the most widely used. Nickel is extensively employed in foundries to replace a portion of the tin in bronze, because it lowers costs, improves many of the properties of the bronze, and permits varied mechanical properties to be obtained in a single composition by means of age-hardening. The age-hardening properties of these alloys first became known through the work of Price, Grant, and Phillips [42] and of Wise [45]. Nickel raises the melting point of the alloys, this rise according to Pilling and Kihlgren [75] is 6.6° C per 1 percent of Ni when nickel replaces copper, and 17.8° C per 1 percent Ni when nickel replaces tin. However, the fluidity of the melt is increased considerably thereby, allowing the use of lower pouring temperatures [136].

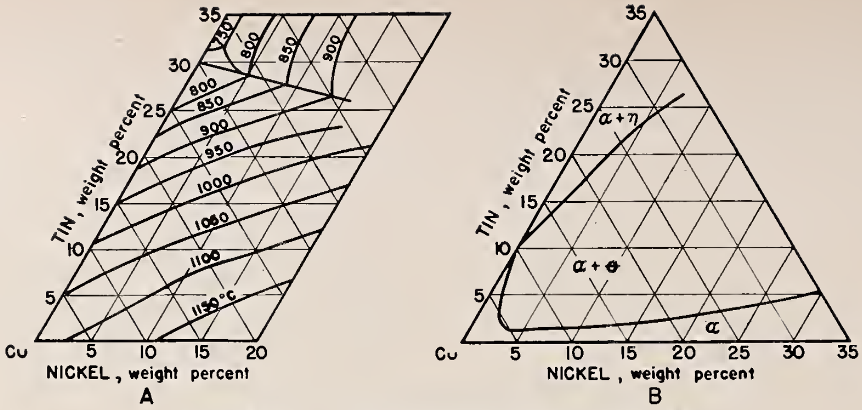

Figure 43. *Copper-nickel-tin alloys* (*Eash* [*372*]).

A, Liquidus temperatures; B, section at 300° C of copper-rich alloys.

Nickel also promotes grain refinement and increases the density and pressure tightness. In amounts greater than a few percent, it may cause troublesome oxidation [75]. Curry [132] listed the compositions of 31 of these low-nickel bronze casting alloys, with nickel contents ranging from 0.5 to 4 percent, and recorded their use for bearings, marine fittings, signs and plaques, bushings, transmission gears, plumbing fixtures, pressure castings, lubricator fittings, bearing backs, railroad car journals, grave markers, etc.

Class 2 bronzes with a nickel content of about 3 to 10 percent maintain a good portion of their strength at high temperature and are applied in steam engineering work [136].

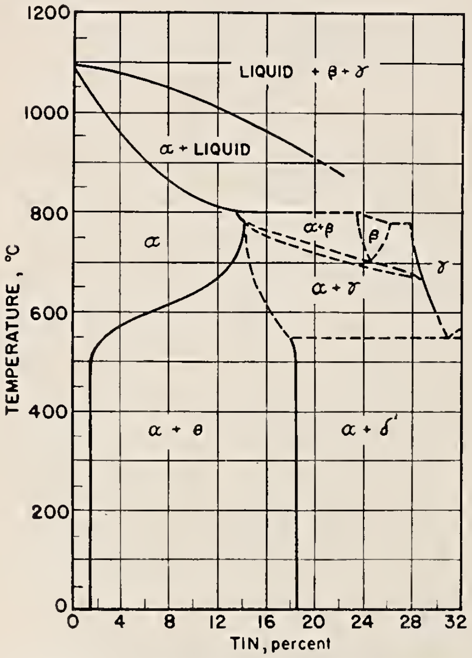

Figure 44. *Copper, 3-percent-nickel-tin system.*

(Eash and Upthegrove [89]).

Bronzes in class 3, with nickel ranging up to 30 percent, are extensively employed for valve fac-

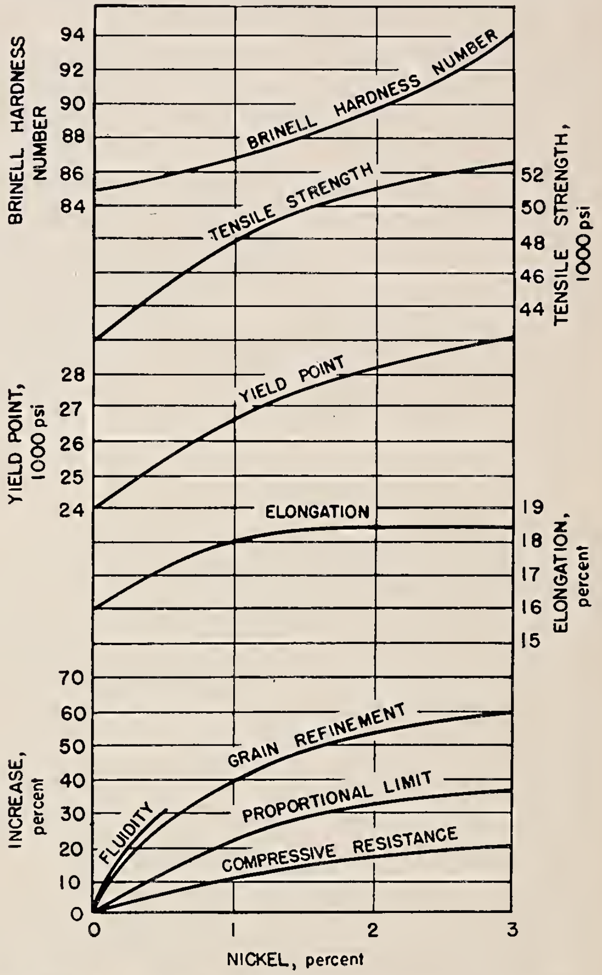

Figure 45. *Effect of nickel on mechanical properties of an 11-percent tin phosphor bronze.*

(Sands and Nemser [219]).

ings and fittings where corrosive waters and steam are encountered [136]. These alloys may be made age-hardenable by the addition of aluminum or silicon [161].

Class 4 alloys containing from 40 to 70 percent of nickel have been used as valve parts for controlling superheated steam [85].

Small amounts of nickel in bearing bronzes act to prevent lead sweat and aid in producing a bronze with a refined texture and exceptionally high compressive properties. According to Marechal [166], nickel increases the amount of lead that can be used without too much segregation. He recommended 35 percent of lead as the maximum allowable without serious reduction of compressive strength.

The coefficients of thermal expansion of a few copper-nickel-tin alloys were determined by Hidnert and Dickson [285]. The thermal conductivity of Admiralty Gun Metal and four nickel bronzes, as determined by Donaldson [203], decreases with increasing nickel content.

Nickel has a beneficial influence on the mechanical properties of tin bronze. Mechanical properties of a number of nickel bronzes are shown in table 41. The effect of nickel on the properties of phosphor bronze containing 11 percent of Sn is shown in figure 45 from data by Sands and Nemser [219]. The paper by Wise and Eash [107] contains many data on the variations of properties with change in composition and the effect of age-hardening on these properties, and should be consulted for further information on mechanical properties.

