DEPARTMENT OF COMMERCE

# CIRCULAR
OF THE
# BUREAU OF STANDARDS

GEORGE K. BURGESS, DIRECTOR

## No. 58

# INVAR AND RELATED NICKEL STEELS

[2d Edition]
June 22, 1923

PRICE, 30 CENTS
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## ABSTRACT.

This circular is mainly a compilation of data obtained during the last 30 years by various investigators on the different properties of nickel steels. Particular attention is given to "invar," a nickel-iron alloy containing about 36 per cent nickel and possessing an extremely small thermal expansivity at ordinary temperatures. The results of investigations made on the various physical properties of nickel steels or pure nickel-iron alloys are presented largely in diagrammatic and tabular form.

The nature of the anomalies in behavior met with in these steels and characterized by their irreversible and reversible phenomena is discussed in the light of the results obtained on their various physical properties. In particular, the anomalous behavior in the thermal expansivity of different nickel-iron alloys at various temperatures is illustrated by a number of diagrams, and the rule of corresponding states formulated by Guillaume has been applied in interpreting some of the results. The theories advanced as an explanation for this anomalous behavior are briefly dealt with. The anomalies in the elastic modulus of nickel steels, of practical importance in the horological industry, and also the constancy in dimensions of invar are discussed. Attention is called to "Elinvar," a recently introduced nickel steel containing 36 per cent nickel and 12 per cent chromium, or its equivalent, and possessing an invariable modulus of elasticity over a large temperature range as well as a low thermal expansivity.

A list of manufacturers of nickel steels and dealers in nickel steels of minimum thermal expansivity and a selected bibliography are appended.

## CONTENTS.

## I. HISTORICAL AND INTRODUCTORY.

The bureau proposes to issue from time to time, as there may be demand for them, circulars of information concerning some of the more interesting and important classes of metals and alloys.

This circular, which is a revision of the original edition published in 1916 and is issued in response to many requests received by the bureau for information concerning invar, describes some of the most important properties of nickel steels, in general, but with particular reference to that alloy, which owes its name to its extremely small thermal expansion at ordinary temperatures. The circular is largely a compilation of results obtained during the last 30 years by various investigators, from the writings of whom figures, tables, and text have been freely taken.

Ferronickels were first made commercially in France in 1885, although our knowledge of them goes back to a publication by Stodart and Faraday in 1822.

In 1889 James Riley, of Glasgow, described before the Iron and Steel Institute his epoch-making investigation which disclosed the remarkable mechanical properties of nickel steels. His tests were made on a series of alloys containing various amounts of nickel up to 49 per cent which had been prepared for him in France by the inventor, Marbeau. At the conclusion of Riley's lecture J. F. Hall, of Sheffield, announced that he, too, had for some time been experimenting with nickel steels; and he supplemented Riley's statements by describing the superior qualities which these steels had exhibited when made into various articles that were subjected to severe treatment.

Later in the same year Hopkinson (45)[1] discovered that a sample of 25 per cent nickel steel furnished to him by Riley was practically nonmagnetizable at ordinary temperatures, the permeability being only about 1.4 and the induction proportional to the magnetizing force. It retained its nonmagnetic condition while being heated up to 700 or 800° C., and it did not recalesce on cooling from a high temperature. But when the temperature was reduced to a little below 0° C., ferromagnetic properties appeared, which were strongly intensified by further cooling. Moreover, cooling to below $-50°$ C. with solid carbon dioxide effected such a transformation that, when the specimen was returned to 13° C., it was found changed from a nonmagnetizable to a decidedly magnetizable substance, and it remained magnetizable on heating until 580° C. was reached. In the neighborhood of this temperature it again became nonmagnetizable and continued so

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[1] The figures given in parentheses here and throughout the text relate to the reference numbers in the Selected Bibliography given at the end of this circular. Where there is for the same reference number more than one volume reference or page reference for the same volume given in the bibliography, the volume or page number under consideration is added following the reference number.

on cooling to the temperature of the room. By these experiments Hopkinson showed that the material can, at ordinary temperatures, exist in either of two quite different states, both of which are stable. In passing he pointed out that the same kind of thing can be seen in a much less degree at a higher temperature with ordinary steel.

Early in the following year (1890) Hopkinson described the results of further experiments on wire of the same material. Among other things he showed that the heat treatment which caused such remarkable changes in permeability produced corresponding changes in the electrical resistance and in the elastic properties. For example, changing from the nonmagnetizable to the magnetizable condition changed the electrical resistivity at room temperature from 72 to 52 microhm-cm[2] and the ultimate tensile strength from 50 tons weight per square inch with 32 per cent elongation to 87 tons weight per square inch with 7.5 per cent elongation. A few months later Hopkinson brought out still another paper, in which he described the magnetic properties of a graded series of steels containing from 1 to 73 per cent nickel; and in June of the following year (1891) he pointed out that the transformations of the 22 per cent and the 25 per cent alloys from the nonmagnetizable to the magnetizable state by cooling to −100° C. were accompanied by such increases in volume that the densities on return to room temperature were found lowered by about 2 per cent.

Systematic studies of the methods of manufacture of nickel steels and nickel-chrome steel, suitable for military purposes—armor plate, cannon, etc.—were carried out on an extensive scale by the metallurgical plants of Europe and America during the decade 1890 to 1900. The metallurgists and engineers associated with certain works, notably those of Hadfield in Sheffield and the French firms of Saint-Etienne and Commentry-Fourchambault d'Imphy, made a series of elaborate investigations of the properties of nickel steels, including many combinations of nickel with iron; the effects of carbon, manganese, and other elements; and the changes due to heat treatments. These studies are set forth at length in the papers of A. Abraham (1) and particularly in that of A. Dumas (16).

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[2] A resistivity of 1 microhm-cm means that a rod having a cross-sectional area of 1 $\text{cm}^2$ will have a resistance of 1 microhm per centimeter of its length. The designation "microhm-cm" is now replacing the familiar "microhms per $\text{cm}^3$."

To Dumas, working at the Commentry-Fourchambault d'Imphy, we owe more than to anyone else for his most thorough and complete metallurgical contribution to our knowledge of nickel steels, thus furnishing a fundamental basis whereby the successful development of the nonexpansible alloys as invar, etc., was realized. He showed, among other things, that pure ferronickels—that is, those containing little or no carbon—were of very different properties from the nickel steels, and that it was not practicable to manufacture without adding manganese, which element, in proportions 0.30 to 0.70 per cent, appears necessary to obtain a forgeable material which may be made in either the open-hearth, crucible, or electric furnace. He also noted that, in general, nickel gives a fibrous texture to steel, increases its tenacity, ductility, and resistance to shock and to oxidation, and to a less degree improves its hardness.

Osmond (54), in a series of contemporaneous investigations on the interrelations between the composition, thermal treatment, metallography, and physical properties, was able to give the first clear rational explanation of the latter in terms of the transformations in the nickel steels. This has permitted a ready classification of the nickel steels, which will be mentioned later.

During 1895 Benoît, then director of the International Bureau of Weights and Measures, in the course of calibrating a length standard of steel containing some 22 per cent nickel and 3 per cent chromium, discovered that the linear coefficient of thermal expansion at ordinary temperatures was more than $18 \times 10^{-6}$ per degree centigrade, or about as great as that of average bronze; that is to say, considerably greater than that of either iron or nickel. Somewhat over a year later Guillaume (23) found the expansion of a bar of 30 per cent nickel steel to be about one-third less than that of platinum, which has a coefficient of only $9 \times 10^{-6}$. In the hope of obtaining alloys of very small expansivity by increasing the proportion of nickel, Guillaume, with the cooperation of the Société de Commentry-Fourchambault, carried out an elaborate study of nickel steels of varied composition. This resulted in the discovery of alloys having coefficients of linear expansion at ordinary temperatures ranging from a small negative value (about $-0.5 \times 10^{-6}$) to a rather large positive value (about $20 \times 10^{-6}$). The dimensions of the alloy containing about 36 per cent nickel along with small amounts of manganese, silicon, and chromium, in all about 1 per cent, were found to remain almost invariable with ordinary atmospheric changes of temperature. For this reason Guillaume, at the suggestion of Professor Thury, named it "Invar."

Improvements have since and steadily been made, chiefly through the efforts of Guillaume, in the constancy and degree of minimum expansivity of invar by means of thermal or mechanical treatment and by the regulation of chemical composition. The production of kilometer lengths of invar wire whose expansion with temperature can be detected only by most precise measurements has been made possible by a method of heat treatment developed and elaborated by Guillaume. Extensive studies have been made by Guillaume and Chevenard on the influence of additions as chromium, manganese, carbon, etc., upon the expansivity and elasticity of the iron-nickel alloys. The former found that the cause of instability in the dimensions of the alloys was due entirely to carbon.

In connection with these studies Guillaume developed the "rule of corresponding states," whereby he was able, through the analogy found to exist between the anomalies of expansivity and elasticity, to predict and realize certain desired properties for the alloy by suitable control of the composition and by proper treatment. A notable instance of this may be found in the case of "elinvar," an alloy of similar composition as that of invar but with the addition of 12 per cent chromium or its equivalent. This new alloy possesses a quite invariable modulus of elasticity over a considerable range of temperature as well as a low thermal expansivity and should prove of considerable value in the horological and possibly the spring scale industry.

Referring to the inclusion of chromium in iron-nickel alloys, attention may be drawn to "Baros," an alloy containing 90 per cent nickel and 10 per cent chromium, which has been reported by Chevenard (10, vol. 14) as being well adapted for a standard length bar in a dilatometer for the study of iron alloys, since it meets very nearly fully the exacting qualities required for such a standard bar. This alloy possesses no thermal anomaly, for as much as about 10 per cent chromium lowers the transformation point of nickel to a temperature as low as about −175° C. It has a markedly high resistance to mechanical deformation, a mean specific heat nearly the same as that of steel, only a slight tendency to oxidation when heated in the air to high temperatures, a nearly exactly reversible expansion, and an average expansivity little different from that of the iron alloys under test. It was observed that no appreciable change in the initial expansivity of the Baros alloy occurred after a hundred cycles of heatings and coolings between the temperature limits 15 and 900° C. Some attention was given by Dumas (16) to nickel-chromium alloys.

The alloy containing 46 per cent nickel and 0.15 per cent carbon, which was found to have nearly the same expansivity as the glass of incandescent electric-light bulbs, and has consequently been used to replace platinum for the sealed-in wires, was called "Platinite."

As Hopkinson had previously found from measurements of magnetic induction, so Guillaume found from measurements of thermal expansion that nickel steels do not follow the usual law of mixtures, but present marked anomalies.

These discoveries of Riley, Hopkinson, Dumas, Osmond, and Guillaume formed the starting point of many important investigations which have resulted not only in accumulating much data on the properties of nickel steels, but also in developing theories for explaining their peculiarities.

## II. REVERSIBLE AND IRREVERSIBLE NICKEL STEELS.

In endeavoring to form an image of what anomalies—thermal, magnetic, electrical, and mechanical—may be expected to exist in nickel steels of various compositions, the characteristics and transformations of pure iron and of medium carbon steels should be kept in mind.

Iron has two thermal transformations—one of considerable magnitude, $A_3$, and a relatively minute one, $A_2$—each accompanied by more or less abrupt changes in some physical properties. The addition of carbon adds a third transformation, $A_1$, and lowers the position of $A_3$ progressively until $A_2$ is reached for about 0.4 per cent carbon, leaving $A_2$ unaltered. With further additions of carbon, $A_3$ becomes identical with $A_1$ at about 0.85 per cent carbon at 695° C. on cooling. In pure iron the transformation on heating, $Ac_3$, is located at 910° C., and on cooling, $Ar_3$, at 898° C., while $Ar_2 = Ac_2$ is located at the constant temperature 768° C. $A_2$ may be called a reversible transformation and $A_3$ an irreversible one. The transformation $A_2$ is associated with the final loss of ferromagnetism on heating and its gain on cooling. Also, the electrical resistance increases very rapidly as $A_2$ is approached, and the resistance-temperature curve has an inflexion at $A_2$.

With $A_3$ is associated a marked change in electrical resistance extending over an interval of about 25°, accompanied by even a drop in resistance with rising temperature if equilibrium is maintained. This is accompanied by marked crystallographic changes and abrupt changes of mechanical properties as well as of volume. The transformation due to carbon, $A_1$, takes place at a temperature some 25° or more higher on heating than on cooling, when it usually occurs at about 695° C., the exact temperature, as well as the range $Ac_1 - Ar_1$, depending on the other elements present and on the rate of heating or cooling.

Certain elements, such as manganese and nickel, are capable of exerting pronounced effects in modifying, retarding, extending, or even suppressing some of the above transformations with corresponding modifications of the physical properties of the material. The properties of such a complex alloy as invar will therefore be found dependent upon its previous history, and especially upon the degree of completeness with which physico-chemical equilibrium has been attained for the temperature at which the alloy is investigated.

### 1. EQUILIBRIUM DIAGRAM.

In Figure 1 is shown the equilibrium diagram of the pure iron-nickel series of alloys according to Guertler and Tammann (22) as determined thermally, slightly modified, as suggested by Tammann, by taking into account the $\delta$ modification of iron above 1,420° as determined by Curie and by Ruer and Schüz (65). It is seen that below 1,420° there are four series of solid solutions, as shown in the figure, and a considerable region, below 25 per cent nickel, consisting of a heterogeneous mixture. The regions shown as dotted are uncertain. The two metals, iron and nickel, are capable of being melted in all proportions into a homogeneous solid solution of $\gamma$ iron and $\beta$ nickel. The nickel is seen to lower greatly the $A_3$ point of pure iron until in the region of the composition corresponding to invar, or from 25 per cent nickel, this transformation has been brought down to ordinary room temperatures.

The diagram applies only, of course, to the pure iron-nickel series and on the assumption that the heat changes are slow enough for the reactions to complete themselves or for the establishment of equilibrium. It is interesting to compare Figure 1, showing the thermal changes, with Figure 12, the diagram of magnetic transformation. It is seen that they are clearly

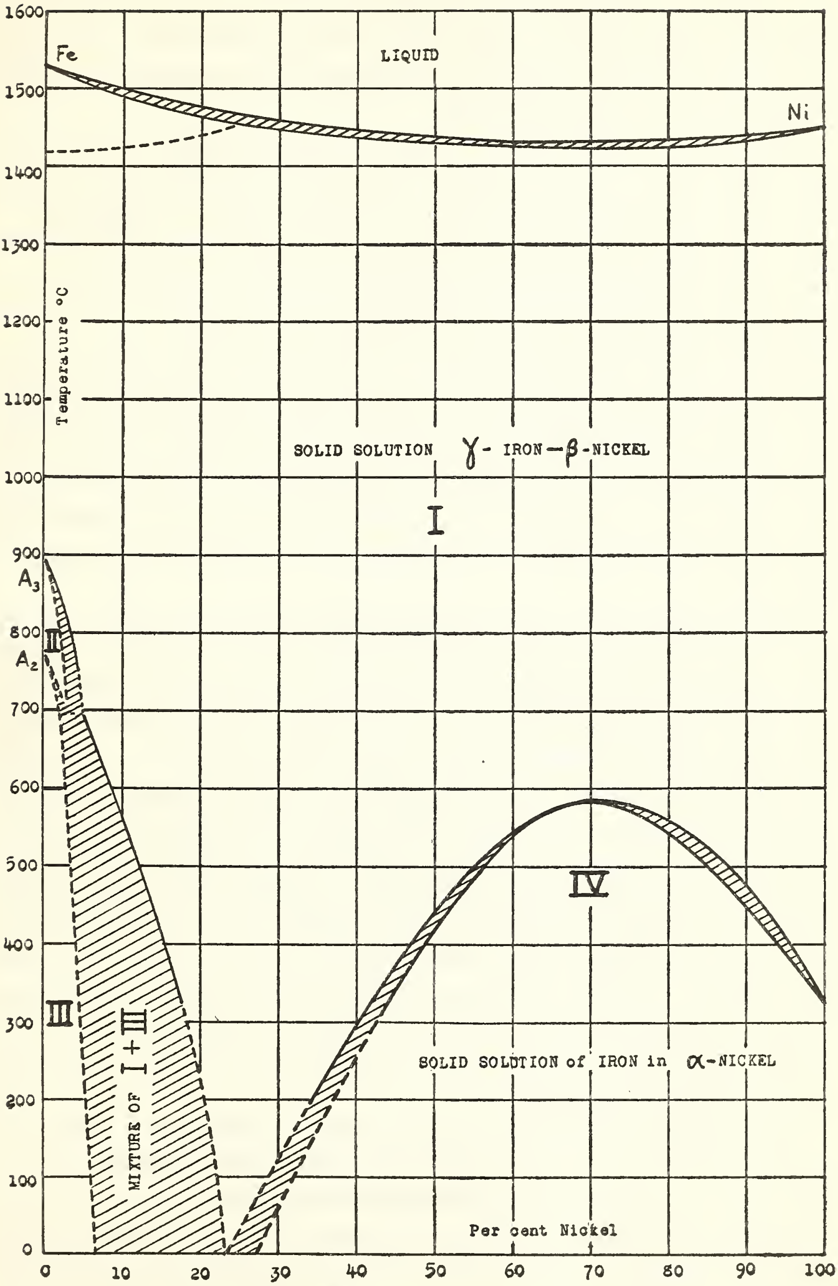


FIG. 1.—*The iron-nickel equilibrium diagram.*

analogous. The addition of carbon, especially if accompanied by sudden or considerable changes in temperature, greatly complicates matters and may give rise to many anomalies. Thus, at the same temperature the same nickel steel may be either magnetic or nonmagnetic, as noted above.

The position of the alloy "invar"—corresponding to about 36 per cent nickel—in the diagram is seen to be such that this alloy would be expected to be subject to changes due to temperature variations, especially as the presence of carbon may still further lower and retard the transformation interval. Thus, invar at ordinary temperatures may readily be in an unstable condition located on the boundary between Regions I and IV.

The diagram prepared about 15 years later by Hanson and Hanson (35) from the thermal curves they obtained on a series of very pure nickel-iron alloys, containing no greater than 0.046 per cent carbon as determined by analysis and ranging in nickel content from 1 to 100 per cent, is in good agreement with the corresponding portion of Guertler and Tammann's diagram (fig. 1).

The critical point ranges of low nickel, medium carbon steels, such as are used for structural purposes, were studied by Scott (67), whose data supply a basis for the direct specification of thermal treatment temperatures of 0.4 per cent carbon, 0 to 4 per cent nickel steels. Dejean (15) has published a diagram illustrating the effect of nickel on the Ar critical ranges of nickel steels containing 0.2 per cent carbon and with the nickel content ranging up to about 25 per cent, and also a diagram (14, p. 429) showing the constitutional changes occurring in cooling alloy steels. Carpenter, Hadfield, and Longmuir (9) also have studied the effect of nickel upon the thermal critical ranges of steels containing 0.4 to 0.5 per cent carbon and 0 to about 16 per cent nickel, although their observations are left unsupported by their failure to make a microscopic examination of the specimens used in the thermal study.

In connection with the development of nickel-iron alloys to which chromium has been added to render the modulus of elasticity of the alloy nonvariable with temperature, as will be discussed in a later section (Sec. IX, 3*c*), it may be of interest to add here reference to the work of Voss (71) on the equilibrium diagram of chromium-nickel alloys. Chromium and nickel combine with each other in all proportions to form a homogeneous solid solution. The solidus and liquidus curves meet each other at a deep depression in both curves corresponding to a temperature of 1,300° C. and a nickel content of 42 per cent, which corresponds to the compound $Cr_3Ni_2$. No work on the equilibrium diagram of the ternary chromium-nickel-iron alloy system has, so far as is known, been published In 1920 Hart (36) published some data on certain physical properties of nickel-chromium-iron alloys as resistivity, temperature coefficient, thermoelectric force, and also Voss's freezing point diagram for nickel-chromium alloys.

### 2. MICROSTRUCTURE AND CONSTITUTION.

The changes produced in the microstructure of steel by the addition of varying amounts of nickel are best illustrated by the method developed by Guillet (31) for the study of ternary steels. The effect of nickel in lowering the critical transformations of iron-carbon alloys (the Ac and Ar changes) has previously been referred to. In case the transformation has been lowered to atmospheric temperature, or nearly so, the microstructure, which in the carbon steels exists ordinarily only at high temperatures, becomes the stable form for the nickel steel at ordinary temperatures.

Figure 2 shows graphically the structural conditions existing in nickel steels of varying composition after slow cooling. The diagram should not, however, be followed too closely, since there are still some points in the behavior of these steels which are not explained by it. The diagram also affords a rational basis for the classification of the nickel-steel series into groups for the study of their various properties. (See IX, Mechanical properties.)