TABLE 41. *Mechanical properties of some nickel bronzes* [*30, 85, 107, 161, 184, 208, 229, 308*]

Composition				Condition	Tensile strength	Elongation in 2 in.	Brinell hardness number
Cu	Ni	Sn	Others				
Percent	*Percent*	*Percent*	*Percent*		*lb./in.²*	*Percent*	
88	0.5	11.2	P, 0.3	Centrifugal casting	45,000	11	95
80.7	1	10	Pb, 8; P 0.3	Sand-cast	35,000	9	70
88.2	1	10.5	P, 0.25	do	35,000	15	78
88.9	2.3	6.4	Zn, 2.4	Sand-cast at 1,100° C	49,900	30	72
Remainder	3	8		Annealed and aged	64,900	71	99
82	3.5	10	Zn, 4	Cast, Tested at room temperature	35,800	25	
				Tested at 427° C	24,600	8	
Remainder	4	4		Annealed and aged	66,000	25	113
88	5	5	Zn, 2	Cast	49,200	35	
				Annealed; quenched	49,700	38	
				do	85,000	5	
Remainder	5	5		Annealed and aged	100,000	23	200
89.1	5.1	3.3	Zn, 2.5	Sand cast at 1,150° C	43,800	38	72
Remainder	7	11		Tested room temperature	45,700	20	
				Tested at 315° C	35,800	15	
Do	7.5	5.5		Annealed and aged	124,000	8	265
Do	7.5	8		do	125,400	11	292
Do	10	5		do	100,000	22	197
Do	15	5		do	89,400	30	162
71	20	7	Zn, 2	Annealed	112,400	1.5	
72.7	20.1	6.2	Zn, 0.6; Mn, 0.3	Sand-cast	60,500	7	138
				Quenched from 760° C	58,300	12	129
69.8	29.1	1.0	Fe, 0.3	Cold-drawn	87,300	4	
60.6	29.7	7.4	Zn, 1.7; Fe, 0.1; Si, 0.5	Sand-cast	56,000	0.5	250
60	30	8	Fe, 2	do	67,200	0	241
40	50	10		Tested at room temperature	85,100	0.5	
				Tested at 480° C	60,500	1	
				Tested at 590° C	43,000	1	
32.6	53.8	12.7	Fe, 0.5; Al, 0.3	Cast, tested at room temperature	71,600	2	
				Tested at 427° C	67,200	2	

Hesse and Basil [284] found that the effect of nickel on the resistance of bronze to corrosion by sea water varied with test conditions. Their tests, in which they progressively replaced tin with nickel in a bronze containing 88 percent of copper, 9 percent of tin, and 3 percent of zinc, were conducted in the brackish water of the Severn River at Annapolis, Md. Fetz [115] found that the mechanical properties of a bronze containing 8 percent of tin and 7.5 percent of nickel did not appreciably deteriorate after a 1-mo exposure to moving sea water. He also found that attack by nitric acid increased with increasing nickel content, whereas attack by hydrochloric acid decreased.

(c) Aluminum Bronzes

Nickel in amounts up to about 5 percent is regarded as a beneficial alloying element in aluminum bronzes, particularly those containing iron [180]. The alloys are age-hardenable, and in the wrought form are used as condenser tube plates and in corrosion-resistant parts for marine service, such as shafting. Some typical uses for cast parts are as valve guides, valve seats in airplane engines, bearing plates under heavy loads, corrosion-resistant parts, gun mounts, and slides. The physical constants for a wrought commercial alloy [364] containing 82.5 percent of copper, 10 percent of aluminum, 5 percent of nickel, and 2.5 percent of iron are as follows:

Density	7.58 g/cm^3; 0.274 lb/in.^{3}
Melting range	1,035 to 1,055° C
Specific heat	0.104 cal/g at 20° C
Thermal conductivity	0.091 cal cm^{-1} sec^{-1} ° C^{-1} at 20° C
Electrical resistivity	22.9 microhm-cm at 20° C.

The mechanical properties of three aluminum bronzes are listed in table 42.

Table 42. *Mechanical properties of three aluminum bronzes [364, 365]*

Composition				Condition	Yield strength	Tensile strength	Elongation	Reduction of area	Brinell hardness number	Modulus of elasticity
Cu	Al	Ni	Fe							
Percent	*Percent*	*Percent*	*Percent*		*1,000 lb/in.^{2}*	*1,000 lb/in.^{2}*	*Percent*	*Percent*		*1,000 lb/in.^{2}*
82.5	10	5	2.5	Wrought	[a] 48 to 94	[a] 90 to 151	[a] 30 to 0.5	-------	---------	[b] 16,000
79	11	5	5	Sand-cast	45	95	7	7	195	17,000
79	11	5	5	Sand-cast; heat-treated	70	115	5	6	235	17,000

[a] Range for various combinations of cold work and heat treatment.
[b] Data for rod, cold reduced 11.5 percent.

II. Nickel-Chromium Alloys

Alloys discussed in this section include binary alloys of nickel and chromium, and complex nickel-chromium base alloys in which iron is present only as a minor constituent. These alloys, and some of the ferrous alloys discussed in previous sections of this report, are used principally for electrical, corrosion-resisting, and high-temperature service.

The binary diagram for the nickel-chromium system is shown in figure 46. The diagram is the one developed by Jenkins, Bucknall, Austin, and Mellor [163], but the phase designations have been altered to accord with modern practice. The broken lines in the high-chromium areas indicate that this portion of the diagram has not yet been determined with certainty. Additions of chromium lower the melting point slowly, as shown in the diagram, but lower the magnetic transformation of nickel rapidly. A chromium content of 5 to 7.5 percent is sufficient to lower the transformation temperature to 0° C, according to Hansen [135] and Marian [167].

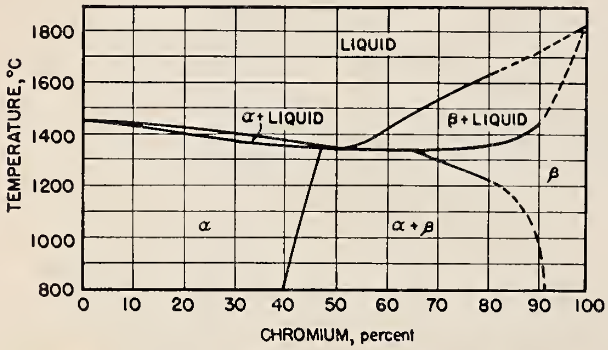

Figure 46. *Constitution of the nickel-chromium system.* (Jenkins, et al. [163]).

Melting points of the ternary Ni-Cr-Fe alloys, according to Pilling and Worthington [123], range from about 1,315° C up to 1,454° C in the nickel-rich corner and 1,538° C in the iron-rich corner. The chromium-rich areas of this ternary system, like the nickel-chromium binary system, have not been determined.

1. Electrical-Resistance Alloys

A wide variety of nickel-chromium and nickel-chromium-iron alloys are used as electrical resistance alloys. Two nominal compositions, 80 nickel—20 chromium (Chromel A, Nichrome V, Tophet A, and others) and 60 nickel—16 chromium—24 iron (Nichrome, Chromel C, Tophet C and others) are designated in American Society for Testing Materials Standards Specifications as

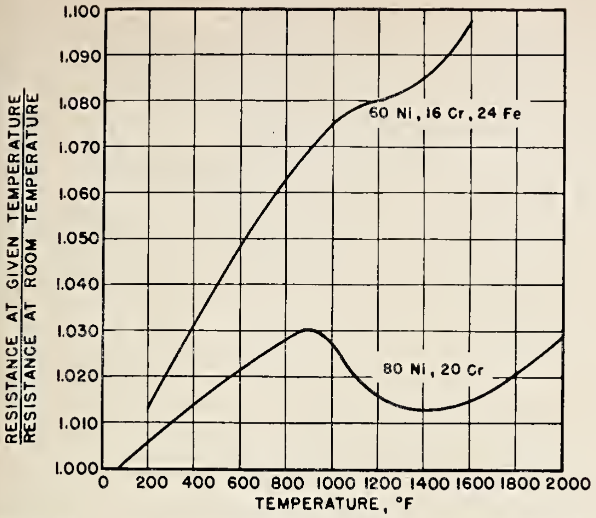

FIGURE 47. *Variation of resistance of nickel-chromium and nickel-chromium-iron alloys with temperature.* (ASTM [320a]).

B82–46 and B83–46, respectively, and form the bulk of materials used for heater elements. These two alloys have the advantage over ferrous and other nonferrous resistance alloys in that grain growth at operating temperatures is only slight. This factor enables these alloys to retain in operation at elevated temperatures, the desirable mechanical characteristics associated with small grain size. The effect of increasing temperatures on the resistance of these types of alloys according to the American Society for Testing Materials [320a] is shown in figure 47. Physical and mechanical properties of these alloys are shown in table 43. The standard method for performing life tests on electrical resisting material is covered by American Society for Testing Materials Standards, designation B76–39. Results of life tests of several varieties of Ni-Cr and Ni-Cr-Fe resistance alloys were reported by Nordstroem [122]; Mantell and Hardy [300] subsequently reported that the practice of adding calcium to these alloys materially improves their service life.

TABLE 43. *Physical and mechanical properties of nickel-chromium alloys* [*105, 121, 123, 256*]

Composition	Tensile strength	Yield strength	Elongation in 2 in.	Electrical resistivity	Resists oxidation	Specific heat (32 to 212° F)	Thermal conductivity (212 to 932° F)	Melting point	
Percent	*lb/in.*^{2}	*lb/in.*^{2}	*Percent*	*Ohm/mil-ft*	*Below ° F*	*Btu lb*$^{-1}$ *° F*$^{-1}$	*Btu in ft*$^{-2}$ *hr*$^{-1}$ *° F*$^{-1}$	*° F*	*° C*
80 Ni, 20 Cr	110,000	60,000	35	650	2,100	0.104	119	2,550	1,400
60 Ni, 16 Cr, 24 Fe	105,280	59,100	40	675	1,830	.107	112	2,552	1,400

The 80 nickel—20 chromium and the 60 nickel—16 chromium—24 iron alloys are outstanding in the field of electrical resistance alloys, but other compositions of nickel and chromium and nickel, chromium and iron find uses in this field. Similarly, the above two alloys also find uses in nonelectrical fields because of their resistance to corrosion at high temperatures.

2. Thermocouple Alloys

Nickel-chromium alloys containing 8 to 10 percent of chromium were reported by Chevenard [38] to have high positive thermoelectric power that was practically free from irregularities. Subsequent work by Hunter and Jones [255], with alloys containing up to 24 percent of chromium, confirmed Chevenard's observations and showed that the thermal electromotive force against platinum at 1,000° C was greatest for the 9- to 11-percent chromium alloys. Such observations have led to extensive use of the 10-percent chromium alloy, known as "Chromel" or "Chromel-P," as an element of a base metal couple, with the nickel-manganese-aluminum-silicon alloy known as "Alumel" as the other element.

The thermal electromotive force of Chromel-Alumel thermocouples at temperatures from −200 to +1,400° C are shown in table 44, as reported by Roeser, Dahl, and Gowens [125]. In an oxidizing atmosphere, Chromel-Alumel thermocouples may be used at temperatures up to 2,200° F or even 2,400° F, but the life at these maximum temperatures is short. In an alternately oxidizing and reducing atmosphere, however, the emf of this couple is subject to change. Chromel has also been paired with stainless steel, for particular applications, but this couple has not yet been standardized [395].

Table 44.—*Thermal electromotive force of chromel-alumel thermocouples with cold junction at 0° C*

Roeser, Dahl, and Gowens [125]

Temperature	emf	Temperature	emf
° C	*mv*	*° C*	*mv*
−200	−5.75	700	29.14
−100	−3.49	800	33.31
0	0	900	37.36
100	+4.10	1,000	41.31
200	8.13	1,100	45.14
300	12.21	1,200	48.85
400	16.39	1,300	52.41
500	20.64	1,400	55.81
600	24.90	-----	-----

Another nickel alloy, although not a nickel-chromium alloy, which finds use as a thermocouple element is constantan, which contains about 45 percent of nickel and 55 of copper. Iron-constantan couples have longer life and are more satisfactory than Chromel-Alumel in an alternately oxidizing and reducing atmosphere up to 1,800° F, but iron-constantan is not recommended for continuous use in oxidizing atmospheres at temperatures above about 1,400° F. The copper-constantan couple is good for continuous use at 700° F and for intermittent use at 1,000° F. Some values for the thermal emf of constantan with platinum, copper, and iron are given in table 45. Reference junctions are at 0° C, or 32° F.

Table 45. *Thermal electromotive force of constantan against platinum, copper, and iron*

Roeser and Dahl [193]

Temperature	emf of constantan against—			Temperature	emf of constantan against—		
	Platinum	Copper	Iron		Platinum	Copper	Iron
° C	*mv*	*mv*	*mv*	*° F*	*mv*	*mv*	*mv*
−200	+5.35	−5.539	−8.27	−300	+5.02	−5.283	−7.87
−150	+4.25	−4.602	−6.80	−200	+3.73	−4.110	−6.01
−100	+2.98	−3.349	−4.82	−100	+2.24	−2.560	−3.63
−50	+1.56	−1.807	−2.52				
0	0	0	0	0	+0.57	−0.671	−0.92
				100	−1.27	+1.516	+2.00
50	−1.69	+2.034	+2.66	200	−3.26	+3.966	+5.03
100	−3.51	+4.276	+5.40	300	−5.39	+6.644	+8.12
150	−5.44	+6.700	+8.19	400	−7.64	+9.521	+11.24
200	−7.45	+9.285	+10.99				
250	−9.55	+12.010	+13.79	500	−9.98	+12.571	+14.35
				600	−12.40	+15.769	+17.43
300	−11.71	+14.859	+16.56	700	−14.88	+19.091	+20.48
350	−13.93	+17.815	+19.32	800	−17.41	---------	+23.53
400	−16.19	+20.865	+22.07	900	−19.97	---------	+26.59
450	−18.48	---------	+24.82				
500	−20.79	---------	+27.58	1,000	−22.55	---------	+29.70
				1,100	−25.15	---------	+32.88
550	−23.12	---------	+30.39	1,200	−27.77	---------	+36.17
600	−25.47	---------	+33.27	1,300	−30.39	---------	+39.58
650	−27.83	---------	+36.24	1,400	−32.99	---------	+43.12
700	−30.18	---------	+39.30				
750	−32.53	---------	+42.48	1,500	−35.58	---------	+46.74
				1,600	−38.14	---------	+50.39
800	−34.86	---------	+45.72	1,700	−40.66	---------	+53.87
850	−37.17	---------	+49.00	1,800	−43.13	---------	+57.16
900	−39.45	---------	+52.29				
950	−41.70	---------	+55.25				
1,000	−43.92	---------	+58.22				