The ordinary commercial nickel steels fall within area *I*, "Pearlitic steels." These do not differ materially in structure from the pure carbon steels; they consist of a pearlitic matrix with excess ferrite or cementite, according to whether the particular steel is above or below the eutectoid percentage (0.85 approximately). The nickel, most probably, is dissolved in the ferrite and does not enter into combination with the carbon to form a carbide, as is the case in some alloy steels.

If the carbon content is held constant, increasing amounts of nickel cause the steel to assume, first, a martensitic structure and, finally, an austenitic one, with intermediate transition stages. Likewise, with a given nickel content, similar changes in the microstructure may be brought about by progressively increasing the percentage of carbon. While the microstructure, and hence the mechanical properties, can be profoundly changed by heat treatment, as in the case of pure carbon steels, the fact should be emphasized that structural conditions which are metastable for ordinary carbon steels and are produced by special heat treatment, may be the stable forms here after slow cooling if the metal has the proper proportion of nickel and carbon. Invar and the

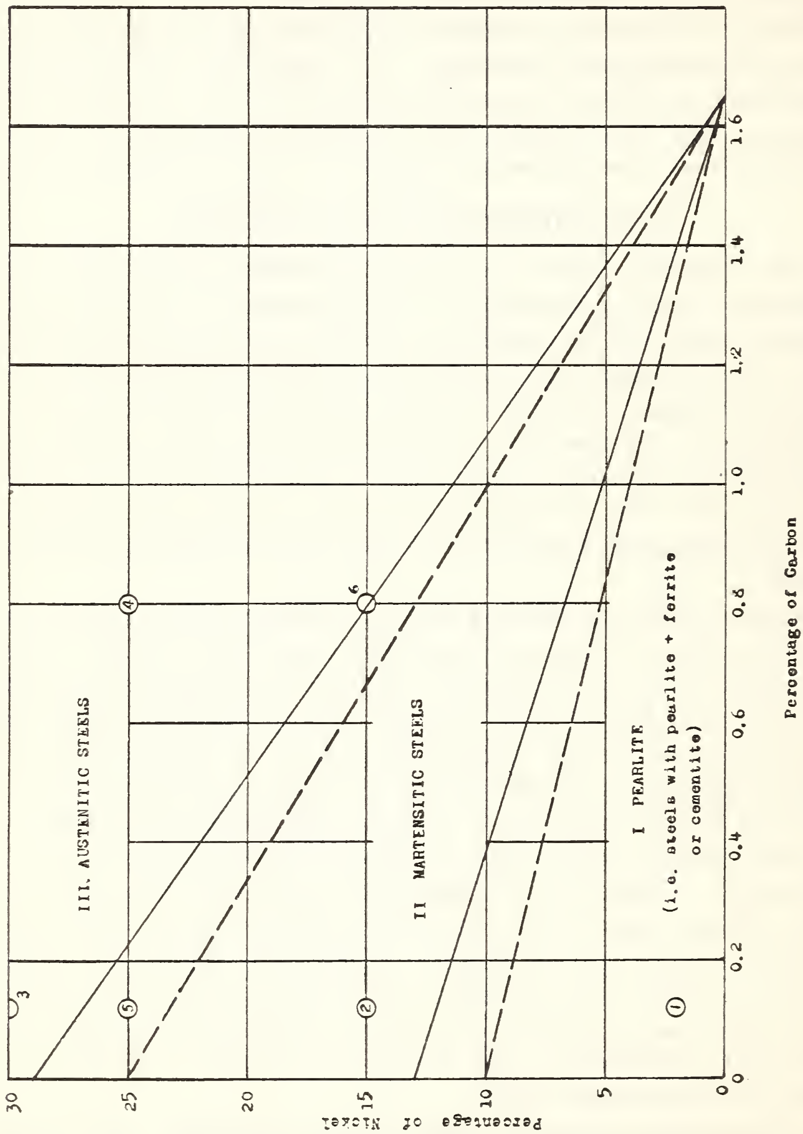


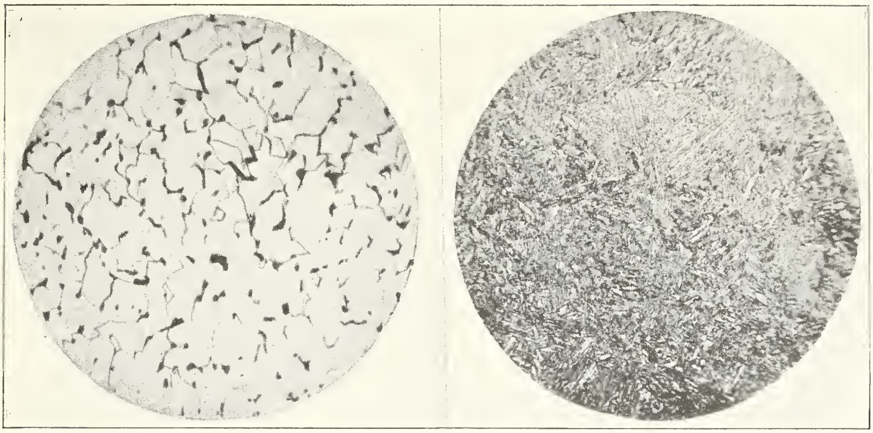
Fig. 2.—*Constitutional diagram for Ni-Fe steels (Guillet).*

closely related alloys fall within area *III*. The microstructure shows the polyhedral crystals characteristic of austenite and of solid solutions in general. The photomicrographs of several selected types (fig. 3) show the structures for varying amounts of nickel. The position of each in the diagram is indicated by a circle inclosing the number designating the specimen.

It follows, therefore, from a consideration of Figures 1 and 2, and is shown by experiment, that when an alloy of iron and nickel (which may contain some 0.3 per cent carbon and small percentages of manganese and silicon) cools from the neighborhood of 1,000° C. its physical properties change regularly until at a certain temperature, which depends upon the composition of the alloy, the appearance of striking anomalies marks the beginning of a transformation. With continued loss of heat the alloy rapidly assumes ferromagnetic properties, contraction almost ceases, or may even be replaced by expansion, the rate of cooling diminishes, and the modulus of elasticity, which had been gradually increasing, drops considerably. After the transformation is complete the properties again change normally with continued cooling. If more than a certain proportion of nickel is present, warming will cause a complete reversal of these changes, so that when any given temperature is again reached the alloy will resume the properties it formerly possessed when cooling through this same temperature. If, however, the proportion of nickel is less, a given property is not resumed on warming until after passing (often considerably) beyond the temperature at which the alloy possessed this property on cooling—that is to say, nickel steels may be separated into two groups, the reversible and the irreversible alloys.

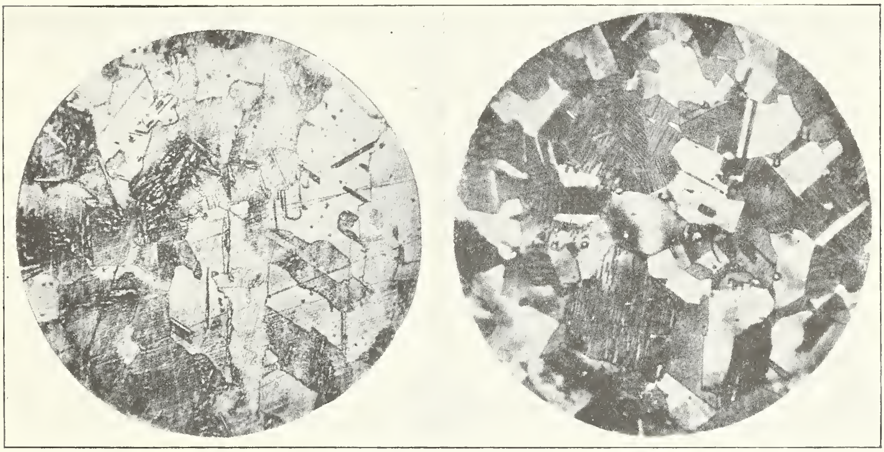
Guillaume (23) classified alloys containing more than 25 per cent nickel as reversible under ordinary conditions and those containing less than 25 per cent as irreversible. He pointed out, however, that a given alloy may under some conditions change reversibly and under other conditions irreversibly. A classification proposed by Dejean (14, p. 334) for the irreversible steels containing less than 25 per cent nickel calls for a division into two classes—the pearlitic steels containing up to 10 per cent nickel as pseudo or quasi-reversible and the martensitic steels containing 10 to 25 per cent nickel as truly reversible. But the curves of magnetic induction which had been published by Hopkinson in 1890 showed unmistakably that the limit of irreversibility had not been reached with even 33 per cent nickel. Much of the long-standing uncertainty in regard to this limit seems to have been cleared up, at least for the pure ferronickels, by the magnetic investigations of Weiss and his pupils Hegg and Foëx, and by the expansion and density measurements of Chevenard, which are discussed later. In 1911 Weiss and Foëx (74) brought out several lines of evidence to prove the existence of the compound $Fe_2Ni$ (34.45 per cent nickel), already noted as probable by Osmond in 1899 (54, vol. 128), and that the pure alloys containing less than this proportion of nickel were solid solutions of $Fe_2Ni$ and iron. Chevenard's work, published in August, 1914 (10), contributes additional evidence of a totally different character and indicates that the dividing line between the reversible and the irreversible groups corresponds at least fairly closely to this compound; but Weiss and Foëx found some irreversible magnetic properties in alloys containing as much as 40 per cent nickel. Chevenard also concludes that the reversible and the irreversible transformations have separate origins and are superposable, and that the irreversible transformation, the magnitude of which is a function of the amount of free iron in the solid solution, and which disappears when this amount becomes zero, is the transformation $\alpha \rightleftarrows \gamma$ of the free iron, modified by the presence of the compound $Fe_2Ni$. Expressing their belief contrary to the relationship of the irreversible transformation to the presence of the compound $Fe_2Ni$, Honda and Takagi (42, 43) have advanced a theory, based upon the property of ferromagnetism, explaining the cause of the irreversibility without assuming the existence of any iron-nickel compounds (see V, 5).

Hanson and Hanson (35) have investigated the constitution and microstructure of pure iron-nickel alloys containing less than 0.1 per cent each of carbon and manganese. The following gives a brief statement of the results of their microscopic study of a series of alloys ranging in nickel content from 1 to 40 per cent. Figures 4*a*, 4*b*, and 4*c* are typical of the structures developed in the alloys of low, intermediate, and higher nickel content that had been annealed at 1,300° C. and cooled in the furnace. Figure 4*a*, taken of a 9.8 per cent nickel alloy, shows a somewhat roughened surface with a rather indefinite pattern. The structure of the 25.5 per cent nickel alloy, shown in 4*b*, is better developed and is very similar to the martensite and austenite-martensite of carbon steels, while Figure 4*c* is typical of alloys containing 29.5,



1. C=0.12; Ni=2.0. Pearlite (dark) and ferrite (white).

2. C=0.12; Ni=15.0. Martensite.



3. C=0.12; Ni=30.0. Austenitic structure; invar is very similar in appearance.

4. C=0.80; Ni=25.0. Similar to No. 3.

5. C=0.12; Ni=25.0. Quenched from 800° C.; the outlines of the polyhedral austenite crystals show in the matrix of martensite.

6. C=0.80; Ni=15.0. The steel, austenitic at ordinary temperatures, has been rendered martensitic by cooling to −182° C. in liquid air; unetched.

FIG. 3.—*Microstructure of selected nickel steels (Guillet).*

Compare with Figure 2 for their relation to the various structural fields of the diagram. Etching with picric acid; magnification in all cases, 300 ×. The material of Nos 1, 2, 3, and 4 is in the "normal" condition; that is, it has received no special thermal treatment after working

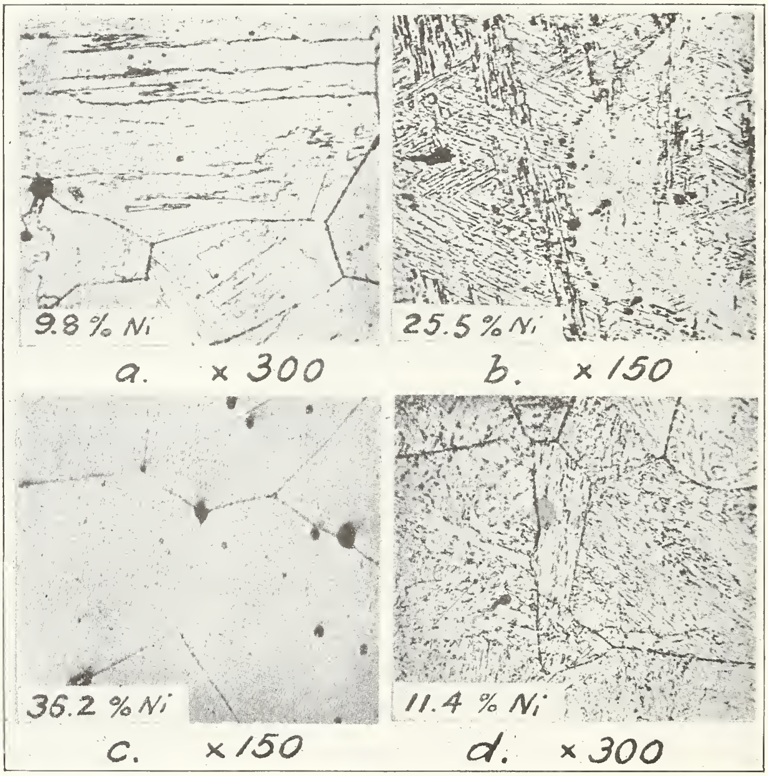


FIG. 4.—*Microstructure of pure iron-nickel alloys (Hanson and Hanson).*

*a*, *b*, and *c*, annealed at 1,300° C. and cooled in the furnace; *d*, quenched at 324° C. after 288 hours' slow cooling.

36.2, and 41.0 per cent nickel. Cooling in carbonic acid snow (−80° C.) developed a martensitic structure in the 29.5 and 41.0 per cent nickel alloys, but not in the 36.2 per cent nickel alloy, which remained unchanged in structure, thus affording evidence as to the presence of a cusp in the transformation range curve somewhere between 30 and 40 per cent nickel. Where ordinary rates of cooling have been used, the 6 to 30 per cent nickel alloys all give either a definite martensitic structure at ordinary temperatures or one which is so finely divided that it is not resolved under high magnifications. Experiments involving prolonged periods of annealing and extremely slow rates of cooling were undertaken with the object of determining, if possible, the manner in which the martensite of these alloys decompose and the extent of the critical ranges through which this decomposition takes place. With reference to the series of alloys containing 0 to 8 per cent nickel, the nickel appears to have the effect of widening the critical range, despite the extremely slow rate of cooling used (from 900 to 350° C. in nearly 1,000 hours), amounting to over 200° C. in the case of the 6 per cent nickel alloy. Thermal curves taken at ordinary rates give no indication of this fact. The upper limit of the critical range, as determined microscopically, agrees very closely with the transformation line determined by thermal curves, though as the nickel content exceeded 8 per cent the determination of the upper limit of the critical range became very difficult and it was not found possible to fix this limit with any certainty by microscopic examination for alloys containing 8 to 40 per cent nickel. With alloys containing more than 8 per cent nickel the extremely slow rates of cooling tried did not appear to lead to the decomposition of the austenite until a temperature of about 345° C. was reached. At this temperature, however, prolonged annealing led to the decomposition of all alloys, containing 9 to 30 per cent nickel with the formation of a "duplex structure" like that shown in Figure *4d*. The 36.2 per cent nickel alloy, nevertheless, appeared to remain in the austenitic state after all treatments. The necessity for extremely slow cooling in bringing about the changes may be attributed to the purity of the alloys. In this connection Guillaume (28, vol. 171; 29) has stated that carbon, even in very small quantities, has a marked effect upon nickel-iron alloys and renders them much more liable to undergo changes.

In order to form a clear idea of the complex phenomena manifested by any given property (thermal expansion, for instance) of nickel steels it is essential to note the relations between variations of the property in question and corresponding variations in other properties. With this end in view it is convenient to begin with the magnetic properties.

## III. MAGNETIC PROPERTIES OF IRON-NICKEL ALLOYS.

The investigations of Hopkinson, referred to in section 1, form an excellent starting point for getting an insight into the anomalies of nickel steels.

### 1. VARIATION OF MAGNETIC INDUCTION WITH TEMPERATURE.

Figures 5, 6, and 7 show the characteristics found for two steels having the following compositions:

| Fe. | Ni. | C. | Mn. | S. | P. | Si. |
|---|---|---|---|---|---|---|
| Per cent. | Per cent. | Per cent. | Per cent. | Per cent. | Per cent. | Per cent. |
| 74.31 | 24.5 | 0.27 | 0.85 | 0.01 | 0.04 | 0.02 |
| 66.19 | 33.0 | .28 | .50 | .01 | .02 | ........... |

Figure 5 represents the relations between induction and magnetizing force at 13° C. after the alloys had been rendered magnetic by cooling to about −50° C. Figures 6 and 7 show the variations of induction with temperature, together with the changes produced by varying the magnetizing force.

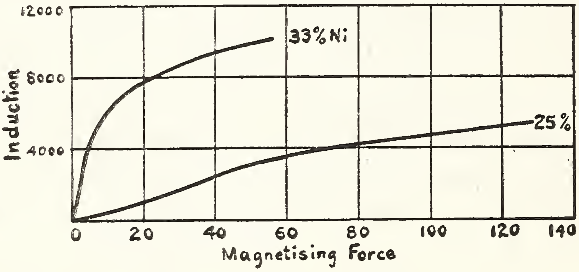


Fig. 5.—*Magnetic induction in two nickel steels at 13° C. (Hopkinson.)*

These two alloys show marked differences in their magnetic properties. The differences are particularly striking in the case of the induction-temperature curves. Small amounts of nickel added to iron have the effect of increasing the magnitude of the irreversible anomaly until a maximum is reached with approximately 25 per cent nickel. Still further increasing the proportion of this metal greatly reduces the anomaly by lowering the temperature at which ferromagnetism disappears on heating and raising that at which it appears on cooling, until both closely approach each other in the neighborhood of 200° C. It is to be noted further that the 33 per cent alloy was found practically reversible when the magnetizing force was increased to 30.3 gausses.

Hopkinson also found that a steel containing 73 per cent nickel showed no material difference between the critical temperatures for heating and for cooling (600° C.). He adds that "it is curious to remark that the induction for considerable forces is greater than in the steel with 33 per cent nickel, and that it is greater than for a mechanical mixture of iron and nickel in the proportions of the analysis, however the particles might be arranged in relation to each other."

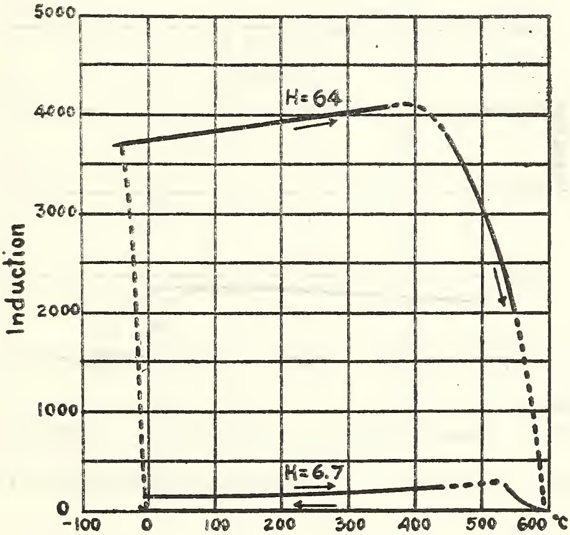


FIG. 6.—*Variation of magnetic induction with temperature in a steel containing 25 per cent Ni. Magnetizing force 6.7 and 64 gausses. (Hopkinson.)*

In 1897 Guillaume(23) showed that the temperature at which ferromagnetism disappears (sometimes called the Curie point or, preferably, the critical point) in reversible nickel steels containing 28 to 40 per cent nickel could be represented approximately by the formula—

$$t = 34.1\ (n - 26.7) - 0.80\ (n - 26.7)^2$$

in which $n$ represents the per cent of nickel in the alloy.

The following year E. Dumont, who studied the effect of temperatures ranging from about −80 to +250° C. and magnetizing forces from 14 to 50 gausses upon 12 of Guillaume's alloys, pointed out that all those containing from 30 per cent up to at least 44 per cent nickel, if annealed, have induction-temperature curves similar to the curve of Figure 7 for $H = 30.3$ gausses, losing their magnetism gradually on heating, and that at the same number of degrees below the critical point all reversible alloys have the same permeability. At any given temperature the permeability of these alloys was found to increase with the proportion of nickel. The permeability of unannealed reversible alloys containing 39.4 per cent and 44 per cent nickel remained constant between 20 and 250° C.

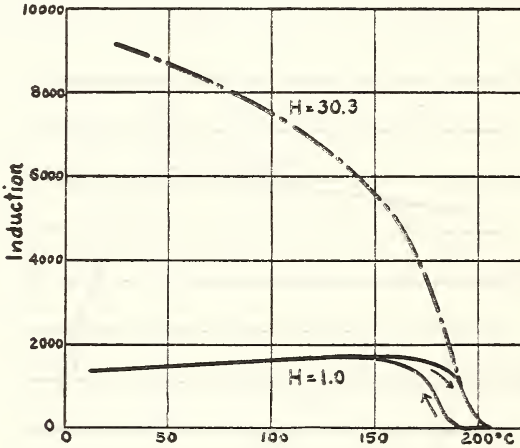


FIG. 7.—*Variation of magnetic induction with temperature in a steel containing 33 per cent Ni. Magnetizing force 1.0 and 30.3 gausses.* (*Hopkinson.*)

## 2. VARIATION OF MAGNETIC MOMENT WITH TEMPERATURE.

In 1910 Hegg (38) published his researches on the magnetic properties of a series of pure ferronickels (i. e., alloys free from carbon), the compositions of which varied by 10 per cent steps from pure iron to pure nickel. His measurements were made on small ellipsoids at temperatures ranging from $-190$ to 760° C. and with various magnetizing forces up to and beyond 10,000 gausses. With $H = 10{,}000$ gausses he obtained the curves reproduced in Figures 8, 9, and 10. These represent for each specimen the magnetic moment per unit mass[3] as a function of the abso-

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[3] For technical purposes it is usual to consider the induction $B$ or the intensity of magnetization $I$ produced by a magnetizing force $H$. $I = \mathfrak{M}/V$, or the magnetic moment per unit volume; but for dealing with chemical problems Weiss has found it convenient to introduce the quanity $\sigma = \mathfrak{M}/M$, or the magnetic moment per unit mass. If the density is represented by $D$, then $\sigma = I/D$ and $B = H + 4\pi\sigma D$.

lute centigrade temperature *K*. Figure 11, representing the alloy containing 50 per cent nickel, is typical of a series of figures (one for each reversible alloy) to show how the intensity of magnetization was found to change with the magnetizing force at each of a number of different temperatures.

After what has been said above the essential features of Figures 8, 9, and 11 are self-explanatory. Some explanation is, however, necessary in the case of Figure 10, representing the irreversible alloys.

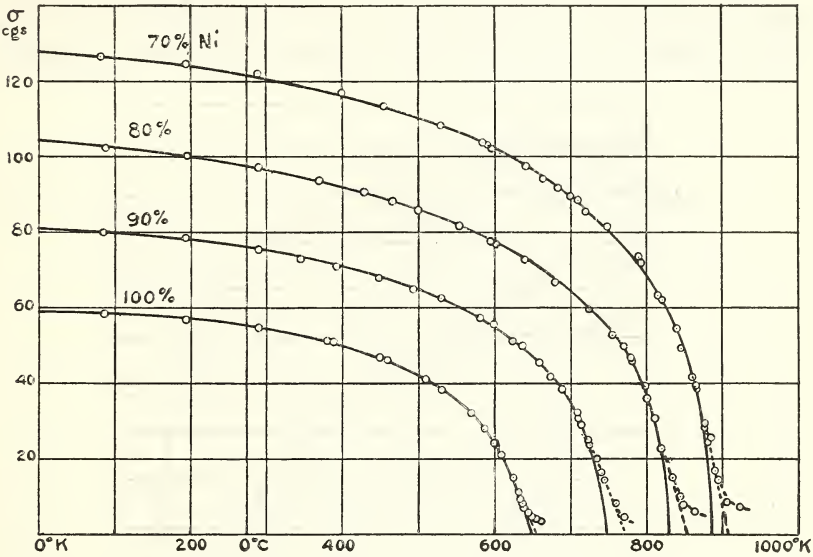

FIG. 8.—*Variation of magnetic moment per unit mass with the absolute centigrade temperature K*[4] *of pure ferronickels. (Hegg.)*

The upper curves *A*, *B*, *C*, which show the successive values of the magnetization on warming, are analogous to those obtained with iron and the reversible alloys in that the disappearance of magnetism occurs gradually and appears to be almost independent of the time. Near *C* the curves commence to drop rapidly, the reversibility disappears, and the state of the alloy is a function not only of the temperature and the magnetizing force, but also of the time, which plays a preponderating rôle. On continuing the heating the material loses its last traces of ferromagnetism at the transformation point on heating, $\theta_1$.

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[4] *K* (from Kelvin) designates temperatures on the absolute centigrade scale; *C* on the ordinary centigrade scale with 0° the temperature of melting ice, or 273° *K*: also $T° K = 273 + t° C$.

During cooling the material retains its paramagnetic characteristics until the transformation point on cooling, $\theta_2$, is passed, after which ferromagnetism appears with great rapidity. If the temperature is reduced enough to return the intensity of magnetization to the value it had before heating, the cycle will be closed. By similar treatment this can be repeated as often as desired.

While the first portions *A*, *B*, *C* of the heating curves are very little influenced by the time and can be regarded as reversible during a series of experiments, the rapidly descending portions to the right of the lines *M N* in Figure 10 can be perceptibly modified by the rapidity of the investigations. The nearer the temperature is to $\Theta_1$ and the longer it is held there the more advanced is the transformation. The return of ferromagnetism on cooling is characterized by still greater instability; the curves *E*, *F*, *G* are not reversible, and it is very difficult to obtain the same values a second time. If on reaching any point of *E*, *F*, *G* heating is resumed, the alloy will pass through a new cycle similar in all respects except size to the one just described. The nearer the point at which reheating begins is to $\Theta_2$ the smaller will it be.

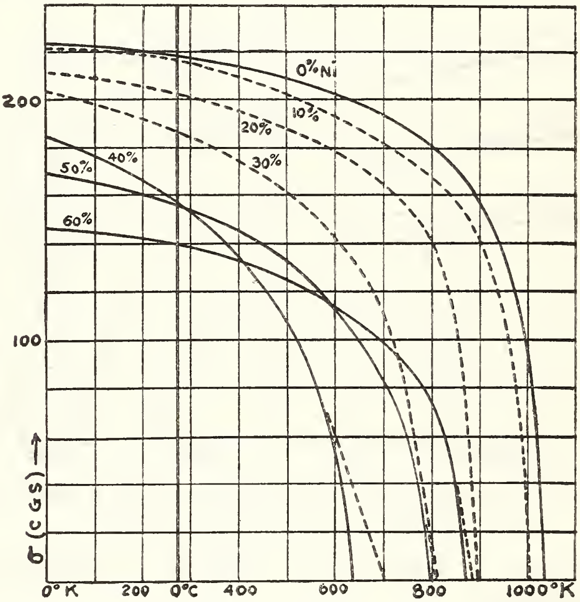

FIG. 9.—*Continuation of Figure 8. (Hegg.)*

Among the properties common to all the curves *A*, *B*, *C*, *A′*, *B′*, *C′*, etc., the most important is their almost complete reversibility up to the region bounded by *M N*. The more rapidly the experiments are made the less do these curves differ from those obtained with the reversible alloys. For the sake of clearness the reversible portions of Figure 10 are drawn with full lines and the irreversible portions with dotted lines, the arrows indicating the directions in which the latter are traversed.

Another quite unexpected property noted by Hegg was that if lines corresponding to any two different temperatures were drawn parallel to the axis of $\sigma$ across the reversible curves for a given alloy the ordinates cut off by these curves would be very nearly proportional. From this he concludes that a part of the material is in the paramagnetic state, and up to a certain temperature *M N* offers such a stability that the reversibility is not altered. It is, then, only in the region between *M N* and the point $\Theta_1$ that the ferromagnetic material not yet transformed would undergo at constant temperature partial or complete transformation to any great extent.

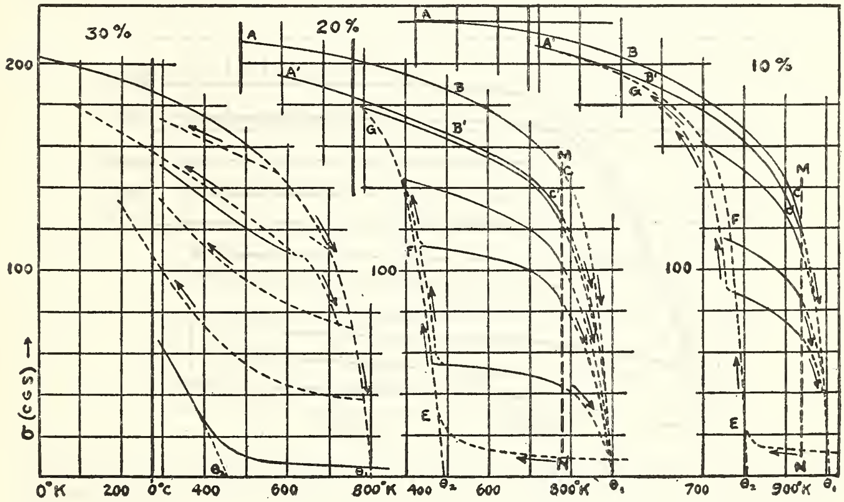

FIG. 10.—*Continuation of Figure 9. Irreversible alloys. (Hegg.)*

If, however, the alloy is maintained at a sufficiently low temperature, the excess of paramagnetic material will very gradually be transformed into the ferromagnetic state. For example, the alloy containing 30 per cent nickel, after having been heated beyond the transformation point, was measured at room temperature.

Three weeks later its permeability was found to be 5 per cent greater Thus, ageing a nickel steel at low temperature increases its ferromagnetic properties, while annealing at a temperature near the transformation point decreases them.

### 3. MAGNETIC TRANSFORMATION CURVES.

Figure 12 represents the magnetic transformation curves of iron-nickel alloys as plotted from the observations of various investigators; those of Honda and Takagi (43), Hegg (38), Ruer and Schüz (65), Guertler and Tammann (22), A. Dumas (16), and Osmond (54, vol. 128) having been obtained magnetically, those of Hanson and Hanson (35) by thermal and electrical conductivity methods, and those of Boudouard (5) thermoelectrically. The carbon and manganese content of the alloys represented by the plotted data did not in most all cases exceed about 0.2 per cent, although all of Osmond's specimens and several of Dumas's specimens contained considerably more manganese, 0.7 to 1.1 per cent for the former and 0.23 to 0.95 per cent with somewhat more than 0.2 per cent carbon in a few cases for the latter, and for this reason were not included in determining the mean values at the various percentages of nickel for plotting the heating and cooling curves. The observation points of many of Osmond's and Dumas's specimens falling within the irreversible alloy range are seen in the diagram to lie somewhat below the heating and cooling curves, thus illustrating the lowering effect of manganese upon the criti-

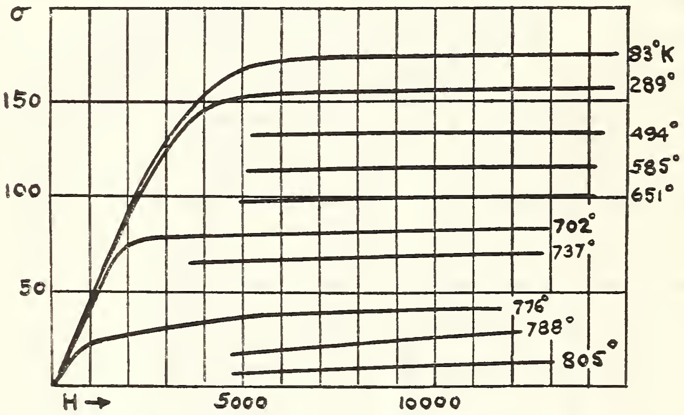

FIG. 11.—*Variation of magnetic moment per unit mass with magnetizing force in an alloy containing 50 per cent Ni and 50 per cent Fe at different absolute centigrade temperatures. (Hegg.)*

cal range. The alloys prepared by Hanson and Hanson, and also Guertler and Tammann, were of a high degree of purity, being very low in carbon and manganese—about 0.1 per cent or less. Hegg obtained his transformation point data by extrapolating to the axis of temperatures the curves representing $I^2$ when the magnetizing force was 10,000 gausses. By prolonging linearly the lower end of the $Ar_{3 \cdot 2}$ curve (the long curve at the left) down to absolute zero, $-273°$ C., the absolute zero abscissa is crossed at approximately 37 per cent nickel.

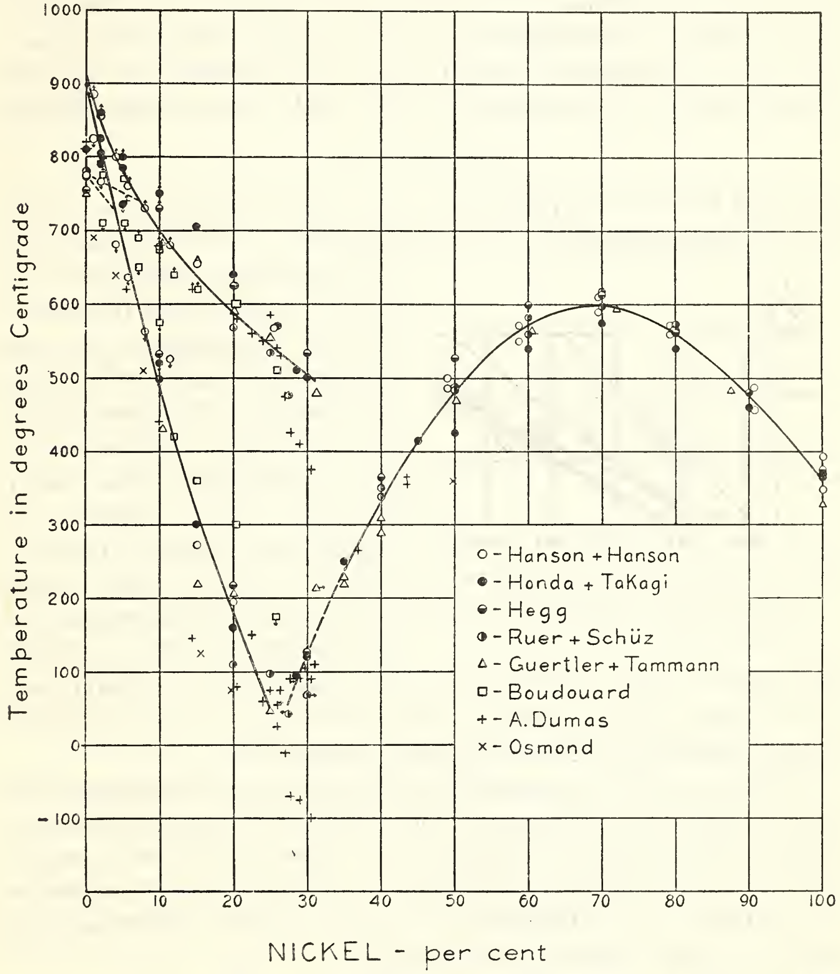

FIG. 12.—*Magnetic transformation (Curie points) curves for ferronickels, as determined from the results of various investigators.*

### 4. SATURATION MAGNETIC MOMENT AND CURIE CONSTANT.

Experiments of Weiss and Foëx (74) made on the identical samples that Hegg used throw additional light upon the nature of the ferronickels. Weiss has pointed out that the two magnetic constants which are particularly characteristic for the solid homogeneous solutions of ferromagnetic bodies are $\sigma_0$, the saturation value of the magnetic moment per unit mass at the absolute zero of temperature, and $C$, the Curie constant.[5] From the kinetic theory of ferromagnetism Weiss has deduced the relation

$$C = \chi\ (T - \Theta)$$

in which $\Theta$ is the temperature of the Curie transformation point and $T$ the temperature of the experiment. $C$ is nothing but the Curie constant which the substance would have if it were to become paramagnetic by the suppression of actions between the molecules. In a great many cases the linear variation of $1/\chi$ with temperature has been observed within intervals of several hundreds of degrees. Weiss has further shown that in the case of homogeneous solid solutions both $\sigma_0$ and $C$ will vary as linear functions of the composition. Honda and others have shown, however, that Curie's law can not be considered generally true and is never exactly true.

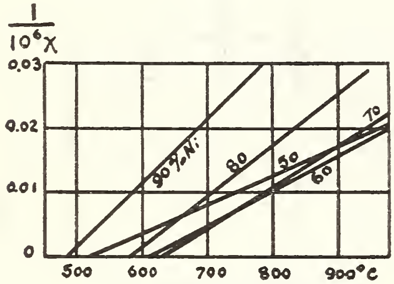

Fig. 13.—*Reciprocals of susceptibilities per unit mass of pure ferronickels as functions of the temperature. (Weiss and Foëx.)*

Figures 13 and 14 represent the values of $1/\chi$ as functions of the temperature which Weiss and Foëx found from measurements on Hegg's ferronickels at temperatures above the Curie points. Each alloy containing more than 40 per cent nickel yielded a straight line from which both $\Theta$ and $C$ could be determined by means of the relation $1/\chi = (T - \Theta)/C$.

The alloy containing 40 per cent nickel presents some interesting features. On cooling from high temperatures $1/\chi$ at first followed a straight line, giving a Curie constant of 0.0256. A second series of

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[5] In the case of paramagnetic bodies the susceptibility per unit mass $\chi$ is, for many substances and over wide temperature intervals, approximately inversely proportional to the absolute temperature $T$. The constant $C = \chi T$ is known as the Curie constant. If $\kappa = I/H = \mathfrak{M}/VH$ is the susceptibility as usually expressed in terms of magnetic moment per unit volume (see note 3, p. 18), then $\chi = \sigma/H = \kappa/D$.

measurements made with increasing temperatures gave a series of points which, except for a small and almost constant deviation, followed the same line. Since the deviation could be explained by lack of adjustment when the attraction was a maximum, the first portion appears to be reversible. The Curie point corresponding to this is $\Theta = (423 + 273^\circ)\ K$ approximately, with $C =$ 0.0251. On cooling from 790 to 730° C. a transformation takes place, after which follows another straight line for which $C = 0.047$ and $\Theta = (335 + 273^\circ)\ K$. Below 730° C. the phenomenon is irreversible. On warming, the points fall below those obtained on cooling, the heating curve tending to join the cooling curve as 730° C. is approached. But the phenomenon is complicated by its variable dependence on the time in the irreversible regions. In the transformation region the alloy is still reversible. The last series of experiments gave a third line, not represented in the figure, which was reversible within a small region and characterized by $C = 0.091$ and $\Theta = (300 + 273^\circ)\ K$.

The alloys containing 10, 20, and 30 per cent nickel resembled the 40 per cent alloy in many respects (fig. 14). All showed the same irreversibilities and the same type of transformation at about 790° C., and all gave several Curie temperatures $\Theta$ and Curie constants $C$ corresponding to restricted temperature intervals.

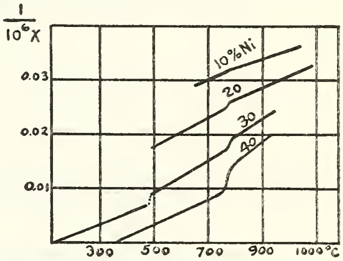

FIG. 14.—*Continuation of Figure 13.* (*Weiss and Foëx.*)

The lower broken line in Figure 15 represents the Curie constants $C$ derived by Weiss and Foëx from Figure 13 and from the high temperature portions of Figure 14. The upper one shows Hegg's value of $\sigma_0$, the magnetic moment per unit mass at saturation, obtained by extrapolating to absolute zero the results of measurements carried down to liquid air temperatures. The results for both $C$ and $\sigma_0$ point strikingly toward the existence of the compound $Fe_2Ni$. Weiss and Foëx draw the following conclusion: "The ferronickels form two uninterrupted series of solid solutions, the first between Fe and $Fe_2Ni$, the second between $Fe_2Ni$ and Ni." The location of $Fe_2Ni$ appears also to be associated with the transition region from irreversible to reversible nickel steels as shown in Figure 12.