III. Corrosion-Resistant Nonferrous Alloys

Nonferrous alloys of nickel find extensive use because of their resistance to various corrosive media, as is also true for ferrous alloys of nickel. The three general classes of alloys considered in this section are nickel-chromium or nickel-chromium-iron alloys containing more than 50 percent of nickel and up to 20 percent of chromium, nickel-copper alloys containing more than 50 percent of nickel, and nickel-molybdenum alloys. Some data on corrosion-resistant ferrous and miscellaneous alloys are included, for comparison.

Strauss and Thum [343] tabulated the corrosion resistance of nickel and its alloys in various media. Their results for commercial nickel, Nichrome V, Inconel, Nichrome, and several stainless steels are presented in table 46.

According to Friend [375], the corrosion rate for nickel-chromium alloys is low in sulfuric acid at normal temperatures but may be severe in hot, strong solutions. Addition of small amounts of oxidizing salts to the acid decreases rate of corrosion of these alloys. Their use with hydrochloric acid is limited to dilute solutions and normal temperatures. Phosphoric acid may be handled at normal temperatures. Sulfurous acid is corrosive at all temperatures, but the low concentrations of sulfur dioxide used in food preservation cause negligible amounts of corrosion. The alloys are highly resistant to nitric acid at normal temperatures, but for hot nitric acid the iron-chromium and iron-chromium-nickel alloys are preferred. The nickel-chromium alloys resist all concentrations of ammonium hydroxide. They resist corrosion by caustic alkalies and alkaline solutions in most concentrations although concentrated sodium or potassium hydroxide is corrosive. They are resistant to rural, urban, marine, and industrial atmospheres; sulfurous industrial atmospheres produce some tarnishing but no significant attack. They are completely resistant to all the common gases when dry and at normal temperatures but are attacked by moist chlorine. Recently reported results [350] of a study of four alloys, to determine their suitability for use as thermocouple tubes for service at high temperatures, showed that all four resisted scaling in air up to 1,900° or 2,000° F; the 80 Ni—14 Cr—6 Fe alloy showed the best resistance to reducing and to alternately reducing and oxidizing atmospheres, followed in order by the 60–14–26 and 32–20–48 alloys; in sulfurous atmospheres the most suitable was the nickel-free 28 Cr—72 Fe alloy with the three Ni-Cr-Fe alloys not recommended for service under these conditions.

Table 46.—*Corrosion resistance of nickel and nickel-chromium alloys*

Strauss and Thum [343]

No.	Nominal composition				Atmospheric		Water							Fruit and vegetable juices	Dairy products	Other food products
	Ni	Cr	Fe	Others	Marine	Industrial	Domestic	Mine	Sea	Saline with H_2S	Brackish with chlorides	Wet steam				
	Percent	*Percent*	*Percent*	*Percent*												
1	99.2	----	----------	----------	E	G	E	FG	FE	FE	FE	E		G	-----	GE
2	80	20	----------	----------	E	G	E	G	FE	FE	FE	E		E	E	E
3	80	14	6	----------	E	G	E	G	FE	FE	FE	E		E	E	E
4	60	15	25	----------	E	G	E	G	FE	FE	FE	E		E	E	E
5	35	18	Balance	Si, 1	E	G	E	FG	PG	PG	PG	E		E	E	E
6	20	25	do	Si, 1.5	E	G	E	G	G	E	G	E		-----	E	-----
7	20	8	do	----------	G	G	G	FG	PG	F	FG	GE		G	FG	G
8	12	25	do	----------	E	G	E	G	G	PG	G	E		E	E	E
9	12	18	do	----------	E	G	E	FE	PG	PG	PG	E		E	E	E
10	12	18	do	Mo, 2.5	E	E	E	E	FE	FE	FE	E		E	E	E
11	8	18	do	----------	E	G	E	FE	FG	PG	FG	E		GE	E	E

No.	Acids 5 to 15% concentration					Alkalies		Salt solutions			Hot sulfite liquor	Dye liquor	Refinery crudes, below 400° F		Oxidation resistance to gas, maximum safe temperature, ° F		
	HCl	H_2SO_4	HNO_3	Acetic	Phosphoric	1 to 20%	Fused	NH_4Cl	$MgCl_2$	$MgSO_4$			Sweet	Sour	Oxidizing	Reducing	Sulfur-rich
1	FG	FG	P	FG	FG	E	E	G	G	G	P	G	E	GE	1,900	2,300	1,000
2	FG	FG	G	G	G	E	G	G	E	G	P	---	E	E	2,000	2,100	1,500
3	F	F	F	G	G	E	G	G	E	G	P	---	E	E	2,000	2,100	1,500
4	F	F	F	G	G	G	G	G	E	G	P	---	E	E	2,050	1,900	P
5	F	G	G	G	G	E	G	G	G	G	PG	---	E	E	2,100	2,000	1,900
6	P	F	E	G	G	E	FG	G	G	G	G	G	E	E	2,100	2,000	------------
7	P	FG	F	G	FG	E	G	FG	G	G	F	---	GE	GE	1,500	1,500	------------
8	P	P	E	E	E	E	G	G	[a] G	G	GE	G	E	E	2,100	2,000	------------
9	P	F	E	G	G	G	F	G	G	G	G	---	E	E	1,650	1,650	1,100
10	PF	G	E	E	E	E	F	GE	G	G	E	---	E	E	-----	-----	------------
11	P	PG	E	E	E	E	F	G	[a] G	G	GE	F	E	E	1,650	1,650	1,100

E = Excellent; almost unlimited service.
G = Good service.
F = Fair.
P = Poor.
[a] May crack under certain conditions.

Two nickel-chromium alloys that are particularly valued for corrosion resistance are Inconel, 77 percent of Ni, 15 Cr, 7 Fe, and Illium "G", 58 percent of Ni, 22 Cr, 6 Cu, 6 Mo, 6 Fe, 1 W. Inconel was first employed in the dairy industry to resist discoloration and corrosion by milk and cooling brines. Subsequently it has been used in many plants for processing wine, fruit juices, and vegetables [162]. Strauss and Thum's results for its resistance to several media are included in table 46, in which Inconel is item 3. According to Friend [375], Inconel resists progressive oxidation at temperatures below 2,000° F; it can be used safely up to about 1,500° F in oxidizing sulfurous atmospheres and to about 1,000° F in reducing sulfurous atmospheres. Inconel is resistant to aqueous hydrofluoric acid at normal temperatures [329], but nickel and Monel are more highly recommended for this reagent, particularly at temperatures above room temperature.