Finding that, according to previous investigations, the Curie constant is really not constant through a wide range of temperature, Curie's law holding good only in a certain range of temperatures well above the critical point, and realizing that at these high temperatures the susceptibility-temperature curves ($\chi$, $t$) have a small inclination to the axis of temperature and the consequent introduction through a small error in the inclination of a large deviation in the value of the Curie constant, Honda and Takagi in 1918 (42, 43) made further determinations on the susceptibility of nickel steels above their critical points. They came to the conclusion that the law $C = \chi\ (T - \Theta)$ holds approximately good only above 700°. Their curve for the Curie constant is shown in Figure 15 as a light solid line, *a b*. They explain the discrepancy between it and that of Weiss and Foëx as being due to the fact that the latter used a too small value, 0.072, as the

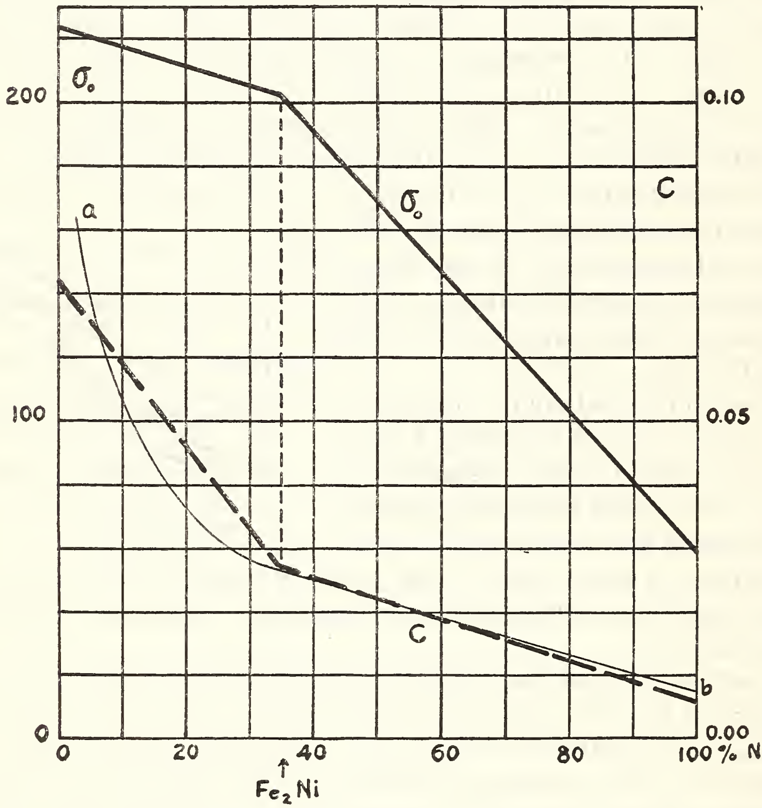

FIG. 15.—*Curie constants and saturation magnetic moments of ferronickels. (Weiss and Foëx.)*

Curie constant, whereas the value 0.17 would have fitted the result of their observations more closely and produced a curve similar to that prepared by the former. The latter measured the susceptibility of only two nickel steels in the range 0 to 30 per cent nickel. The former do not accept the assumption as to the existence of the compound $Fe_2Ni$.

Table 1 contains some of the numerical data given by Hegg and by Weiss and Foëx which are plotted in Figures 12 and 15. The values for the temperatures of the Curie points deduced by the latter investigators from lines representing $1/\chi$ as functions of $T$ are not included because they differ considerably from those obtained by the more direct methods of other observers even in the case of the reversible alloys, while they contain such fictitious results as temperatures below the absolute zero in the case of the irreversible alloys and $\gamma$ iron.

## 5. MAGNETOSTRICTIVE EFFECTS.

Magnetostrictive effects in iron, nickel, and nickel steels have been studied by the Japanese physicists Nagaoka, Honda, and Shimizu, the alloys investigated containing various amounts of nickel ranging from 24 to 70 per cent. In all the nickel steels examined, longitudinal magnetization produced increase of length (the Joule effect), and, reciprocally, mechanical elongation produced increase of magnetization. A specimen after annealing elongated more than when in the hard-drawn state. The elongation caused by magnetizing a wire under tension was reduced and in some cases even changed to a contraction by increasing the load.

The effect of cooling on the magnetic elongation was similar to its effect on the intensity of magnetization. In steels containing more than 28.7 per cent nickel the elongation was diminished in weak fields and increased in strong fields by cooling in liquid air. In steels containing less nickel the initial decrease of elongation vanished. The ratio of the elongation in liquid air to that at ordinary temperatures increased in strong fields with decrease of nickel content. With a magnetizing force of 500 gausses it amounted to 1.6 with 36 per cent nickel, 3.7 with 28.3 per cent, and 160 with 24.4 per cent. The elongations before and after cooling reversible nickel steels were the same, but the elongations of irreversible steels were always greater after cooling. A 25 per cent nickel steel did not elongate appreciably at either ordinary temperatures or that of liquid air.

Because of its bearing on the use of nickel steels in constructing measuring apparatus the length changes produced by fields as weak as that of the earth were investigated and found to be generally less than $10^{-7}$.

The increases in volume of magnetized ellipsoids were found to be practically proportional to the magnetizing forces for each alloy tried. In the alloys of small thermal expansivity the effect observed was far greater than anything that had ever been found in other ferromagnetic substances.

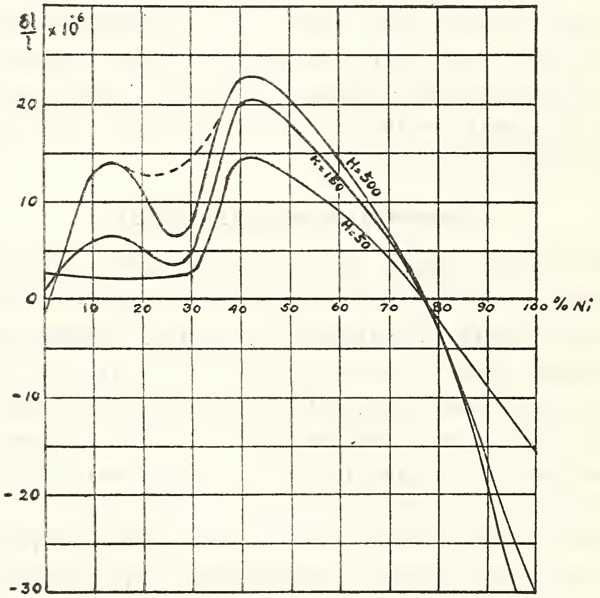

FIG. 16.—*Variation of magnetostriction with nickel content in nickel-iron alloys, using different magnetizing forces. (Honda and Kido.)*

The torsion produced in nickel steels by the combined action of longitudinal and circular magnetic fields (the Wiedemann effect) was found similar to that previously observed in the case of iron.

The results of further studies in the magnetostrictive effects in a series of nickel-iron alloys made by Honda and Kido (41) are diagrammatically set forth in Figure 16. The chemical composition of these alloys, other than nickel, is not stated, although the alloys presumably are the same ones used by Honda in an earlier investigation (40, vol. 7) on the thermal and electrical conductivities. It should be noted in passing that the copper content of these alloys must have been high, since in the published results of the last-mentioned investigation the copper content of the nickel and iron used in the preparation of the alloys amounted to 4.20 and 0.288 per cent, respectively, while the carbon content was 0.29 per cent in the former and 0.09 per cent in the latter. It will be seen in Figure 16 that the curves for the constant fields, $H=150$ and $H=500$, have two maxima at 15 and 45 per cent nickel and a minimum at 27 per cent nickel, but that in the curve for $H=50$ the first maximum vanishes while the second maximum still remains present. The results obtained by Nagaoka and Honda for nickel steels of different percentages of nickel agree with those here obtained, except for an inconspicuous maximum at 29 per cent nickel which was not observable in this case. The dotted portion of the $H=500$ curve represents the results obtained by dipping the specimens into liquid air and then heating to room temperature, which procedure has lessened considerably the minimum at 27 per cent nickel. Reference to magnetostrictive and other experiments at the Bureau of Standards is given in Section VI (10).

## IV. ELECTRICAL PROPERTIES OF IRON-NICKEL ALLOYS.

Guillaume (23) failed to find any marked differences in the electrical resistivities of his various nickel steels, all those studied ranging between 80 and 90 microhm-cm at ordinary temperatures. For temperature changes between 20 and 150° C. he also failed to find any anomalies in the resistance corresponding to the anomalies in other properties. The results he obtained for several alloys are given in Table 2.

### 1. VARIATION OF ELECTRICAL RESISTIVITY WITH TEMPERATURE.

That the nickel steels do, however, show anomalies in the change of electrical resistance with temperature was pointed out by Hopkinson in 1890, as mentioned on page 4. Figure 17, which is reproduced from Hopkinson's paper, shows the irreversibility of his 25 per cent alloy over a region which coincides fairly closely with the region in which he found such remarkable irreversibility in magnetic properties. Boudouard in 1903 located transformation regions by resistance changes in three steels containing from 3 per cent to 3.7 per cent nickel. Schleicher and Guertler (66) have also found anomalies in the resistance changes with temperature. The three alloys which they examined, containing 25.2, 30.6, and 35.26 per cent nickel, behaved very irregularly in passing through the critical regions.

## 2. VARIATION OF ELECTRICAL RESISTIVITY WITH NICKEL CONTENT.

Numerous investigators besides Guillaume have measured with commercial accuracy the electrical resistivity of nickel steels at room temperatures. Since, however, the results have been complicated by the presence of irregularly varying elements in addition to iron and nickel, it is difficult to see just what effect follows directly from changing the proportion of the latter metal. Portevin (58) found an initial increase in the resistivity amounting to 1.51 microhms per 1 per cent of nickel in nickel steels containing 0.1 per cent carbon that had been normalized and also had been water quenched at 975°. Honda (40, vol. 7) later obtained the same value, about 1.5 microhms per 1 per cent, in nickel steels containing 0.1 per cent carbon that had been cooled from 900 to 30° and also had been heated from −190 to 30°.

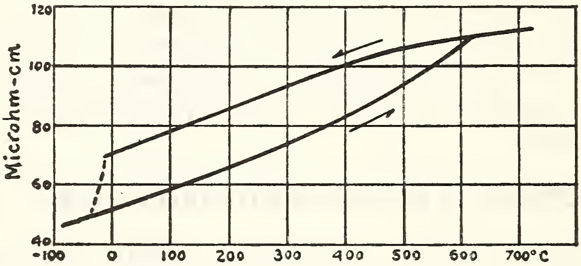

FIG. 17.—*Variation of electrical resistivity with temperature in an irreversible steel containing 25 per cent Ni. (Hopkinson.)*

Resistance measurements made by C. F. Burgess and James Aston (8) on a graded series of very pure ferronickels, prepared by melting together electrolytic iron and electrolytic nickel, are in close agreement with those later obtained by T. D. Yensen (75) on similar series of ferronickels, though these alloys differed from the first-mentioned series of alloys in the nickel content and with particular attention being given to the 0 to 10 per cent nickel range. The latter prepared two series of alloys, one containing small amounts of silicon or manganese added purposely to improve the forging qualities of the alloys and the other to which no additions were made. Their results are given in Table 3, together with those of Ruer and Schüz (65) obtained on a series of ferronickels prepared by melting pure iron and granulated nickel in a graphite crucible lined with magnesite and those of Ingersoll and others (48) obtained on the same alloys prepared by Burgess and Aston (Table 4). In Figure 18 all these results have been plotted against the nickel content. The point for 100 per cent nickel, represented in the diagram by a triangle, was calculated as at room temperature from the data mentioned by Fleming for pure nickel at several temperatures and published in the Smithsonian Physical Tables (7th edition, 1920). Yensen's results appear to answer in the affirmative Burgess and Aston's question, "Might not the maximum point in this curve of resistance be at 34 per cent of nickel, corresponding to the compound $Fe_2Ni$?" although the cusp shown in Figure 18 is seen to extend from about 30 to 35 per cent nickel. Ruer and Schüz's and Ingersoll's results point to the same conclusion, which is also strengthened in view of the magnetic observations of Osmond

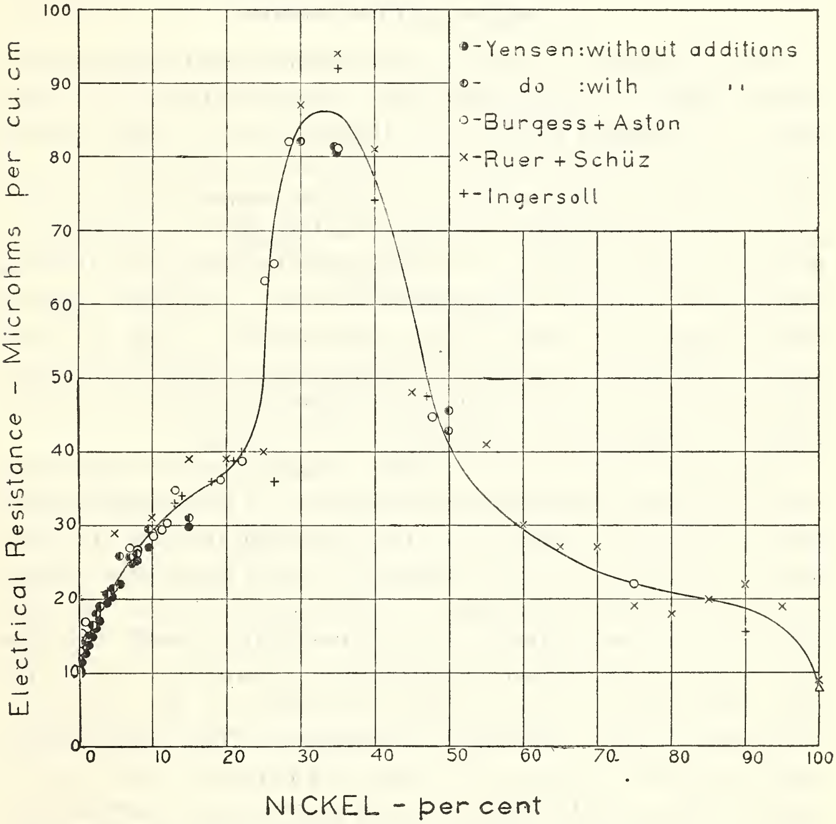

FIG. 18.—*Electrical resistivity of pure ferronickels.*

and of Weiss and Foëx noted above, of the expansion measurements of Chevenard, of the temperature coefficient of elastic modulus determinations of Guillaume, of the thermal observations of Guertler and Tammann, and of the specific heat, specific resistance, thermoelectric power (against copper), and thermal conductivity determinations of Ingersoll and others made on Burgess and Aston's alloys referred to above.

### 3. THERMOELECTRIC POWER.

Table 4 contains the values of the electrical and thermal properties obtained by Ingersoll and others (48) on Burgess and Aston's alloys. The curves published by Ingersoll for the thermoelectric power and specific resistance at different temperatures up to 300° C. show a minimum and a maximum, respectively, at about 35 per cent nickel, while that for specific heat shows a maximum at the same nickel content. It would appear from the table that the temperature coefficient of resistance assumes a minimum value at approximately the same nickel concentration. Pepe (55) has recently determined the thermoelectric power of nickel-iron alloys, containing 22, 36, 44, and 49 per cent nickel, as against pure iron or copper at temperatures ranging from −185 to 843° C.

Boudouard in 1903 (5) located transformation regions by means of thermal electromotive forces due to temperature differences between the ends of 10 cm bars that resulted from the natural temperature gradient along the axis of the electric furnace in which the bars were heated. Dupuy and Portevin (18) published in 1912 some results of an investigation made into the thermoelectric properties of ferronickel containing 0 to 30 per cent nickel and 0.1 to 0.8 per cent carbon in the "as cast," "annealed," and "hardened" conditions. The measurements made between −78 and 0° C. and also between 0 and 100° C. indicate that a simple relation exists between the thermoelectric power and the nickel content. Curves representing the thermoelectric power as plotted against the nickel content give a minimum at 20 to 25 per cent nickel when the carbon content is 0.1 to 0.25 per cent and at about 12 per cent nickel with 0.8 per cent carbon.

## V. THERMAL EXPANSION OF IRON-NICKEL ALLOYS.[6]

### 1. VARIATION OF LENGTH WITH TEMPERATURE.

(*a*) IRREVERSIBLE ALLOYS.—At the same time that an irreversible nickel steel gradually assumes ferromagnetic properties on cooling it gradually undergoes a change in volume—a change which is also irreversible, as Figure 19 well illustrates. When a rod of an irreversible steel is cooled from a high temperature, it contracts according to a straight line law along *A H B*. At a certain temperature, *B*, the contraction becomes less rapid, and

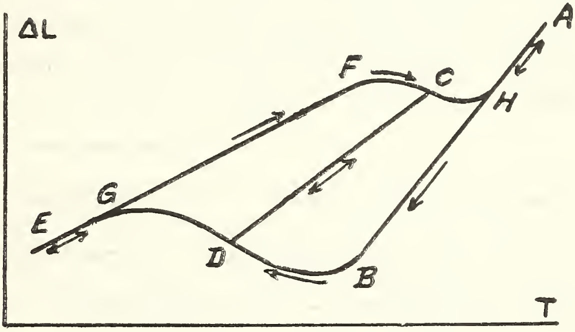

FIG. 19.—*Typical curve representing the variation of length with temperature in an irreversible nickel steel. (Guillaume.)*

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[6] The term "thermal expansivity" is used in this circular to designate the expansion per unit length of a material, whether this characteristic is expressed by means of a numerical coefficient, an equation, or a curve.

If $L_0$ represents the distance between two points of a body at 0°C. and $L$ the distance between the same two points at some other temperature $t°$, it is often convenient to express the expansivity by an equation of the form—

$$\frac{L-L_0}{L_0}=at+bt^2+ct^3+\ldots\ldots \quad (1)$$

It is more common, especially among technical men, to use the *mean zero coefficient of linear expansion* between two limiting temperatures $t_1$ and $t_2$, defined as

$$\overline{\alpha}_{12}=\frac{1}{L_0}\cdot\frac{L_2-L_1}{t_2-t_1} \quad (2)$$

Again, when one is concerned with the rate at which a length changes at a particular temperature $t$, it may be desirable to use the *true zero coefficient of linear expansion* at $t°$, defined as the limit approached by $\overline{\alpha}_{12}$ as both $t_1$ and $t_2$ approach $t$, which, in the notation of the differential calculus, is

$$\alpha=\frac{1}{L_0}\frac{dL}{dt} \quad (3)$$

The expression "coefficient of expansion" is often used so indiscriminately that it is difficult to make out whether the user has in mind $\overline{\alpha}_{12}$ or $\alpha$ or something else. For small temperature ranges and the accuracy ordinarily required it is immaterial; but the expansion frequently deviates enough from a linear function of the temperature change to make discrimination a matter of importance. If the expansivity is expressed by some such equation as (1), it is a matter of simple algebra to derive whatever coefficient may be needed for a given purpose; but the behavior of the alloys described in this circular is so complicated that even such equations are not feasible except within restricted temperature ranges, so that curves must be resorted to.

finally a progressive increase of volume sets in which continues steadily until the transformation is complete. Following this the contraction resumes its regular irreversible path, *G E*. If the rod be again heated, it is seen to expand along *E G F*, and then contraction sets in which restores it to the straight line *A H B*. If the cooling is arrested at a point *D* and the bar reheated the changes of volume that occur at first follow the line *D C* and then along *C H A*. Guillaume (29) states that the inclination of the line *A B* is about $18 \times 10^{-6}$ per °C. and that of *E F* between 10 and $11 \times 10^{-6}$ per °C.; the former figure represents the expansibility of a nonmagnetic iron-nickel-chromium alloy and the latter the value obtained in the case of ordinary steels. Along *A B* the

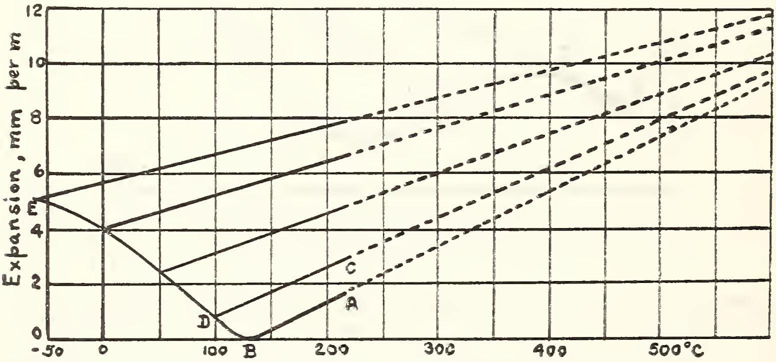

FIG. 20.—*Variation of length with temperature in an irreversible steel containing 15 per cent nickel. (Guillaume.)*

steel is in a state stable from high temperatures downwards, and along *E F* from low temperatures upwards.

To cite a case in greater detail, Figure 20 illustrates the behavior of a bar containing 15 per cent nickel which was investigated by Guillaume (23). On cooling from cherry red it contracted at first, following the nearly straight line *A B*. Near 130° C. a rapid expansion began, which soon reached as high a value as 40 $\mu$[7] per meter per degree. If the bar were then reheated, it did not expand according to the curve *B E* it followed on cooling but according to some such line as *D C*. Cooling again caused the bar to return to *D* and then continue along the curve toward *E*. At low temperatures under certain circumstances the contraction along such a line as *C D* might continue perhaps 15° C. beyond the curve *B E*, and then be followed by a sudden change which brought the bar to the same length it would have reached at

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[7] 1 $\mu$ (1 micron)=0.001 mm.

the existing temperature if it had followed the curve *B E* immediately after reaching *D*—a phenomenon analogous to the undercooling of a saturated solution or of a liquid that has passed below its normal freezing temperature.

Since by appropriate cooling the changes of length with temperature may be made to follow any such line as *C D*, it is evident that the coefficient of expansion, which is proportional to the slope, may, for the very same bar, be caused to assume any desired value between the limits allowable by the transformation. These limits may include values ranging all the way from 10 millionths to 20 millionths. In the case of the 15 per cent nickel steel, illustrated in Figure 20, lowering the temperature to −60° C. was not sufficient to complete the transformation into the state which is stable at very low temperatures.

All the irreversible nickel steels exhibit the phenomena just described, which correspond strikingly with the magnetic anomalies discussed in Section III. They differ from one another only in the magnitude of the changes and in the particular temperature regions within which the transformations occur.

(*b*) REVERSIBLE ALLOYS.—The expansion phenomena exhibited by the reversible nickel steels appear to be quite different. By applying the principle of corresponding states to the results of measuring different alloys within a moderate temperature range Guillaume concluded that the thermal expansion of a reversible nickel steel would be represented by a curve having the general characteristics of the uppermost curve shown in Figure 21. Expansion measurements carried up to 900° C., which were published by Charpy and Grenet in 1902, supported this conclusion.

On cooling a reversible alloy from a high temperature there is, first, a normal contraction following a nearly straight line *F E*, the inclination of which always corresponds to an expansivity greater than that of iron or of a mixture of iron and nickel at ordinary temperatures, and is reduced by increasing the proportion of nickel except for small nickel contents. Then, within the temperature range which is characterized by the appearance of magnetic properties, there is a region of rapid change *E D*, which is soon followed by a regular region *D C* of very small slope. At still lower temperatures this is followed by another region of rapid change, *C B*, and then by a regular one, *B A*, the slope of which corresponds to the expansivity of a mixture of iron and nickel at ordinary temperatures.

At ordinary atmospheric temperatures the expansivity of an alloy containing very little more than 25 per cent nickel would be represented, roughly, by *E F;* between about 27 and 32 per cent by *D E;* up to 36 or 37 per cent by *C D;* up to 48 or 50 per cent by *B C;* and above this, especially above 60 per cent, by *A B.* At higher temperatures each region corresponds to alloys containing greater proportions of nickel. The complete curve from *A* to *F* gradually deforms somewhat and shifts as a whole parallel to the axis of temperatures, following step by step the curve of magnetic transformation, Figure 12.

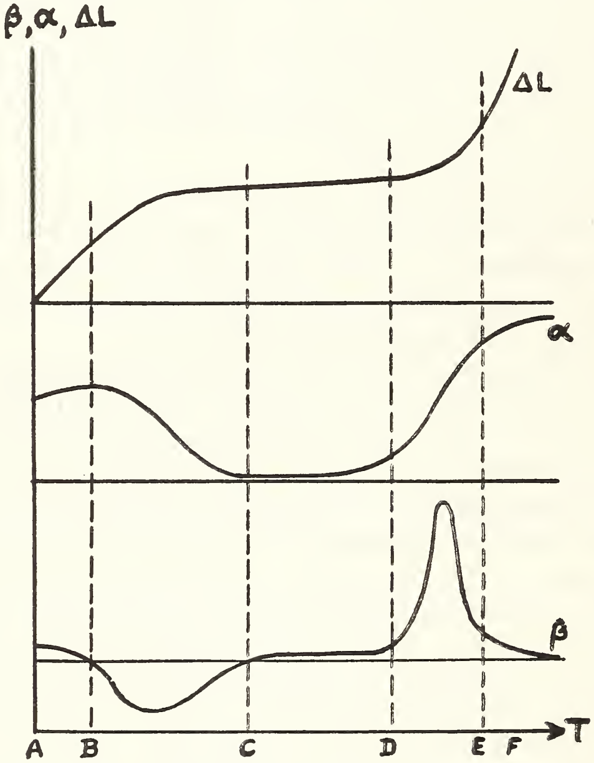

Fig. 21.—*Typical curves representing the variation of length (ΔL), true coefficient of expansion (α), and quadratic coefficient (β) with temperature in a reversible nickel steel. (Guillaume.)*

## 2. INFLUENCE OF COMPOSITION AND OF THERMAL OR MECHANICAL TREATMENT UPON EXPANSIVITY.

Tables 5 and 6 show how Guillaume found the thermal expansivity of nickel steels to change with the composition and with the temperature. Figures 22 and 23 (29) show how varying the composition affected the true coefficient of linear expansion and the quadratic coefficient at 20° C. These curves represent typical alloys containing 0.4 per cent manganese and 0.1 per cent carbon that had been cooled in the air after being rolled hot; that is, in the "natural state." The straight line *A B*, connecting the values of these coefficients for pure iron and nickel in the condition stable at low temperature and representing the results to which the law of mixtures would lead, shows clearly the magnitude of the anomaly. With regard to the quadratic coefficient, $\beta$ (fig. 23), this anomaly is positive at first and then becomes negative. The same appears at first sight to be the case with the true coefficient, $\alpha$ (fig. 22), but on following the line *C B*, which starts at the value of the coefficient for pure iron in the gamma state, the anomaly becomes entirely negative. It may also be seen that the expansibilities of the irreversible alloys are limited by the straight lines *A B* and *C B*. The lowest value, $\alpha = 1.19 \times 10^{-6}$, possessed by the

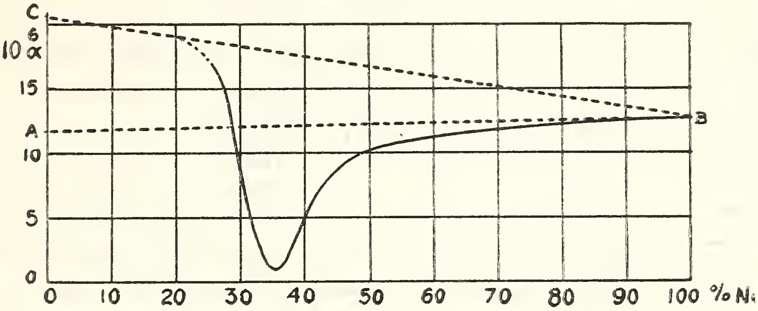

FIG. 22.—*True coefficient of linear expansion* ($\alpha$) *at 20° C. of typical nickel-iron alloys, containing 0.4 per cent Mn and 0.1 per cent C.* (*Guillaume.*)

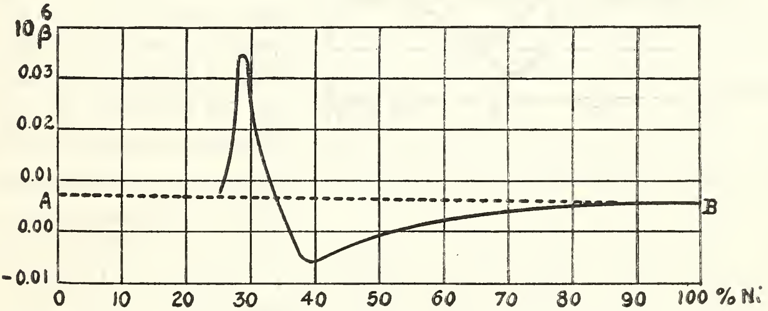

FIG. 23.—*Values of the quadratic coefficient* ($\beta$) *in the formulas for the linear expansivity of typical nickel-iron alloys, containing 0.4 per cent Mn and 0.1 per cent C.* (*Guillaume.*)

typical alloys corresponds to a nickel content of 35.6 per cent. In fact, these values would only hold true in an alloy in which the proportion of other elements than iron and nickel was fixed arbitrarily—of the order of the average quantities present in industrial alloys. Proportions of additional metals present in the alloys exert a considerable influence upon the position of the minimum, as will later be discussed. Figure 24 shows (25) the effect upon the expansivity of nickel steels produced by the addition of 1 per cent manganese or of chromium. Furthermore, all treatment—thermal or mechanical—which the alloys undergo modifies their expansibility; the value rising in case of heating followed by slow cooling but falling when the cooling is rapid, and still more so when the alloys are cold-rolled or drawn. It is thus possible by quenching a rod and then drawing it to the limit to reduce the value of the expansibility by an amount $1.5 \times 10^{-6}$ below that corresponding to the natural state, and thus to confer upon it a negative value. Then a moderate reheating, for instance, at 100° C. for several hours, brings the value up to the immediate neighborhood of zero. Realizing these facts, a method has been elaborated by Guillaume (29) whereby the production of kilometer lengths of invar wire, whose expansion with temperature can only be detected by most precise measurements, has been made possible—an accomplishment of great practical importance, especially to geodesy, and indicating what perfection has been attained in the industrial production of invar.

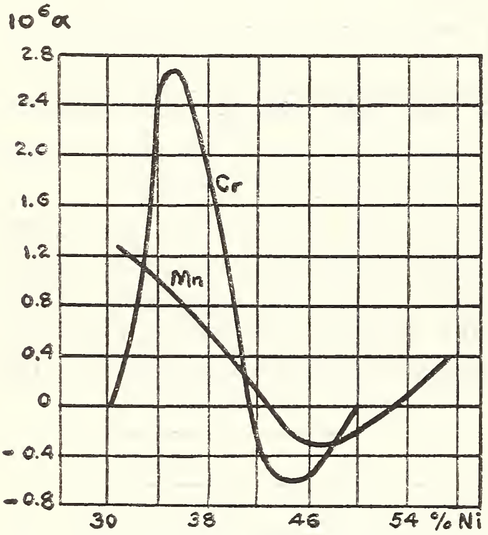

FIG. 24.—*Effect upon the linear expansivity of nickel steels produced by adding 1 per cent manganese or chromium. (Guillaume.)*

### 3. RULE OF CORRESPONDING STATES.

Guillaume (29) extended his expansivity measurements over a more extended range of temperatures, up to 220°, in order to determine the manner in which the quadratic coefficient $\beta$ varies.

He found that by taking the values of the expansibilities over the range of temperatures in question and plotting them against the nickel content the resulting curve is of a similar shape to that representing the expansibility of one and the same alloy through all the transformations which it undergoes over a large interval of temperature. From this was developed the "rule of corresponding states" for the reversible nickel steels, which when employed with care, for it is not a precise law, has proved of the greatest utility. In order to apply this rule one may start with the value of $\beta$ appropriate to the alloys containing 70 per cent nickel, at which percentage the temperature of magnetic transformation attains its maximum value, and pass progressively through the alloys of gradually diminishing nickel content down to that containing from 26 to 27 per cent nickel, for which the magnetic transformation occurs at the ordinary temperature. (See fig. 12.) On plotting the values of $\beta$ at ordinary temperatures against nickel content a curve is obtained, which proves to be none other than that found on plotting the value of $\beta$ for a single alloy against temperature over a considerable range. Referring to Figure 21, the value of $\beta$, starting at $A$, is positive, and the portion $A\ B$ of the expansion curve is slightly concave upwards. Next, the region of negative values for $\beta$ is entered, the curve bends downwards ($B\ C$) and then passes into the region of low coefficient of expansion ($C\ D$). $\beta$ then recrosses the zero line and becomes rapidly positive, its value reaches a maximum, then falls to the region of normal values, the coefficient of expansion remaining, however, very high ($E\ F$). The series of values thus deduced directly from $\beta$ is found to agree closely with that obtained on examination of the corresponding values of $\alpha$. Thus, from a comparison of the middle and lower curves of Figure 21, the unity derived from the consideration of corresponding states is seen to be perfect.

Guillaume (29) states that the results derived by the examination of the expansion of a great number of nickel steels over a range of 1,000° and also those of an extensive series of investigations made by Chevenard have verified the general forecasts made with the aid of the rule of corresponding states. They have at the same time shown that the expansion curve of the alloys gradually changes character. With increasing nickel content the range of temperature over which the volume remains practically constant becomes smaller and smaller, the expansion curve concurrently altering in slope, so that in the alloys of large nickel content no very low value of the coefficient is to be found anywhere within the total temperature range.

### 4. CHEVENARD'S INVESTIGATIONS ON EXPANSIVITY WITH TEMPERATURE.

By means of expansion measurements at temperatures ranging from −195 to over 700° C. and density measurements at ordinary temperatures Chevenard (10, 11, vol. 159) extended the earlier work of Guillaume and has accomplished much in the way of giving us organized knowledge of the peculiarities of nickel steels of low-carbon content. His experiments, published in 1914, were conducted on a graded series of 26 forged alloys containing from 0 per cent to 98 per cent nickel. These contained less than 0.05 per cent carbon, less than 0.10 per cent silicon, and a total of foreign elements which hardly exceeded 0.50 to 0.70 per cent. Chevenard, as well as Guillaume, states that the most important of the additional elements is manganese, and that a minimum amount is indispensable for mechanical working, as was previously noted by Dumas.

Before measuring expansions Chevenard took the precaution to have all his specimens cooled sufficiently to transform them completely into the state which is stable at very low temperatures. Some of them were cooled with liquid hydrogen to −253° C. (20° K.) by Kamerlingh Onnes in the cryogenic laboratory at Leyden. After these had returned to room temperature they were found to have been permanently elongated by the following amounts:

| Per cent Ni. | Millimeters per meter. |
|---|---|
| 25.9 | 7.6 |
| 29.2 | 5.5 |
| 30.6 | 5.0 |
| 31.9 | 1.2 |
| 33.5 | 0.3 |
| 34.1 | Imperceptible. |
| 35.4 | Imperceptible. |

The change in dimensions of the 31.9 per cent alloy was found to be exactly the same if the cooling was carried to only −195° C. instead of −253°. Consequently, the transformation of this alloy, which begins at about −125°, is entirely completed at −195°, so that the vanishing of the irreversible elongation can not be ascribed to failure to effect complete transformation. From this Chevenard, bearing in mind the results obtained magnetically by Weiss and his pupils, concludes that the limit of the irreversible alloys corresponds to the compound $Fe_2Ni$ (34.45 per cent nickel).

(*a*) IRREVERSIBLE ALLOYS.—This conclusion is further supported by the curves of Figures 25 and 26, which represent the elongations found by Chevenard on changing the temperature of his irreversible steels in the directions indicated by the arrows.

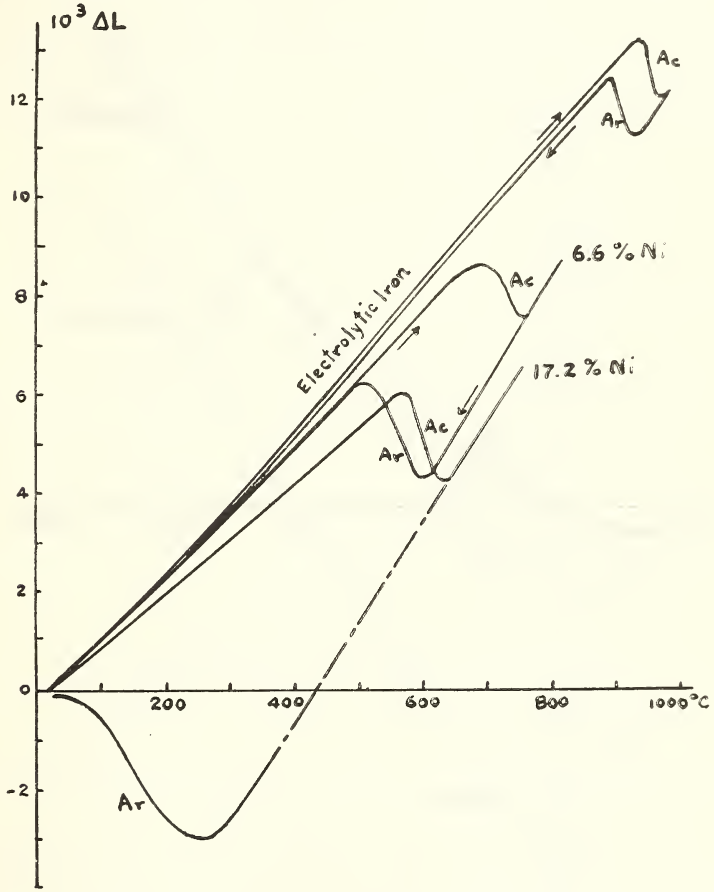

FIG. 25.—*Variation of length with temperature in electrolytic iron and in irreversible nickel steels having compositions between Fe and $Fe_2Ni$. (Chevenard.)*

When the iron is very pure, the two temperatures Ac and Ar (which mark the beginning of the transformation on heating and on cooling) differ but few degrees. The addition of nickel produces, on the one hand, a lowering of the transformation Ac, and, on the other, a considerable increase in the difference Ac–Ar. For a given alloy this difference depends upon the conditions of cooling, principally on the rate of temperature change; but if the experiment is repeated with slower and slower rates, the difference Ac–Ar will be found to approach a finite limit which is the true thermal hysteresis of the transformation.

When the proportion of nickel exceeds 25 per cent, the point Ar falls below ordinary room temperatures (fig. 26). Consequently, nickel steels containing more than 25 per cent habitually show the characteristics of the state which is stable at high temperatures, and behave quite differently from the steels containing less nickel, which are normally in the state that is stable at low temperatures. In the 31.9 per cent alloy the transformation point Ar is at −125° C. Comparison of the curves for the two alloys represented

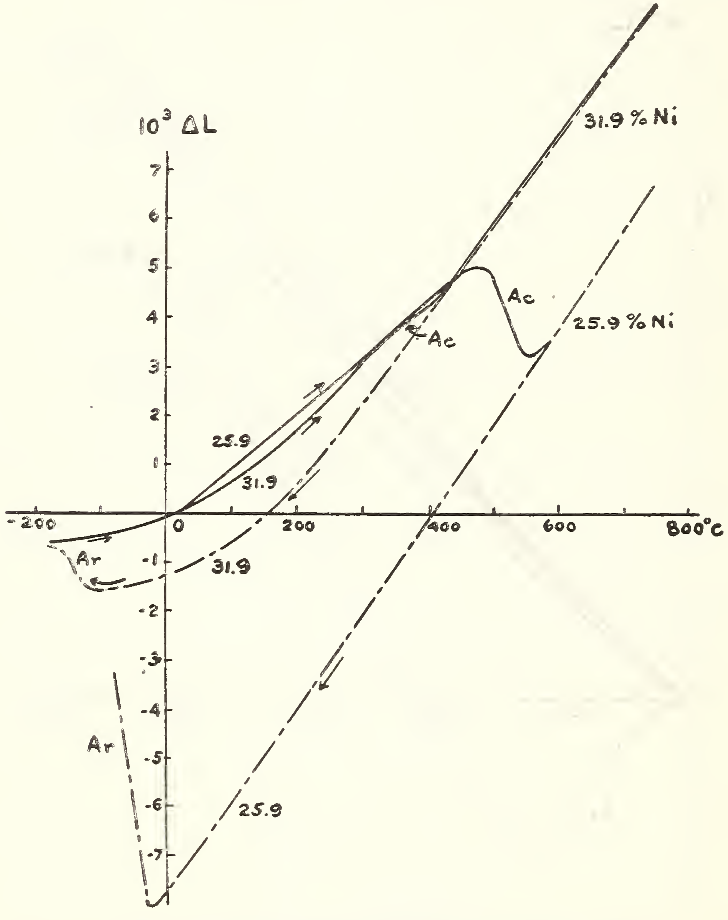

FIG. 26.—*Continuation of Figure 25. (Chevenard.)*

by Figure 26 shows that as the proportion of nickel approaches that in the compound $Fe_2Ni$ the length change accompanying the irreversible transformation diminishes and appears to approach zero as a limit.