Illium "G" is virtually immune to corrosion in the atmosphere, fresh water, salt water, and neutral and alkaline salts. It is highly resistant to severely oxidizing conditions. It resists sulfuric and nitric acids over a wide range of concentrations and conditions and has limited applications in hydrochloric acid and acid chlorides. It is highly resistant to phosphoric acid and is resistant to sulfurous acid, mixtures of sulfurous and sulfuric acids, and to hydrogen sulfide. It is highly resistant to organic acids and to neutral and alkaline organic compounds. Illium is used for pump parts, agitators, piping, and for the construction of kettles, crystallizers, etc. in various chemical industries, and particularly in sulfuric acid plants [248, 375].

Nickel-copper alloys containing more than 50 percent of nickel are, in general, more resistant than nickel under reducing conditions and more resistant than copper under oxidizing conditions. They have excellent resistance to atmospheric exposure, except that sulfurous atmospheres produce superficial tarnishing, to natural waters of all kinds, to salt solutions, organic acids and compounds, and to most alkaline solutions, including concentrated caustic soda solutions at temperatures below the boiling point. The alloys are resistant but are not immune to attack by mineral acids including sulfurous acid and sulfites. Dry gases, including anhydrous ammonia, are not actively corrosive. and the alloys are resistant to chlorine up to about 850° F. However, in the presence of water the alloys are attacked by nitric oxide, chlorine and other halogens, sulfur dioxide, and ammonia. In reducing sulfur atmospheres the alloys are subject to intergranular attack at temperatures above 700° F [375]. Monel contains 67 percent of nickel and 30 of copper; the remainder is chiefly iron and manganese, as discussed in previous sections of this circular. It is primarily a corrosion-resistant alloy for handling acids, alkalies, brines, water, and food products, and is also resistant to dry and moist atmospheres [398]. It is malleable and ductile and is readily fabricated into desired shapes.

The Hastelloy alloys [215, 249, 333, 375] include Hastelloy A, 60 Ni, 20 Mo, 20 Fe; Hastelloy B, 65 Ni, 30 Mo, 5 Fe; Hastelloy C, 58 Ni, 17 Mo, 15 Cr, 5 W, 5 Fe; and Hastelloy D, 85 Ni, 8 to 11 Si, 3 Cu.

Hastelloy A is resistant to corrosion, to the extent that it is useful, in all concentrations of hydrochloric acid at room temperature and to unaerated solutions at temperatures below about 160° F, particularly in the absence of oxidizing salts. It is resistant to sulfuric acid in concentrations up to 50 percent at temperatures up to the boiling point and to higher concentrations at temperatures up to about 160° F. It is resistant to organic acids and their compounds; to acid chloride, sulfate, and phosphate salt solutions; to atmospheric oxidation and to oxidizing and reducing flue gases at temperatures below about 1,450° F. However, Hastelloy A is not recommended for service with nitric or other strongly oxidizing acids.

Hastelloy B is notable for its high resistance to all concentrations of hydrochloric acid at all temperatures up to the boiling points. Hastelloy B is more resistant than A, C, or D to boiling sulfuric acid up to about 60 percent, but is less resistant than D to boiling acid of higher concentrations. Alloy B resembles alloy A in its resistance to miscellaneous media and like alloy A is not recommended for service with strongly oxidizing acids.

Hastelloy C is unusually resistant to oxidizing solutions, especially to those containing chlorides. It is unique among alloys in its resistance to hypochlorite solutions and moist chlorine. It resists all concentrations of hydrochloric acid at room temperature and is somewhat superior to alloy A in resistance to sulfuric acid. It is one of the few metallic materials that has useful resistance to hypochlorites and other solutions containing free chlorine, below about 100° F. Hastelloy C is resistant to the same gases as alloy A and to somewhat higher temperatures, up to about 1,800° F.

The most important property of Hastelloy D is its resistance to concentrated solutions of sulfuric acid at elevated temperatures. It is resistant to many corrosive media but is only moderately resistant to hydrochloric acid and is not recommended for service with nitric or other strongly oxidizing acids. It cannot be cold-worked and is machined with difficulty.

IV. Heat-Resistant Nonferrous Alloys

The term heat-resistant, as used here, refers to those alloys that contain appreciable amounts of nickel and have useful mechanical properties at high temperatures. Alloys considered in this section include nickel-chromium, nickel-chromium-iron, nickel-molybdenum-iron, nickel-chromium-cobalt, and cobalt base alloys. Some are used as castings, others in wrought forms, and the range of high temperatures varies widely in the different applications, which include furnace construction, carburizing boxes, high-speed tools, and extremely high-temperature uses, as in gas turbine and jet engines. Some of these alloys are also noteworthy for their resistance to oxidation and to chemical corrosion, or for their electrical resistance, and, consequently, have been mentioned in preceding sections of this circular but are included here because of their mechanical properties at high temperatures. Some of these alloys are low-iron members of series discussed under the heading of Ferrous Heat-Resistant Alloys. The type compositions listed in table 47 were assembled chiefly from data published by Knight [333] and by the ASM Metals Handbook Subcommittees on Heat Resistant Castings [394] and Wrought Heat Resisting Alloys [396].

The designations HP, HT, HU, HW, and HX, assigned by the Alloy Casting Institute, refer to nickel-chromium-iron casting alloys that are resistant to combinations of heat and corrosive attack, and are useful as metallurgical retorts, furnace parts, quenching fixtures, etc. The high-temperature usefulness of these alloys, i. e., their resistance to thermal shock and to oxidizing, carburizing, and nitriding atmospheres, in general increases with increasing total nickel plus chromium content. The maximum temperatures at which these alloys can be used range up to about 2,100° F.

TABLE 47. *Nonferrous heat-resistant alloys* [*333, 394, 396*]

Designation	Composition					
	Ni	Cr	Co	Mo	Fe	Others
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Castings:						
HP	30	30			Remainder	
HT	36	15			do	
HU	39	19			do	
HW	61	12			do	
HX	67	17			do	
Hastelloy A	57			20	20	
Hastelloy C	58	15		17	5	W, 5
61; Stellite 23	2	23	Remainder		1	W, 5
6059; Stellite 27	32	23	do	6	1	
422–19; Stellite 30	16	23	do	6	1	
X–40; Stellite 31	10	23	do		1	W, 7
Cast or wrought:						
Hastelloy B	65			30	5	
S–816	20	20	43	4	Remainder	W, 4; Cb, 4
Vitallium; Stellite 21	2	27	Remainder	6	1	
Wrought:						
N–155	21	21	21	3	Remainder	W, 2; Cb, 1; N, 0.1
S–590	20	20	20	4	do	W, 4; Cb, 4
Inconel X	73	15			7	Cb, 1; Ti, 2.5; Al, 0.7
K–42–B (type 5)	42	18	22		13	Ti, 2.6; Al, 0.6
Refractaloy 26	37	18	20	3	17	Ti, 3; Al, 0.25