(*b*) REVERSIBLE ALLOYS.—The alloys comprised between the limits $Fe_2Ni$ (34.45 per cent Ni) and $FeNi_2$ (67.75 per cent Ni) were found to be reversible and to follow expansion curves having the general characteristics of Figure 21 discussed above. Figure 27 reproduces a group of such curves. It is seen that the alloy of composition approximating invar (35.4 per cent Ni) behaves normally as to expansion above 200° C., and, in fact, has very closely the constants of Bessemer steel.[8] The variation in the true coefficient of expansion of each alloy is represented by Figure 28, which shows clearly how the anomaly changes progressively with the composition. The corresponding curves for the alloy containing 34.1 per cent nickel (very nearly $Fe_2Ni$) are given separately

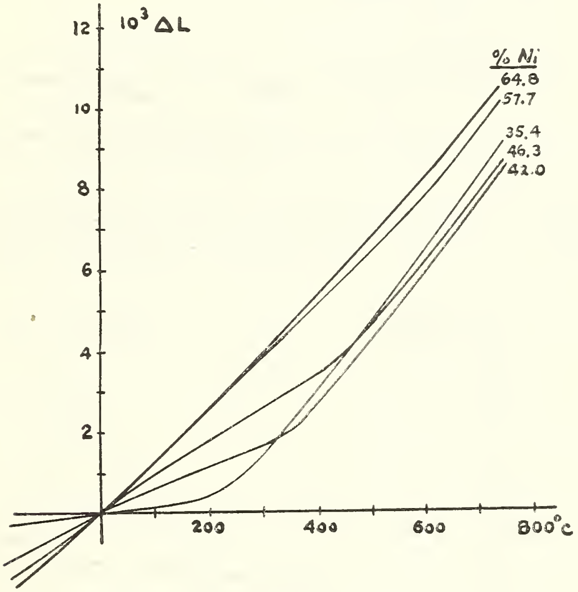

FIG. 27.—*Continuation of Figure 25. Reversible nickel steels with compositions between $Fe_2Ni$ and $FeNi_2$. (Chevenard.)*

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[8] The results of careful determinations made by Souder and Hidnert (Bureau of Standards Scientific Paper No. 433, "Thermal Expansion of a Few Steels," 1922) on the expansivity, over the temperature range 0—900° C., of a 34.5 per cent nickel steel (with 0.14 per cent C.) are in good agreement with those of Chevenard for the 34.1 per cent and 35.4 per cent nickel alloys with respect to the contour of the expansion curves shown in Figures 27 and 29, though the values for the expansivity with temperature obtained by the former are a little higher than those for both of Chevenard's alloys.

in Figure 29. This alloy is the only one of the group that does not show a bend corresponding to *B C* in Figure 21; that is to say, its true coefficient of expansion always decreases with cooling until at least −150° C. The bend *B C* appears in the alloy of

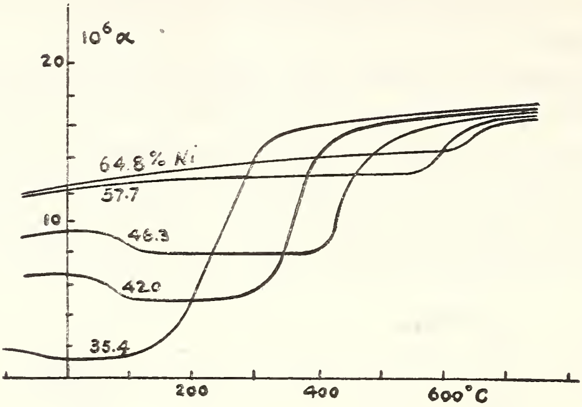

FIG. 28.—*Variation of the true coefficient of linear expansion with the temperature in the nickel steels represented in Figure 27. (Chevenard.)*

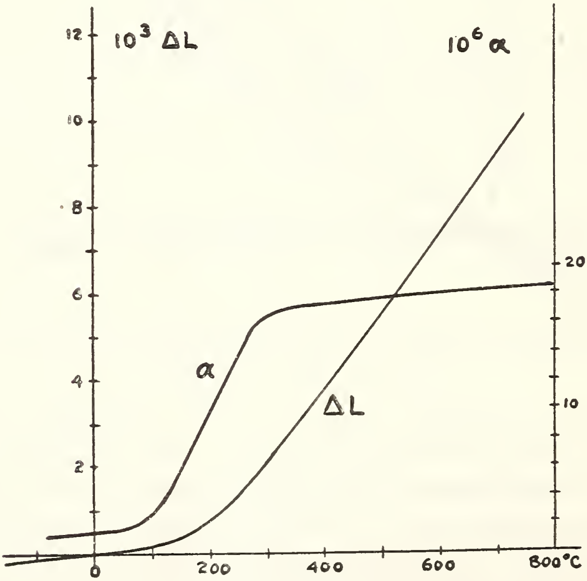

FIG. 29.—*Variation of length and of the true coefficient of linear expansion with temperature in a reversible steel containing 34.1 per cent Ni. (Chevenard.)*

35.4 per cent, and the curve of the true coefficient has a minimum—the minimum of invar.

From these results it appears that the reversible anomaly gradually disappears as the alloy approaches the composition corresponding to $FeNi_2$, which contains 67.75 per cent nickel.

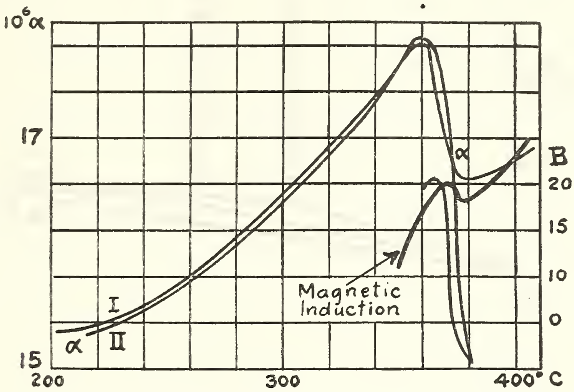

FIG. 30.—*Variation of the true coefficient of linear expansion and of magnetic induction with temperature within the critical region of electrolytic Ni.* (*Colby.*)

Various observers have noticed peculiarities in the thermal expansion of nickel at temperatures above 300° C. Colby (12) examined three specimens of different origin and found that all showed abrupt changes in the value of the true coefficient of expansion as ferromagnetic properties disappeared on heating. The curves which he obtained with a sample prepared electrolytically are reproduced in Figure 30. Chevenard's measurements indicate that the ferronickels comprised between the limits $FeNi_2$ and Ni show expansion anomalies of the same sort, decreasing with the addition of iron to pure nickel until they disappear completely when the composition $FeNi_2$ is reached. He found that the change with temperature in the true expansion coefficient of such an alloy was represented by two straight-line segments meeting on the ordinate through the Curie point, as shown in Figure 31, and he points out that in the whole series of ferronickels the one having the composition $FeNi_2$ is the only one the expansion of which can be represented by a single parabolic function of the temperature between 0 and 800° C.

Figure 32 is a résumé of Chevenard's expansion measurements on nickel steels. Each curve shows how varying the proportion of nickel affects the true coefficient of linear expansion at the temperature indicated. The alloys containing less than 34.45 per cent nickel are represented in the state that is stable at high temperatures, in which state their properties are reversible. The curve for 0° C. differs but little from Figure 22, which Guillaume derived from measurements of far greater precision.

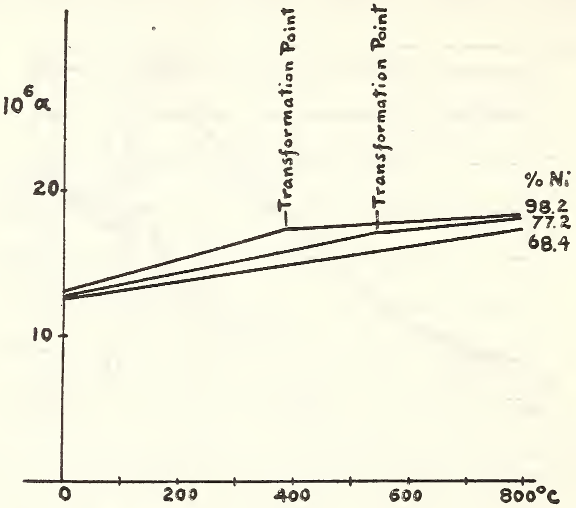

Fig. 31.—*Variation of the true coefficient of linear expansion with the temperature in reversible nickel steels having compositions between $FeNi_2$ and Ni.* (*Chevenard.*)

The curve for 700° C. begins at the point corresponding to 5 per cent nickel, because alloys containing less than this amount do not exist at 700° C. in the state which is stable at high temperatures. Nevertheless, it is interesting to note that if this curve,

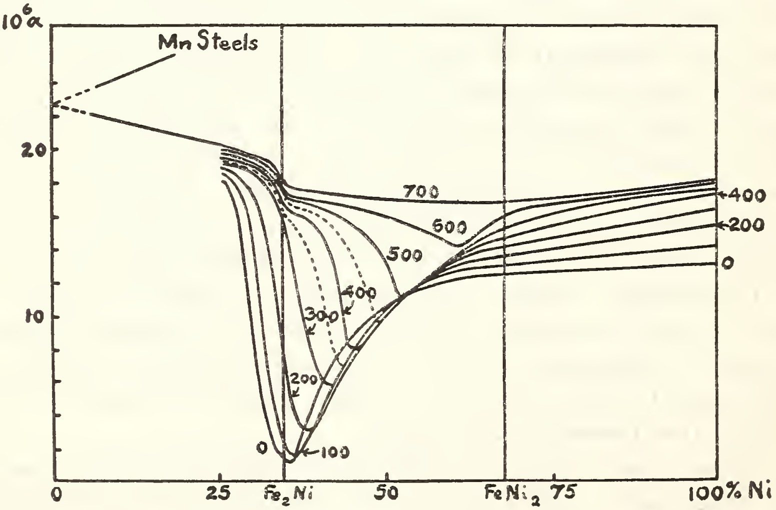

Fig. 32.—*Variations in the true coefficient of linear expansion of Ni steels at various temperatures.* (*Chevenard.*)

which is almost a straight line, is prolonged backward it will cut the ordinate corresponding to pure iron in the same point as the prolongation of the line through the results of measurements on nickel steels containing considerable amounts of manganese. Chevenard refers to this point as indicating (hypothetically) the expansion coefficient of $\gamma$ iron at 700° C.

### 5. THEORIES AS TO CAUSE OF IRREVERSIBLE AND REVERSIBLE PHENOMENA.

The expansion investigations of Chevenard, supplemented by his measurements on density (which will be treated in a later section), led him to the following general conclusions concerning the ferronickels: The irreversible phenomena are associated with the transformation of iron; the reversible anomaly with a modification of the compound $Fe_2Ni$. While the external manifestations of these phenomena show such common features as reduction of volume and increase of rigidity on warming, nevertheless there is an essential difference between the two.

According to Chevenard, the *irreversible transformation* consists in a reaction between the two solid solutions

$$(Fe\,\alpha + Fe_2Ni) \rightleftarrows (Fe\gamma + Fe_2Ni),$$

each of which can exist within a certain temperature region. The two members of the reaction are two different phases, and the passage from one state to the other is accompanied by change in crystalline structure.

The *anomaly*, on the other hand, consists of a progressive and reversible modification of the properties of the alloys, which is spread over a large temperature interval. The reversible anomaly reaches a maximum in the neighborhood of the compound $Fe_2Ni$ and gradually disappears on approaching the composition $FeNi_2$, which forms the boundary between the anomalous reversible alloys and those showing the peculiarities of nickel.

Disagreeing with the explanation thus advanced to show that the nonexpansibility of invar is due to a property characteristic of the compound $Fe_2Ni$, Honda and Takagi (42, 43) offered a theory accounting for this phenomenon without assuming the existence of any compounds.[9] The characteristic form of the critical point-concentration curve of the constitutional diagram was explained on the basis of ferromagnetism possessed by the

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[6] It is of interest to note here that Andrews (Phys. Rev., **18**, p. 245; 1921) in an X-ray analysis of a series of pure iron-nickel alloys obtained no evidence as to the existence of such a compound as $Fe_2N$, or any change in structure in the neighborhood of 35 per cent Ni.

constituents of the alloy. To express in general terms, iron is more ferromagnetic than nickel, and the addition of the former to the latter, or vice versa, increases or decreases, respectively, the ferromagnetism of the resulting alloy, consequently raising or lowering the critical point of the alloy. They attributed the irreversibility of nickel steels to the $A_3$ transformation as affected by the nickel in solid solution, and expressed their belief that the irreversibility did not terminate at 35 per cent nickel but probably extended to about 70 per cent nickel.

Finally, Guillaume stated in 1920 (29) that there was as yet no complete and final theory explaining the phenomena displayed by the nickel steels. He, however, has offered a tentative sketch (shown in fig. 33) throwing light on the main causes of these phenomena. In the pure metal gamma iron exists unaccompanied at all temperatures above 890° C. Up to that point iron expands along *A B* according to a function affected by an important quadratic term; at that point it undergoes a sudden contraction *B C*, and then resumes its expansion with a greater coefficient, of the value $23 \times 10^{-6}$ but with smaller curvature *C D*. When a metal is added to the iron, forming a solid solution with it, the transformation temperature of the resulting alloy is lowered and at the same time it will cease to be sudden, being spread over a longer and considerable period as the transformation temperature is lowered. The abrupt dip is thus converted into a more

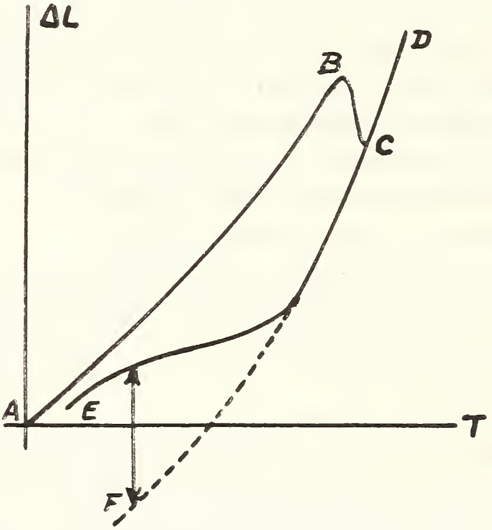

Fig. 33.—*Expansion curves of pure iron and of a solid solution. (Guillaume.)*

gradual curve *C E*, at each point of which the change of volume accompanying the transformation is superposed on the ordinary expansion (contraction) curve *D C F*, and the two phenomena being of opposite signs the result is the negative anomaly revealed by experiment. Guillaume adds that this theory, applied in detail, gives an adequate explanation of reversible transformation; but in the case of irreversible changes another factor intervenes. The intersection of the transformation curves discovered by Dumas has been followed to the fullest extent by Chevenard, who has shown that as the nickel content increases the irreversible transformation diminishes in degree, whilst at the same time the temperature of transformation falls, the transformation vanishing in the alloy containing 34.4 per cent nickel, corresponding to the formula $Fe_2Ni$. Chevenard has thus been led to attribute an important rôle in irreversible transformations to this definite combination which corresponds very closely to the maximum of the anomaly.

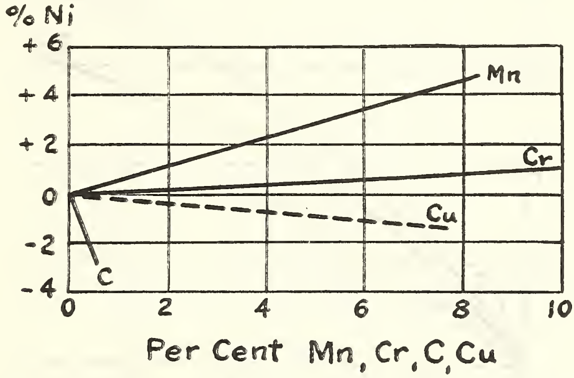

FIG. 34.—*Displacement of the abscissa of the minimum of expansibility of the nickel steels as a function of the proportions of a third constituent.* (*Guillaume.*)

Abscissas denote percentages of the additional constituent (Mn, Cr, Cu, C); ordinates denote the changes in percentages of nickel content, starting from the content corresponding to the minimum in the typical alloys.

## 6. EFFECTS OF ADDITIONS AS CHROMIUM, ETC., ON ANOMALY OF EXPANSIVITY.

Guillaume (28, vol. 170) made an extensive study on the influence of additions as chromium, manganese, carbon, and copper made to iron-nickel alloys upon the expansivity of these alloys. His results may be summarized in Figures 34 and 35, which will enable one to follow the displacement of the minimum expansivity, both as regards abscissas and ordinates, produced by the presence of the added element. In Figure 34 the zero point of the ordinate corresponds to the nickel content of invar, to start from which the abscissa of minimum expansivity for the ternary alloy is displaced toward the nickel content—a higher nickel content in the case of manganese and chromium and a lower nickel content for carbon and copper—according to the amount of the addition represented by the abscissa in per cent, made to the alloy. Figure 35 shows the change produced in the minimum expansibility in the nickel steels when a third constituent is added, starting from the minimum value found in typical alloys as invar. The rest of the expansibility curve (see fig. 22) rises as a whole, so as gradually to obliterate the depression representing the anomaly. But on account of the displacement in abscissas in the three cases in which this is very rapid (Mn, C, and Cu), there occurs to the right of the minimum for Mn, to the left for C or Cu, a narrow range of contents within which the ternary alloys may have a coefficient of expansion slightly less than that of the iron-nickel alloys.

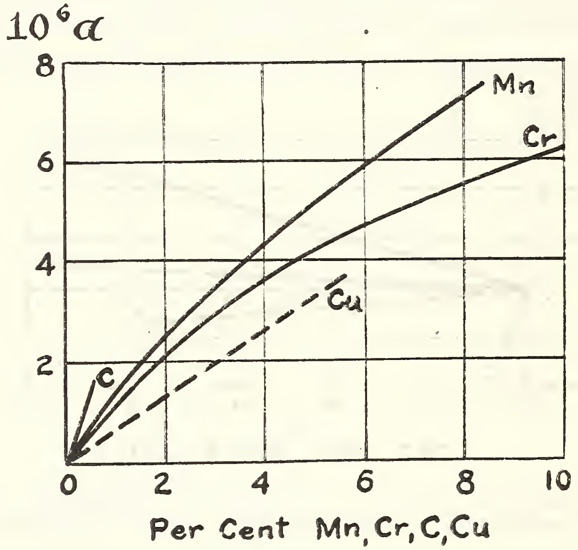

FIG. 35.—*Change in the minimum expansibility of the nickel steels when a third constituent is added. (Guillaume.)*

Abscissas denote percentages of the added element; ordinates denote the changes in $10^6\alpha$ at 20° C., starting from the minimum value appropriate to the typical alloys.

The effect of chromium additions upon the anomaly of expansibility in reversible ferronickels was studied by Chevenard (11, vol. 172), whose results are presented in diagrammatic form in Figures 36 and 37. In order to characterize numerically the intensity of the anomaly, the total amplitude of the relative change of length resulting from the transformation (*Ao*) as distinguished from the normal expansion was adopted. In Figure 36, representing the results as determined for a 40.4 per cent nickel steel over a temperature range of −183 to 900° C., the experimental expansion curve *C* joins a hypothetical curve of normal expansion, *c*, at an elevated temperature where the transformation has been completed. The differential curve, Γ, is a measure of the difference of values represented by curves *C* and *c* and is extrapolated as far as to absolute zero. The ordinate at the origin is the total anomaly, *Ao*. Figure 37 illustrates the lowering effect upon the extent of the total anomaly, *Ao*, as well as the shifting of the maximum point to higher nickel content, of chromium additions. Curve *I* expresses the variation of total anomaly of a pure ferronickel containing no chromium but a small quantity of manganese (0.3 to 0.7 per cent) added in order to make the alloy forgeable, in function of the nickel content. It rises rapidly from a point on the abscissa corresponding to about 25 per cent nickel, for which nickel content the Curie point approaches absolute zero, until it reaches a well-pronounced maximum point at a nickel content corresponding to the compound, $Fe_2Ni$.

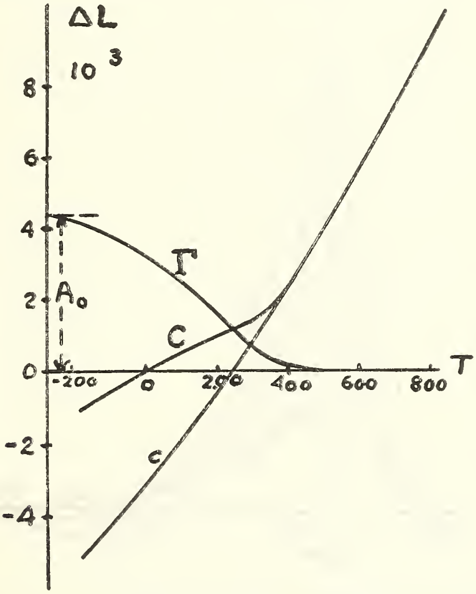

FIG. 36.—*Intensity of anomaly, Ao, in a 40.4 per cent nickel steel.* (*Chevenard.*)

Descending from this point somewhat less rapidly it again reaches the abscissa at about 58 per cent nickel, corresponding to the point where the experimental expansion curve meets the hypothetical normal expansion curve. The *Ao* then changes in sign, and finally from 80 to 99 per cent nickel it again changes in sign twice, but preserves a very weak intensity. Curves *II*, *III*, and *IV*, representing ferronickels with 5, 10, and 15 per cent chromium, respectively, have, in general, similar forms as curve *I*, though with their maxima lowered in progressive degree. It has been suggested that the intense diluting action which chromium exercises on the anomaly of ferronickels may be due to the formation of the compound $Ni_2Cr_3$. Chevenard recently (11, vol. 174) has studied the expansibility of commercially pure chromium and of a series of nickel-chromium alloys containing up to 16 per cent chromium over the temperature range 0 to 900° C. He concluded that the addition of chromium, which is much less dilatable than nickel, affects the expansibility of the latter a little at ordinary temperatures, though this effect tends to increase at elevated temperatures, and that this considerable discrepancy with respect to the rule of mixtures is probably attributable to the presence of the compound $Ni_2Cr_3$, whose existence has been pointed out by Voss (71) in his equilibrium diagram for Ni-Cr alloys.