The Hastelloy alloys, A, B, and C, are well known for their corrosion resistance at normal and somewhat elevated temperatures; they find use as carburizing equipment, and as chain conveyors and other parts of heat-treating furnaces and equipment and are among the alloys investigated for service in engines at high temperatures. The alloys are age-hardening; results of short-time tensile and stress-rupture tests, after suitable heat treatments have been reported [394] as follows:

	Tensile strength, short time at—		Stress for rupture in 1,000 hr at 1,500° F
	1,500° F	1,950° F	
	lb/in.^{2}	*lb/in.*^{2}	*lb/in.*^{2}
Hastelloy A	41 to 52, 000		8, 800
Hastelloy B	55 to 61, 000		10, 700
Hastelloy C	50 to 61, 000	13 to 16, 000	10, 700

These high-temperature data for the Hastelloy alloys are presented as matters of interest; not as a basis for evaluating the relative merits of the alloys as engineering materials for jet engines or turbines or other super temperature applications. The field is so new and is changing so rapidly, and testing technique for high-temperature performance is not yet standardized, so that no attempt will be made here to compare the merits of different alloys for service at high temperatures.

Stellite alloys originally were cobalt base with 25 to 35 percent of chromium, with or without 6 to 20 percent of tungsten or molybdenum or both and were used for tool bits, hard-surfacing alloys, etc. A similar cobalt base alloy known as Vitallium was used for dental and surgical purposes. Modifications of these alloys, for example, by substitution of up to 30 percent or more of nickel for some of the cobalt and by control of the carbon content, were essentially World War II developments, the results of which are not yet fully available.

The modified Vitallium alloy (Stellite 21), listed in table 47, was used for highly stressed gas turbine blades in 1941. This application involved temperatures no higher than those at which Fe–Cr–Ni and Fe–Ni–Cr alloys are used, but did involve high stresses, and the modified Vitallium was superior to the older alloys in creep and stress-rupture properties. The wartime use of Vitallium (Stellite 21) was primarily for buckets of the GE type B turbosupercharger for operation at 1,500° F. Precision castings also were used for turbine blades in jet engines operating at 1,200° to 1,350° F and for blades for nozzle vanes for stationary gas turbines operating up to 1,800° F.

The cobalt-base alloys are hard to machine, even with cemented carbide tools, because they work-harden so readily. They are usually precision-cast and can be fabricated or assembled by welding, although the high-carbon types are somewhat difficult to weld. S–816 was developed as a wrought alloy but has since been used more in the cast form. Cast alloys have better stress-rupture and creep properties but not as good short-time, high-temperature properties as the forged or wrought alloys. In all of these cobalt-base alloys, the best high-temperature mechanical properties and resistance to creep are obtained by progressive aging at temperatures between 1,300° and

2,100° F. Available data, including results of short-time tensile tests, stress-rupture, and creep tests for these cobalt-base alloys were reported by the American Society for Testing Materials Subcommittee on Heat Resistant Castings [394], the creep data being reported as experimental values not for design use. Selected values from the Subcommittee's data are given in table 48.

Table 48. *High-temperature properties of heat-treated cast cobalt-base alloys*

Subcommittee on Heat-Resistant Castings [394]

Alloy	Tensile strength, short time at—		Stress for rupture in 1,000 hours at—		Endurance strength for 10^8 cycles at—	
	1,500° F	1,800° F	1,500° F	1,800° F	Room temperature	1,500° F
	lb/in.^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}
Stellite 21; Vitallium	59,000	33,000	14,200	7,000	35 to 40,000	33,000
Stellite 23; 61	58,500	33,000	21,800	5,400	------------	38,000
Stellite 27; 6059	51,200	33,700	18,400	6,800	36,000	31,000
Stellite 30; 422–19	64,000	37,800	21.700	7,100	------------	--------
Stellite 31; X–40	59,600	--------	23,400	9,800	------------	--------
S–816	71,000	--------	21,000	7,800	------------	33,000

The wrought alloys that contain about 20 percent of cobalt, alloys N-155, S-590, K–42–B (type 5), and Refractaloy 26 in table 47, are included in the "superstrength" wrought heat-resistant alloys discussed by the American Society for Metals Subcommittee on Wrought Heat Resisting Alloys [396]. According to the Subcommittee, the superstrength wrought heat-resistant alloys as a class include those which contain 18 percent or more of chromium with enough nickel to make them austenitic; additions of cobalt are necessary for the best strengths at high temperatures, and additions of tungsten, molybdenum, and columbium improve the strength at high temperatures. Wartime and manufacturer's test data show that fabrication procedures and heat treatment may be at least as important as composition in determining the properties of these wrought alloys. Above about 1,350° F cast alloys have higher rupture strength than forged alloys, which is another way of saying that alloys that can be forged or wrought are not as resistant to deformation as the alloys that cannot be forged or wrought at the specified temperatures. The wrought heat-resistant alloys are more difficult to machine and to weld than either the ferritic or 18:8 steels.

K–42–B and Refractaloy 26, both precipitation hardening alloys, are classed among the strongest of the group at 1,350° F and under high stresses at 1,500° F. Under low stresses at 1,500° F, they enter the third stage of creep relatively early in a creep test. Data compiled by the Subcommittee [396] are in general confined to temperatures below 1,500° F and are complicated by the effects of prior thermal and mechanical history. Some results for alloys N-155, S-590, and K–42–B are recorded in table 49.

Table 49. *Stress-rupture, creep, and endurance values for alloys N–155, S–590, and K–42–B*

Subcommittee on Wrought Heat Resisting Alloys [396]

	Stress for rupture in 1,000 hours at—		Stress at 1,500° F for creep rates of—		Endurance strength, 10^8 cycles at—		
	1,500° F	1,800° F	0.0001% per hr	0.00001% per hr	1,200° F	1,350° F	1,500° F
	lb/in.^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}
N–155, low carbon; annealed; aged	--------	2,800	9,000	6,500	66,000	--------	33,000
S–590, water-quenched; aged	14,000	3,500	11,000	9,000	--------	--------	--------
K–42–B, aged	--------	-------	--------	-------	54,000	48,000	--------

Inconel X is an age-hardening modification for high-temperature service, in which the composition shown in table 47 is substituted for that of conventional Inconel. The first of the modified age-hardening alloys was Inconel W, which contained 75 percent of nickel and did not contain columbium. The W alloy was used for airplane exhaust manifolds, high-temperature springs, and for combustion chambers and tail pipes on jet engines. For most or all of its uses, Inconel W has been supplanted by Inconel X. A recent modification is Inconel B, which has about 2 percent more chromium and 2 percent less nickel than regular Inconel and offers improved resistance to oxidation and strength at high temperatures [386].