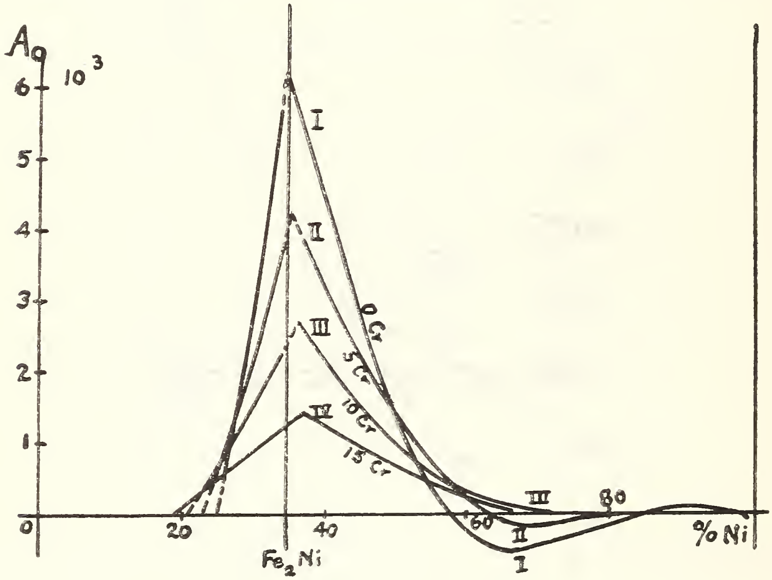

FIG. 37.—*Effect of chromium additions upon total anomaly, Ao, of reversible nickel steels.* (*Chevenard.*)

## VI. CONSTANCY IN THE DIMENSIONS OF INVAR.

### 1. TRANSITORY LENGTH VARIATIONS FOLLOWING TEMPERATURE CHANGES.

In outlining the principal characteristics of the thermal expansion of nickel steels certain secondary phenomena were left out of consideration, although important in the practical application of reversible alloys where precision is a requisite. In reality the expansion does not follow rigorously a unique curve of the type shown in Figure 21. After effects, similar to those observed in glass, are quite pronounced, so that the length of a bar at a given temperature depends, at least in the beginning, on the temperatures to which it has previously been subjected, and also on the rapidity with which the final temperature has been attained.

Consider, for example, a forged bar in the state corresponding to the region *C D* of Figure 21, and suppose that its dimensions be measured from time to time while it is maintained constantly at any given temperature. If the bar had previoulsy been exposed to a higher temperature, it will, after completing the main contraction accompanying the attainment of temperature equilibrium, slowly elongate somewhat in the course of time. If, on the other hand, the bar has been brought to the given temperature from a lower one, it will contract. The duration of such length changes is always greater when the final temperature is reached by cooling than when it is reached by heating. In either case the higher the temperature the greater the speed with which the changes occur. Guillaume found that a meter of invar brought to 100° C. immediately after forging elongates at the rate of about 0.067 $\mu$ per minute, whereas if brought to 100° C. after a long rest at room temperature it contracts at the rate of 0.8 to 0.9 $\mu$ per minute. At 15° C. the elongation is 0.07 to 0.08 $\mu$ per day after forging and 0.03 $\mu$ per day after annealing to 40° C. Again after a long rest at room temperature (10 to 20° C.) the contraction that occurs after assuming a higher temperature is complete in about half an hour at 100°, but continues for several days at 40°.

### 2. PERMANENT CHANGES IN LENGTH AT CONSTANT TEMPERATURE.

In addition to these transitory length variations that follow change of temperature there are other changes that continue for a long time while the temperature remains constant. Thus, a bar of invar left to itself at any constant temperature gradually elongates slightly, at first rapidly, then more and more slowly, following an exponential function of the time as it approaches asymptotically a definite length. The rate at which this limiting length is approached increases with the temperature. In order to reduce these secular changes to a minimum Guillaume (28, vol. 163, p. 654) employs an ageing process or heat treatment which he calls étuvage (steaming or stewing) to differentiate it from the ordinary process of annealing (recuit). After the bars have been forged they are subjected to a series of very slowly decreasing temperatures, starting, for example, at 100° C. and ending at 20 or 25° after an interval of two or three months.

### 3. HEAT TREATMENT OF FORGED BARS.

The effects of heat-treating forged bars are shown in Tables 7, 8, and 9 and in Figure 38 (26). The upper curve of this figure represents the elongations observed during a period of 4,500 days in a bar of invar simply cooled in the air after forging at red heat and then maintained almost constantly below 20° C. The lower curve represents the changes in a similar bar which had previously been reheated to 150° and then cooled in 50 days to 40°. Other experiments have shown that a bar of the same alloy cooled gradually for several weeks more down to 25° elongates afterwards according to the same curve, but starting from the point of which the coordinates are 100 days and 3 $\mu$ per meter. A curve

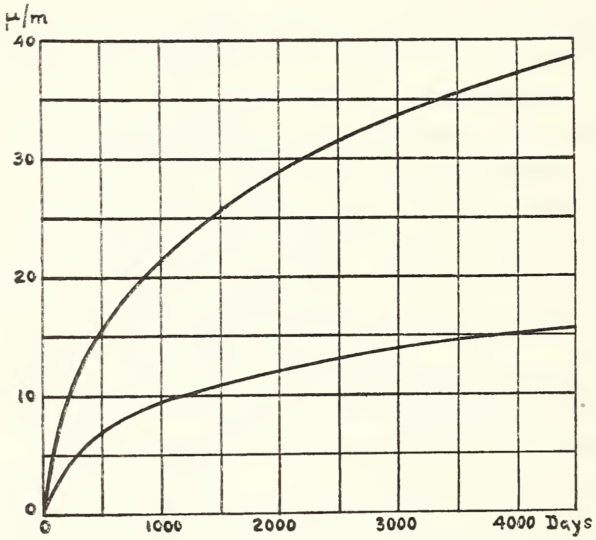

Fig. 38.—*Elongations in microns per meter of invar with time. (Guillaume.)*

Upper curve, forged bar not treated; lower curve, forged bar cooled in 50 days from 150 to 40° C.

which is almost the same has been found for bars that have been quenched or drawn, and even for wires, kept at the temperature of the laboratory after very slow cooling from 100 to 25°. On the other hand, rest at a higher temperature has continued the effect of the previous heatings and accelerated the elongation. In this way invar wires used for geodetic measurements in equatorial Africa have been found elongated after several years by three or four millionths of their length beyond what would be predicted according to the curve.

That the thermal expansivity of nickel steels is increased somewhat by the process of very slow cooling appears on examining the last column of Table 9; but after this treatment has once been completed the expansivity appears to remain constant for a long period, as is seen in the case of bars Nos. 6 and 7. Quenching, on the other hand, has been found to lower the expansivity of invar.

### 4. BEHAVIOR OF DRAWN BARS.

Guillaume has found the behavior of drawn bars somewhat different from that of forged ones. The first reheating to 100° C. caused an elongation for several hours followed by a contraction. At lower temperatures they behaved as forged bars, even if the contraction at 100° had hardly commenced. A drawn bar kept for a long time at the temperature of the laboratory and then brought to 100° shortened for perhaps half an hour, then elongated for several hours, and finally shortened again for more than 100 hours. Thus one can observe successively in the same bar three distinct variations, differing in magnitude and in duration, of which the first two resemble those observed in forged bars, while the third is peculiar to drawn bars.

### 5. ELONGATION OF INVAR WITH TIME.

Table 10 gives the elongations which a drawn forged bar of invar undergoes in the course of time counted from the completion of a gradual cooling lasting three months, starting at 100° C. and finishing at 25° C.; but in applying these corrections to the length of a geodetic wire or tape the time is never counted from this point, since a wire or tape is rarely in suitable condition for calibrating until four or five months later. If, for example, calibration takes place 200 days after the cooling process is completed, a year still later the length indicated by the calibration equation should be corrected by adding $4.7-2.5=2.2\ \mu$ per meter. Benoît and Guillaume (4) have found the corrections in Table 10 to hold for wires kept in the laboratory; but after use in the field under extremes of climate these values should be considered only as provisional, and the equation of the wire should be checked by a new direct determination.

### 6. RANGE OF TRANSITORY LENGTH VARIATIONS FOLLOWING TEMPERATURE CHANGES.

The transitory length changes discussed at the beginning of this section are similar to variations which occur in reaching a state of chemical equilibrium that depends upon the temperature. As there stated, the higher the temperature the more rapidly is this equilibrium attained. These variations leave the expansion of a bar of invar indeterminate between two extreme limits, namely, that corresponding to sudden attainment of the final temperature and that corresponding to a rest at this temperature which is theoretically of infinite duration. For a temperature $t$ between 0 and 100° C. the difference between these two limits has been found to be well represented by the empirical formula—

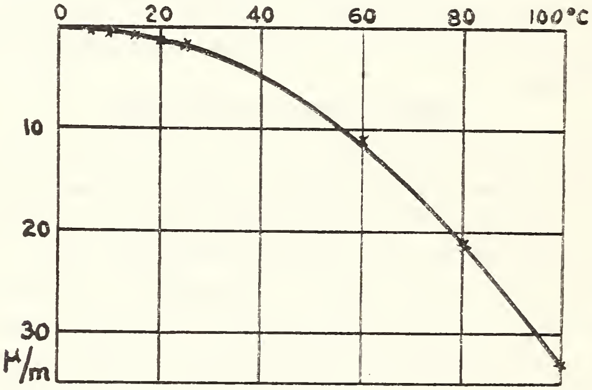

Fig. 39.—*Temporary variations, in microns per meter, in the length of invar following rapid change in temperature. (Benoît and Guillaume.)*

$$\Delta L/L = -0.00325 \times 10^{-6} t^2$$

Figure 39 represents the results of measurements, together with those given by the interpolation formula. The latter are also collected in Table 11.

### 7. RAPIDITY OF INVAR TRANSFORMATIONS.

Observations made upon the speed of transformation of invar lead to this practical rule: At ordinary temperatures consider daily variations as sudden and seasonal variations as infinitely slow. For example, if invar were employed in a base measurement, the mean temperature of the weeks immediately preceding would be considered as attained slowly, whereas the equation for thermal expansion is based on rapid changes, so that if the mean temperature of the season were 20° C., while the equation of the invar had been determined after a long rest at 12°, the length should be corrected by $-1.3+0.4$ or $-0.6-0.3=-0.9\,\mu$ per meter for all the observations during the course of several days. Then, in addition, each separate measurement should be corrected for the temperature existing at the time of observation by applying the expansion formula determined during the calibration. Inspection of Table 11 shows that an uncertainty of 5 or 6° in the temperature assumed for the season does not ordinarily affect a length determination by one part in a million. Except under very unusual conditions, then, one can apply these corrections with a certainty entirely sufficient for the needs of geodesy.

## 8. EFFECT OF COMPOSITION ON INSTABILITY.

Guillaume has found that at a given temperature the instability of a nickel steel is greater the nearer this temperature is to that at which the alloy loses its magnetic properties. At ordinary temperatures the stability as regards variations produced either by time or by temperature change is increased by adding nickel up to a maximum of about 43 per cent. On exceeding this amount the direction of the length change becomes reversed, the contraction with time increasing slightly on adding still more nickel, but never becoming very great. A bar containing 43.6 per cent was measured immediately after forging and was then submitted to a gradual cooling from 100 to 30° C., which lasted three months. After this treatment its length was found only 0.7 $\mu$ per meter shorter than immediately after forging. A meter of 44.2 per cent nickel steel was shortened 2.6 $\mu$ by 66 hours at 100° immediately after forging. It then contracted 0.4 $\mu$ more during 2,000 days and 1.1 $\mu$ during 4,000 days at room temperature. A meter containing 56.2 per cent nickel was shortened 8.8 $\mu$ by 130 hours at 100° and subsequently 2.5 $\mu$ by 2,000 days at room temperature.

Later, in a study made of ternary alloys, Guillaume (28, vol. 171, p. 1039) established the fact that the cause of instability was entirely due to the presence of carbon. Acting on the hypothesis that the stabilizaton of nickel steels is related to the absence of iron carbide, $Fe_3C$, or to the addition to the alloy containing some carbon of a metallic constituent as chromium, tungsten, or vanadium having a greater affinity for carbon than for iron, with the consequent formation of the carbide of the element added, and thus eliminating in a more or less complete degree the presence of iron carbide, he attained almost complete success by producing an invar, even in the form of a casting, containing very little carbon and a slight amount of chromium which showed a stability 10 times greater than that by ordinary invar containing 0.1 per cent carbon. The expansivity of almost stable alloys remains slight, for the tendency of chromium to raise the position of the minimum of anomaly is counterbalanced by the lowering action due to the deficit in carbon content as compared with that present in the usual alloys. He concluded that in order to attain complete stability it would seem necessary to add to the alloy an excess amount of the third metal, and consequently, in view at least of the extraordinarily small amount of carbon, the expansivity would rise a little above the normal minimum. It might then be necessary, in order to obtain alloys of an absolute stability, to tolerate in the natural state an expansivity of the order of $2 \times 10^{-6}$, which assuredly could be lowered by thermal and mechanical treatment in the same manner as with ordinary alloys, however, with an action much weaker than that of long-continued heating (étuvage).

The alloy of 42 per cent nickel is preferred for constructing standards of length because of greater stability than is possessed by invar, resistance to oxidation, and a thermal expansivity appreciably less than that of platinum. The alloy of 56 per cent, having an expansivity about the same as that of ordinary steel, and at the same time being more stable and less subject to corrosion, can be used in industrial measuring machines to avoid temperature corrections in testing the dimensions of steel parts.

### 9. REPRODUCIBILITY OF THE PROPERTIES OF INVAR.

As to the uniformity of invar, it may be said that different wires from the same melt and subjected to treatments that are apparently identical show measurable differences in thermal expansivity; but the average deviation of these from the average does not amount to more than $\pm 0.03 \times 10^{-6}$; so that if the same expansion formula is adopted for all the wires or bars from the same melt it will require on the average a difference of 30° C. between the temperature of calibration and that of use to introduce an error of one part in a million. This is more than is required for actual geodetic operations. Since the conditions for producing small expansivity are now well established, wires are regularly made which, after heat treatment, show an expansivity that does not exceed $\pm 0.1 \times 10^{-6}$ per degree. Thus, a precision of one part in a million does not require a knowledge of the temperature closer than about 10°.

### 10. INVESTIGATION OF NICKEL STEELS BY THE BUREAU OF STANDARDS.

In cooperation with the Midvale Steel Co., the Bureau of Standards conducted several years ago an investigation for the purpose of producing American steels of specified thermal expansivity, combined with stability of dimensions and other desirable properties. Steels of small expansivity were studied to determine the effect of various thermal, magnetic, and mechanical treatments, as well as of slight variations in the constituents. Expansion measurements were made at many temperatures distributed between −150 and +620° C. In conformity with the experience of Guillaume it was found that cold-drawing and quenching lower somewhat the expansivity at room temperatures while annealing raises it. Also, the curve representing the expansion on heating was found to lie above that representing the contraction on return to room temperature, except in the case of a cold-drawn specimen, in which the relation was reversed. At any temperature, however, above that at which the alloy assumes ferromagnetic properties on cooling the length was always found to be the same whether the temperature in question was reached by warming or by cooling.

The effects of cold-drawing, annealing, and quenching are apparent from the following figures, which give in millionths per degree centigrade preliminary values of the true coefficient of linear expansion at 20° C. found on warming specimens of the alloy marked No. 6 in Table 15 after they had been subjected to the treatments indicated:

| Treatment. | A. | Annealed B. | Quenched C. |
|---|---|---|---|
| Rolled | 1.2 | 1.7 | 0.7 |
| Cold-drawn | .3 | 1.2 | .7 |

Additional significant figures are not given here because even those that are given may be expected to vary a few units in the last place with different specimens that are supposed to have the same composition and to have undergone the same treatment.

Even after warming the specimens just described to 100° C. the coefficients at 20° C. were found to have changed, and in some cases greatly changed.

Magnetostriction measurements were also made at various temperatures extending from −75 to over 300° C., and the expansion measurements were carried up to 620° C. Observations made by Nagaoka, Honda, and Shimizu were confirmed and extended. (See Sec. III.) It will suffice to mention here that complete magnetostriction cycles showing hysteresis, similar to those first observed by Nagaoka in the case of iron, were taken at a series of temperatures up to that at which the magnetostriction vanishes, and that magnetic elongations exceeding $45\mu$ per meter were measured. This appears to be the largest longitudinal magnetostriction effect on record. The greatest elongations in nickel steels noted by Honda and Shimizu were less than $31\mu$ per meter, and were observed in steels containing 36 and 46 per cent nickel when cooled in liquid air. Even the maximum contraction recorded by Nagaoka and Honda for nickel was only about $38\mu$ per meter.

## VII. THERMAL CONDUCTIVITY AND SPECIFIC HEAT OF IRON-NICKEL ALLOYS.

### 1. THERMAL CONDUCTIVITY.

Honda (40, vol. 7) appears to have been the first to study this property of nickel steels over any extended range of nickel content. Results obtained by Ingersoll and others (48) on pure ferronickels prepared by Burgess and Aston (see Sec. IV) are in substantial agreement with those of Honda and are given in Table 4. Their results have been plotted in Figure 40, although the curve is drawn for Ingersoll's data alone, inasmuch as Honda's alloys were prepared from low-carbon steel and ordinary commercial nickel, the latter containing 0.29 per cent carbon and 4.2 per cent copper. The contour assumed by Honda's results (each value being the mean of five observations) is, however, closely parallel to the curve. The nickel content corresponding to the minimum conductivity found by Honda and by Ingersoll was about 30 and 35 per cent, respectively. The alloys used by both investigators were annealed at 900° C. previous to the tests. Honda made electrical conductivity measurements in addition to those of thermal conductivity and found that Wiedemann-Franz's law, namely, the ratio of thermal and electrical conductivity is independent of the nature of substances, holds substantially true in the case of nickel-iron alloys, the curves for both thermal and electrical conductivities plotted against nickel content following quite parallel courses.

### 2. SPECIFIC HEAT.

Ingersoll and others (48) determined the specific heat of Burgess and Aston's pure ferronickels, and their results are in good agreement with those of Brown (76), although the nickel content of the alloys investigated by the latter did not exceed 31.4 per cent. The curve drawn from Ingersoll's data which are given in Table 4, shows a maximum at about 35 per cent nickel, even though the actual change in the values of the specific heat for the series of alloys covering the range of nickel content is small.

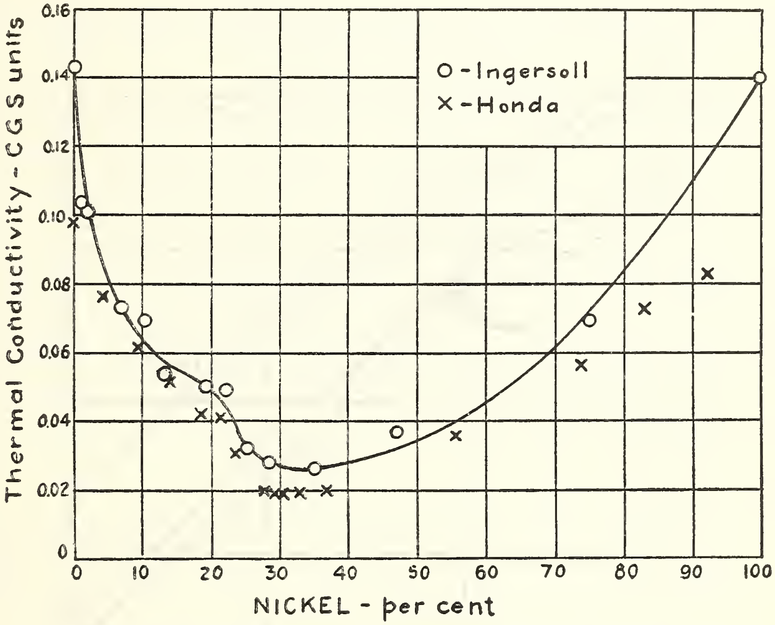

FIG. 40.—*Thermal conductivity of pure ferronickels.* (*Ingersoll.*)

## VIII. DENSITY OF IRON-NICKEL ALLOYS.

Table 12 contains values of the density in grams per cubic centimeter which Guillaume (23) found for some specimens of his nickel steels, which, as has been pointed out above, contained small amounts of other elements. The values which Hegg (38) found for a series of pure ferronickels are contained in Table 1.

Chevenard (10, 11, vol. 159) determined the densities of the nickel steels described on page 40, taking great care to make sure that the specimens were free from bubbles, cracks, or other imperfections that might lead to errors. Internal strains were removed by annealing from a high temperature, and two specimens were taken from each melt. His results are reproduced by Figure 41, in which the abscissas represent the percentages of nickel and the ordinates the specific volumes in cubic centimeters per gram (reciprocals of densities) at three different temperatures—0° absolute, 0° C., and 750° C. His determinations of thermal expansivity (see Sec. V) were used to compute these values from the values actually measured.