Aged Inconel X has a tensile strength of about 184,000 lb/in.^{2} at room temperature and retains appreciable proportions of this strength at temperatures up to about 1,000° F. Stress-rupture data reported by Crawford [326] showed that the stress for rupture of Inconel X in 1,000 hr was 69,000 lb/in.^{2} at 1,200° F, 42,000 lb/in.^{2} at 1,350° F, and 18,000 lb/in.^{2} at 1,500° F. These results, together with data for standard Inconel reported by Rolle [169], and by Betty and co-workers [306, 307] show that both the standard and X modifications have useful high-temperature properties, including resistance to oxidation, but, as is also true of other wrought alloys, they are not equal to some of the cast alloys for service at extremely high temperatures.

V. Miscellaneous Nonferrous Alloys

The nonferrous alloys of nickel discussed in previous sections of this Circular account for most of the tonnage of nickel that is consumed in nonferrous alloys. However, there are a number of alloys that have interesting and unusual properties and, in some instances, commercial importance out of proportion to the total amounts of nickel required for their production. Some of these alloys are discussed briefly in this section.

1. Aluminum-Copper-Nickel; Aluminum-Silicon-Copper-Nickel

Alloys combining light weight, strength, and corrosion resistance are in demand for structural uses; particularly in the fields of aviation and transportation in general. Aluminum is usually the base metal for these alloys with small amounts of nickel and other elements added to improve the mechanical properties. Commercial alloys of magnesium usually contain only negligible amounts of nickel, less than 0.1 percent. Jones and Wolfe [187] reported that about 1 percent of nickel improved the mechanical properties of a magnesium–1.5-percent copper alloy, but the presence of nickel in any amount is generally considered to be detrimental to the resistance of magnesium to corrosion in salt water [253].

The first of these aluminum-base alloys to achieve popularity was the Y alloy developed at the National Physical Laboratory in England to meet World War I demands for a strong, light alloy for aircraft engine pistons, cylinder heads, etc. The type composition of Y alloy and of several of the alloys subsequently developed in this country and in Europe are shown in table 50.

TABLE 50. *Trade names and compositions of some aluminum-base alloys containing nickel [108, 143, 317, 318, 339]*

Alloy	Composition					
	Cu	Ni	Mg	Fe	Si	Others
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Alcoa 142	4.0	2.0	1.5	---	---	---
Avial	3.0	1.0	.75	---	.5	Cr, 1.0
Birmasil special.	.1	3.0	--	.6	12.0	Mn, 0.5
Bohnalite Y	4.0	2.0	1.5	1.0	.4	---
Ceralumin C	2.5	1.5	.8	1.2	1.2	Ce, 0.15
Huron A-5	6.6	1.25	.5	---	---	Co, 0.25; Cd, 0.5
Hyb-lum	--	--	--	---	---	Ni+Cr=2.0
Lo-Ex	.9	2.0	1.0	---	14.0	---
Magnalite	2.5	1.5	1.3	---	---	Zn, 0.5
Magnalium	1.76	1.16	1.6	---	---	---
Major Metal	3.0	.4	--	2.0	---	Zn, 0.4
P-2	4.0	2.0	.5	3.0	5.0	Mn, 0.5
Reynolds 18S	4.0	2.0	.5	---	---	---
Reynolds 32S	.9	.9	1.0	---	12.5	---
Romanium	.25	1.75	--	---	---	Sn, 0.15; W, 0.17
RR 50	1.3	.9	.1	1.2	2.25	Ti, 0.18
RR 53	2.2	1.3	1.5	1.2	1.25	Ti, 0.07
RR 56	2.0	1.3	.8	1.2	.6	Ti, 0.07
RR 59	2.2	1.3	1.5	1.2	.85	Ti, 0.07
Y alloy	4.0	2.0	1.5	.6	.6	---

Most of these alloys can be age-hardened by the usual procedure of a solution heat treatment, followed by quenching and aging. For some chill-cast alloys, only the aging treatment is needed; the rapid cooling of the metal from the molten state, in the chill molds, takes the place of the solution heat-treatment and subsequent quench that are required for the wrought alloys. Some of these alloys, the Y alloy for example, can be aged at room temperature, but aging is completed more rapidly at temperatures in the range of 100° to 200° C. The tensile strengths of the various alloys range from about 20,000 to about 70,000 lb/in.^{2} for both wrought and cast material, depending upon the composition, section, thermal, and mechanical treatment. The corresponding yield strengths range from 15,000 to 50,000 lb/in.^{2} [164, 278, 318, 363, 383]. Details of the properties and behavior of these alloys will be found in books and publications on aluminum alloys.

2. Antimony-Nickel

Nickel, in amounts from 0.7 to 1.5 percent, combines with antimony to form a compound that acts as the hardening agent in lead-base bearing metals [160].

3. Cadmium-Nickel

Cadmium containing about 1.3 percent of nickel is used as a bearing metal under conditions of heavy loading and high temperatures. The structure consist of particles of a hard cadmium-nickel compound in a matrix of softer cadmium-nickel eutectic. The coefficient of friction of this alloy is nearly the same as that of the tin-base bearing metals; the tensile and compressive strengths, and the melting point of the cadmium-nickel alloy are higher, and it is easily bonded to the steel backs of the bearings [124, 196].

4. Copper-Aluminum-Nickel

An alloy containing 92-percent copper, 4 aluminum, and 4 nickel was recommended [113] for condenser and heat-exchanger tubes and for some structural applications.

5. Copper-Manganese-Nickel

The Manganin-type alloys contain 9 to 12 percent of manganese, 3 to 4 nickel, balance copper, and have low thermoelectromotive forces against copper, low-temperature coefficients of resistivity between 0.00002 and 0.000005 per ° C at 25° C, and a specific resistance of 290 ohms per circular mil foot. The alloys are used in electrical shunts, multipliers and coils, and in Wheatstone bridges and other precision instruments.

An age-hardening alloy with 60 percent of copper, 20 manganese, and 20 nickel has a fatigue strength of 60,000 lb/in.^{2} for 10^8 cycles and high hardness, and has been recommended as a spring material [296].

6. Copper-Cobalt-Nickel

Cunico is a permanent magnet material containing 50 percent of copper, 29 cobalt, and 21 nickel. It is ductile and malleable and is produced as castings, strip, rod, and wire. Typical magnetic values are maximum magnetizing force (H max) 3,200 oersteds, maximum magnetic flux density (B max) 8,000 gausses, residual magnetism (Br) 3,400 gausses, corrosive force (Hc) 710 oersteds, and maximum external energy (BdHd) maximum 850,000 [340, 389a].

7. Copper-Nickel-Tungsten

Contact points containing these three metals have been prepared by powder metallurgy technique [303].

8. Gold-Nickel

Nickel exerts a strong bleaching or whitening action on the color of gold, the optimum whitening action being obtained with nickel contents between about 20 and 23 percent. The 23-percent alloy has the appearance of platinum. Above 23 or below 20 percent of nickel the alloys are yellowish. To obtain optimum whiteness the alloys should be quenched from 800° to 850° C, as yellowish tints may develop on slow cooling or on aging at slightly elevated temperatures [46, 93].

Most of the white gold currently used in jewelry and dentistry consists of 10-, 12-, 14- and some 18-karat gold containing copper and zinc as well as nickel [399]. According to Jarrett [233], nickel improves the corrosion resistance, hardness, strength, and yield point of the 10- and 14-karat alloys. In the 10-karat gold-copper-nickel alloy, whiteness was obtained with 23.85 percent of nickel. With higher gold contents, zinc or silver was required, in addition to nickel, to produce freedom from pink tints.

9. Manganese-Copper-Nickel

Alloys containing more than 50 percent of manganese, with the remainder copper and nickel are used in the electrical industry for variable and fixed resistors [283].

An alloy containing 72 percent of manganese, 18 of copper, and 10 of nickel is commercially employed as the high-expansion member of bimetal strip. It has an expansion coefficient of 27.5×10^{-6} per °C, electrical resistivity of about 175 microhm-cm, and can be used at temperatures up to about 200° C [296].

10. Nickel-Barium

According to Randolph [103], the resistance of nickel to hot corrosive gases and to tarnish in ordinary atmospheres is increased by the addition of 0.20 percent of barium. Alloys containing about 0.10 percent of barium are used as base metal for oxide coated cathodes in radio tubes [70].

Nickel containing a few hundredths of 1 percent of barium is used for the electrodes in certain types of spark plugs, because of the high thermionic emission of these alloys at 1,100° C.

11. Nickel-Beryllium; Nickel-Beryllium-Titanium

Nickel containing 1.7 to 2.0 percent of beryllium can be worked and heat-treated to obtain a yield strength of 210,000 lb./in.^{2}, ultimate tensile strength of 260,000 lb/in.^{2}, and Brinell hardness number of 460, coupled with a high degree of toughness. Additions of chromium and iron increase the stability of the alloy. It is used in Europe, for mainsprings in watches, for springs to be used at temperatures up to about 500° C, for diaphragms, and injector needles, but it is little used in the United States [148, 354].

Nickel containing 2 percent of beryllium and 1 percent of titanium has been used for injector needles, pump valves, and ball bearings [335].

12. Nickel-Cobalt

Sokov [194] reported that nickel-cobalt alloys containing 20 to 30 percent of cobalt could be prepared by electrodeposition, had a silver-white appearance, were harder, and had better corrosion resistance than nickel alone.

A cobalt-nickel alloy, containing about 80 percent of cobalt, was developed during World War II by the Brush Development Co., for magnetic recording. It is electroplated on nonmagnetic metals, such as brass or bronze, in the form of tapes, disks, and cylinders. The usual thickness of the plated layer is about 0.0003 in.; the plated alloy has a retentivity of about 10,000 gausses and a coercivity of about 200 oersteds [358].

13. Nickel-Cobalt-Iron-Titanium

The alloy called "Konal" contains 73 percent of nickel, 17 of cobalt, 7.5 of iron, and 2.5 of titanium and is used to replace iridium-platinum filaments in some vacuum tubes [209].

14. Nickel-Copper-Aluminum

Additions of small amounts of aluminum to nickel-copper alloys make them age-hardenable. An example of this type of alloy, discussed in previous sections of this report, is "K" Monel, which contains 2.75 percent of aluminum.

15. Nickel-Manganese

"D" nickel and "E" nickel are really nickel-manganese alloys containing, respectively, 4.5 and 2.0 percent of manganese. They are malleable and ductile; the manganese improves the resistance to attack by sulfur compounds at elevated temperatures in both oxidizing and reducing atmospheres [382].

16. Nickel-Molybdenum

A heat-treatable cast alloy, recommended for resistance to chlorides, hydrochloric acid, and a number of reagents, contains 63 percent of nickel, 32 of molybdenum, with small amounts of iron, silicon, and manganese. A chromium bearing variation of this composition is preferred for some types of corrosion service [328].

Alloys of nickel and molybdenum are used in radio tubes, and similar alloys, prepared by powder metallurgy processes, have been used as thermocouples with nickel [303].

17. Nickel-Tantalum

A nickel-tantalum alloy containing 30 percent of tantalum, prepared by powder metallurgy processes, is nonmagnetic, hard but easily worked, and can be drawn into wire. An advantage over metallic tantalum is that this alloy can be heated to a high temperature in a moist atmosphere without being oxidized [17].

A German patent was obtained on carbon-free alloys of nickel with 5 to 49 percent of tantalum, with or without other elements. The alloys are claimed to be hardenable, resistant to deformation, and useful for surgical instruments [217].

18. Nickel-Thorium

Alloys of 65 percent of nickel, 30 of copper, 5 of thorium; 70 of nickel, 20 of iron, 10 of thorium; and 77 of nickel, 19 of chromium, 4 of thorium were claimed by Guertler [100, 134] to be mechanically strong and resistant to chemical attack.

19. Nickel-Tin

Copson and Wesley [277] found thin nickel-tin coatings to be a useful substitute for somewhat thicker coatings of tin on food container cans. The sheet steel was electroplated first with nickel, then with tin to total thicknesses of 0.00002 or 0.00006 in. After plating, the assembly was heated to form the compound Ni_3Sn_4 at the interface. The corrosion resistance was compared with that of straight tin 0.000074 in. thick.

20. Nickel-Tungsten

Fink and Jones [71] reported that alloys of about 50 percent of nickel and 50 percent of tungsten could be prepared by electrodeposition and were resistant to the action of acids and alkalies. Vaaler and Holt [344] electrodeposited alloys containing 10 to 35 percent of tungsten, depending upon the conditions of electrolysis.

Nickel-tungsten thermocouple elements, prepared by powder metallurgy processes, have been used in conjunction with nickel elements at temperatures up to 1,400° C in hydrogen atmospheres [303].

21. Nickel-Zinc

Corronizing is a process whereby nickel and zinc are successively electroplated on other metals. The assembly is then heated until the zinc combines with part of the underlying nickel. The nickel-zinc alloy affords protection against SO_2 and SO_3 in combination with moisture and heat, and is resistant to salt spray and to brine [325, 332].

22. Platinum-Nickel

Platinum containing about 1 percent of nickel is used for spinnerettes through which glass is drawn at high temperatures [400].

23. Rhodium-Nickel

Alloys containing 25 to 80 percent of rhodium and the remainder nickel, with or without other elements, have been proposed for use as pen nibs, reflectors, electrodes, in chemical and dental applications, and for other purposes [142].

24. Silver-Nickel

Alloys of silver and nickel are used in some circuit breaker applications [283]. Contact points have been made from powdered silver and nickel by powder metallurgy techniques [303, 311].

25. Tungsten-Nickel-Copper

Tungsten base alloys with nickel and copper are prepared by powder metallurgy processes and are called "Heavy Alloys". These alloys have been used as electrical contacts for high-current densities, as containers for radium, in X-ray work, and as counterweights in high-speed motors. The alloys are machinable in spite of hardnesses up to 300 Brinell. Densities range up to 17 g/cm^3 or more; tensile strengths approximate 80,000 lb/in.^{2} One of the best compositions is 90 percent of tungsten, 7.5 of nickel, and 2.5 of copper [266, 303, 334].

Part 4

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