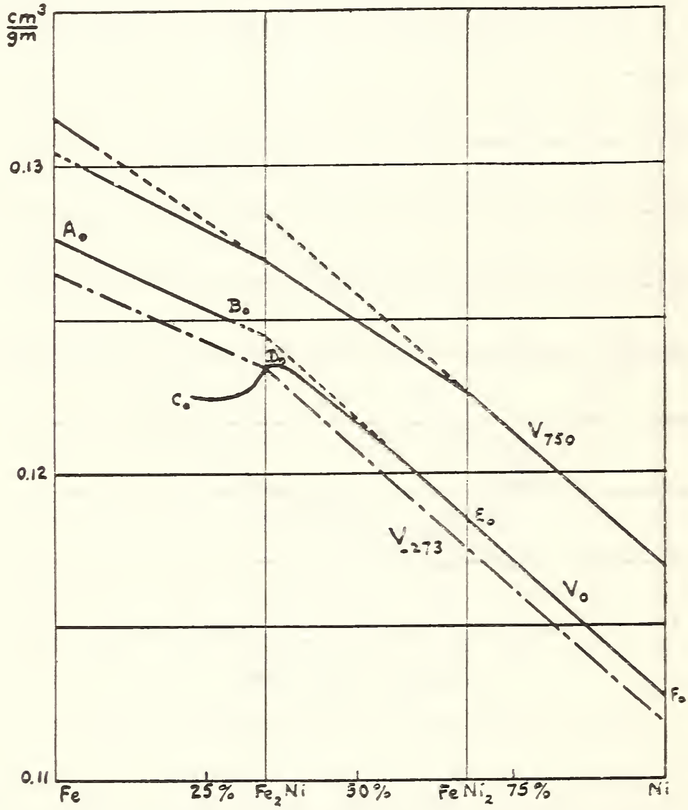

FIG. 41.—*Specific volumes of nickel steels at 0° K., 0° C., and 750° C. (Chevenard.)*

The specific volume curve for 0° C. has two separate branches. The first, $A_0B_0$, which represents alloys in the state that is stable at low temperatures, is straight. The second, $C_0D_0E_0F_0$, representing alloys in the state that is stable at high temperatures, begins with a marked anomaly (corresponding to the reversible expansion anomaly discussed in Sec. V), which gradually disappears as the composition of $FeNi_2$ is approached. Those alloys, which can exist at 0° C. in both states are represented by points on both branches.

The curves for both 0° absolute (by extrapolation from measurements carried to −195° C.) and for 750° C. are broken lines showing no trace of the anomaly. It is significant to note that the changes of direction occur at points corresponding to $Fe_2Ni$ and $FeNi_2$.

## IX. MECHANICAL PROPERTIES OF IRON-NICKEL ALLOYS.

### 1. TENSILE PROPERTIES.

(*a*) Effect of Composition and Heat Treatment.—The mechanical properties of nickel steels are dependent not alone on the nickel content and the treatment which they have received, but small amounts of other elements usually found in steels, such as carbon and manganese, affect the properties appreciably. This may readily be seen when nickel steels are divided into groups according to their mechanical properties or their metallographic structures and depending on the carbon and nickel contents. Guillet (31) gives the following division:

| Per cent carbon. | Per cent Ni. | | |
|---|---|---|---|
| | Group 1. | Group 2. | Group 3. |
| 0.12 | 0–10 | 10–27 | +27 |
| 0.25 | 0– 7 | 7–25 | +25 |
| 0.80 | 0– 5 | 5–15 | +15 |

In his discussion of the properties of nickel steels Giesen (19) has a similar division but gives slightly higher percentages of nickel as the limits of each group. The properties of the first group are similar to those of carbon steels with the strength and hardness slightly increased by the nickel. The alloys of the second group have about the same properties as quenched high-carbon steels, having high tensile strength and elastic limit and low elongations. The third group, including invar, have a medium breaking strength, low elastic limit, and are very ductile, though difficult to forge.

Figures 42 and 43 show the results of observations on the tensile strength, elastic limit, elongation, and reduction of area of nickel steel with the carbon content ranging from about 0.10 to 0.30 per cent, mostly under 0.20 per cent. The data for the steels with the nickel content running up to 20 per cent are entirely for annealed specimens. For the steels with more than 20 per cent nickel there was but little data for annealed specimens available, and in order to locate approximately the course of the curves data for specimens tested in the forged, unheated, or "naturally hard" state were incorporated.

The probable curve showing the variation of reduction of area with nickel content is dotted and might not appear to follow the plotted results of all observers. The values obtained for the reduction of area of annealed nickel steels by Les Aciéries de Saint-Étienne[10] do not agree closely with those of other investigators, and the explanation of this difference is not apparent. The results of other observers on annealed nickel steels and a consideration of results on nickel steels in other than the annealed state would indicate that the curve for reduction of area should be as shown.

It is evident from a consideration of the groups of nickel steels that the greatest variation of properties with small additions in carbon would occur with a nickel content less than 27 per cent. However, the changes in alloys of the third group, including invar, are not small. The following are the results obtained by Dumas (16) on steels containing about 29 per cent nickel:

| Per cent carbon. | Tensile strength. | | Elastic limit. | | Elongation. | Reduction of area. |
|---|---|---|---|---|---|---|
| | Kilograms per square millimeter. | Pounds per square inch. | Kilograms per square millimeter. | Pounds per square inch. | | |
| | | | | | Per cent. | Per cent. |
| 0.11 | 52 | 74,000 | 34 | 48,000 | 34.0 | 64.0 |
| 0.32 | 68 | 97,000 | 45 | 64,000 | 33.0 | 57.0 |

Guillet (31) made some tests on forged bars of nickel steel containing up to 30 per cent nickel and with 0.12, 0.25, and 0.80 per cent carbon. The results for a 30 per cent nickel steel were:

| Per cent carbon. | Tensile strength. | | Elastic limit. | | Elongation. | Reduction of area. |
|---|---|---|---|---|---|---|
| | Kilograms per square millimeter. | Pounds per square inch. | Kilograms per square millimeter. | Pounds per square inch. | | |
| | | | | | Per cent. | Per cent. |
| 0.12 | 45 | 64,000 | 29 | 41,000 | 29.5 | 63.9 |
| 0.25 | 56 | 79,000 | 33 | 47,000 | 32.0 | 71.3 |
| 0.80 | 80 | 114,000 | 48 | 68,000 | 32.5 | 50.0 |

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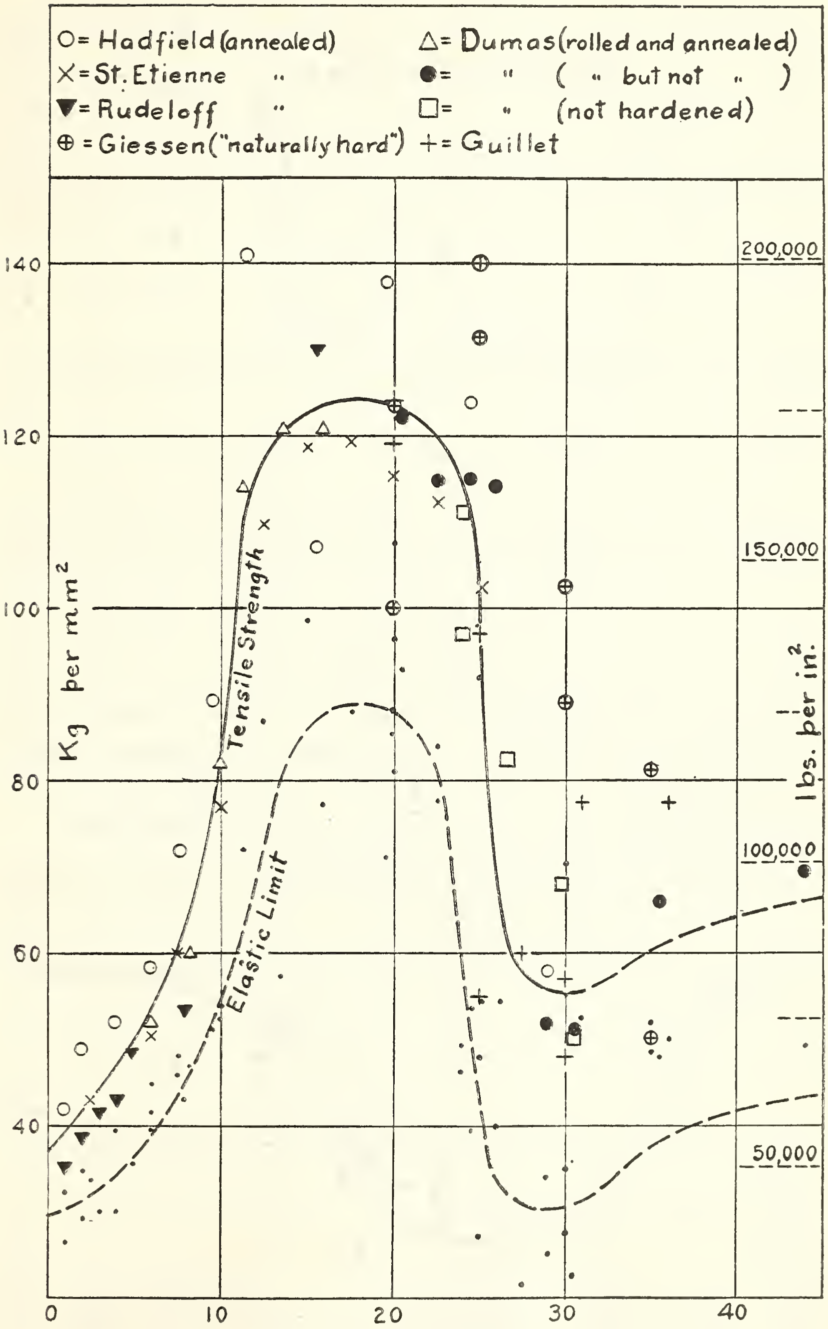
[10] See Dumas, Annales des Mines, Mémoires, 1, p. 377 (1902).



PER CENT NICKEL.

FIG. 42.—*Tensile strength and elastic limit of nickel steels.*

The elastic limit data for all investigators have been plotted as small dots to obviate confusion with the data plotted for tensile strength and in accordance with the legends shown.

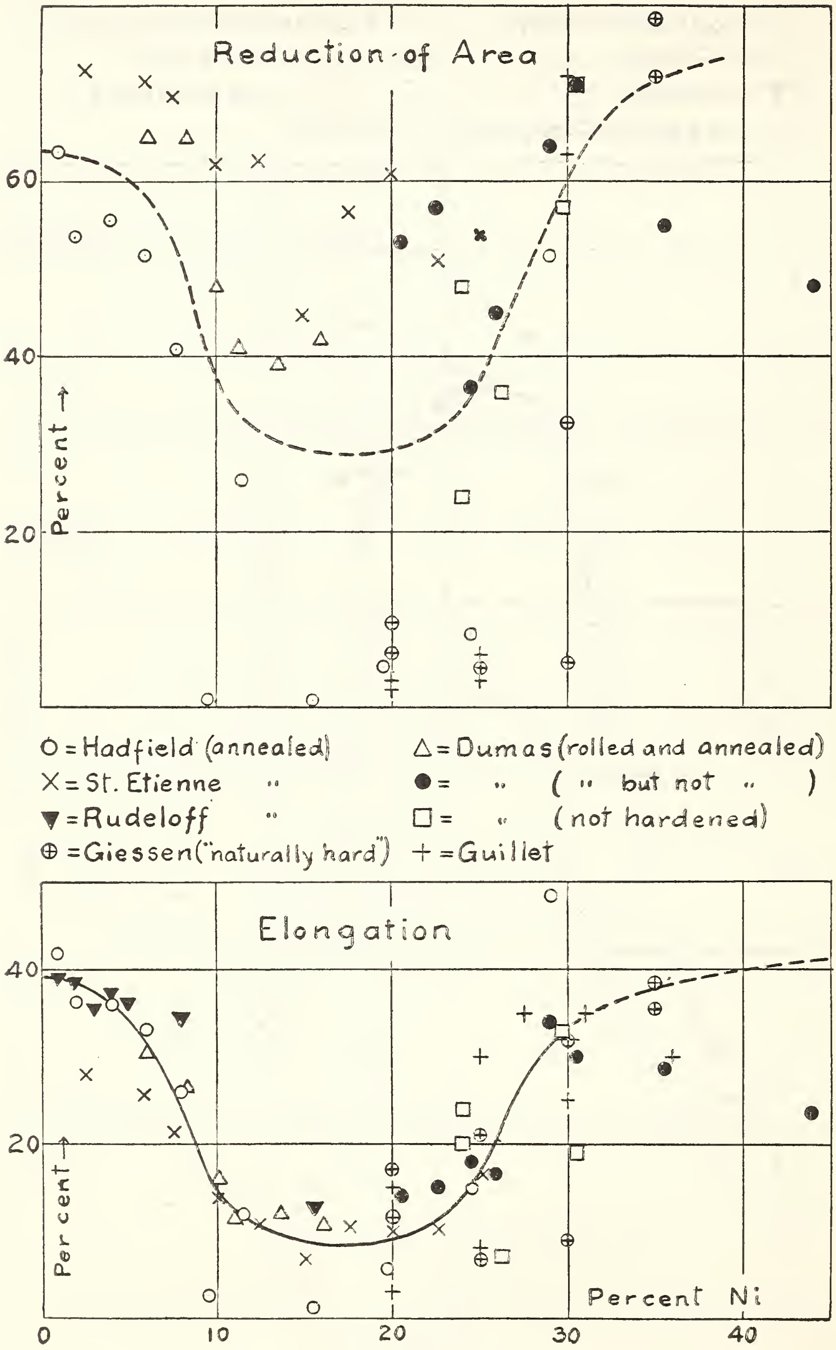


FIG. 43.—*Elongation and reduction of area of nickel steels.*

The investigation of Giesen (19) included steels which approach more nearly the composition of invar. His work was on nickel steels with nickel content up to 35 per cent, carbon 0.15, 0.30, and 0.95 per cent, and the maximum amounts of other elements contained were Mn 0.131 per cent, Si 0.10 per cent, and S 0.0073 per cent. He described the specimens as being naturally hard. The steels with 35 per cent nickel gave the following results:

| Per cent carbon. | Tensile strength. | | Elastic limit. | | Elongation. | Reduction of area. |
|---|---|---|---|---|---|---|
| | Kilograms per square millimeter. | Pounds per square inch. | Kilograms per square millimeter. | Pounds per square inch. | | |
| | | | | | Per cent. | Per cent. |
| 0.15 | 50 | 71,000 | 42 | 60,000 | 35.5 | 71.8 |
| 0.30 | 81 | 115,000 | 48 | 68,000 | 38.3 | 78.6 |
| 0.95 | 79 | 112,000 | 61 | 87,000 | 39.1 | 62.7 |

The effect of small changes in the amount of other elements than carbon contained in nickel steel has not been so thoroughly investigated, but it has been found that vanadium exerts almost as much influence as carbon, and, like carbon, it is more active with low content of nickel. The action of manganese and chromium is not felt with small changes in the percentage of either element. The addition of a few per cent of chromium to steels of the third group increases the tensile strength and elastic limit, but slightly lowers the elongation. Chromium has also been found to increase the resistance to wear of nickel steels.

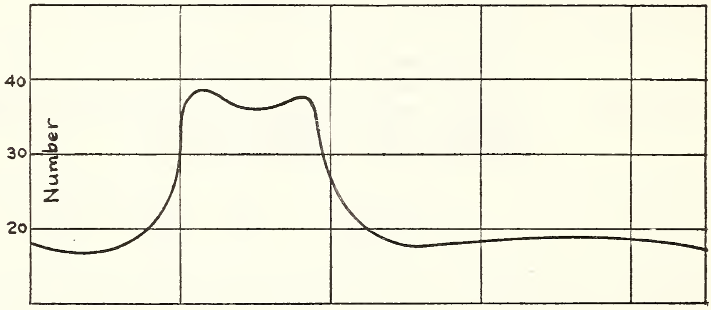
In Table 15 are shown results obtained by the Midvale Steel Co. on several nickel steels made by this firm. The elastic limits given in Table 15 are the apparent elastic limits as determined by the Johnson method. (T. B. Johnson, Materials of Construction, p. 18.) Physical properties are those obtained from material rolled to 1 inch round and subjected to various treatments.

(*b*) EFFECT OF TEMPERATURE.—The effect of temperature on the tensile properties of rolled 30 per cent nickel steel (0.29 per cent C; 2.80 per cent Mn) has been studied by Bregowsky and Spring, with the following results:

**Tensile properties of 30 Per Cent Nickel Steels at Elevated Temperatures.**

| Temperature in degrees centigrade. | Tensile strength. | Elastic limit. | Elongation in 2 inches. | Reduction in area. |
|---|---|---|---|---|
| | Lbs./in.$^2$ | Lbs./in.$^2$ | Per cent. | Per cent. |
| 21 | 94,498 | 39,850 | 51.2 | 59.8 |
| 149 | 97,000 | 37,100 | 64.1 | 65.0 |
| 233 | 84,950 | 32,250 | 62.5 | 65.0 |
| 275 | 83,000 | 26,200 | 59.4 | 66.8 |
| 317 | 69,575 | 25,650 | 56.3 | 72.6 |
| 399 | 45,650 | 21,100 | 43.0 | 59.0 |
| 555 | 36,350 | 15,500 | 37.5 | 55.7 |

The effect of low temperatures on the tensile properties and resistance to impact of ferronickels and high nickel steels has been studied by Chevenard (77). Reference is made in Section XII, 2 *e* to the development of the alloy "AMF," which possesses high tensile properties and resistance to impact at liquid air temperatures. Curves are given by Chevenard showing the variation in the mechanical properties of the "AMF" alloy, previously annealed at 900° C. over the temperature range – 190 to 800° C. Guillet and Cournot (78) have also obtained data on the hardness and resistance to impact of ferronickels at a series of low temperatures.



Scleroscope Hardness

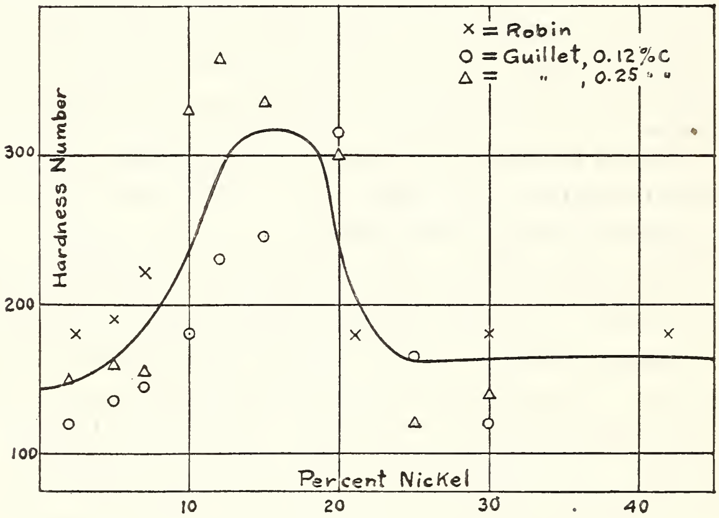


FIG. 44.—*Hardness of nickel steels.*

## 2. HARDNESS AND ABRASION.

The hardness of nickel-iron alloys varies somewhat as the tensile strength varies, in that it reaches a maximum and then decreases rapidly to a nearly constant value. Some results on hardness are shown graphically in Figure 44. The work of Roush (63) with the Shore scleroscope was on forged alloys of nearly pure nickel and electrolytic iron, so it can not be compared to results on commercial steels, although we might expect the curve to be similar. The results shown on the curve for Brinell tests are for untreated steels.

Robin (62) has done considerable work on the wear of steels with abrasives. He found that the resistance to wear of nickel steels of the first group diminished with increase of nickel content· that of the second group was very low; and of the third group higher, being particularly high considering their low hardness value as measured by other methods.

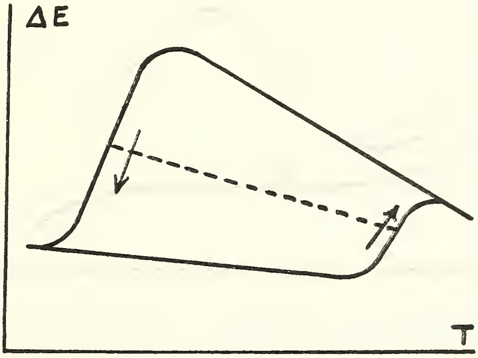


FIG. 45.—*Typical curve representing variations in the modulus of elasticity of an irreversible nickel steel with temperature.* (*Guillaume.*)

## 3. ELASTICITY.

(*a*) VARIATION OF MODULUS OF ELASTICITY WITH TEMPERATURE.—Guillaume (25) found that during transformation the nickel steels present anomalies in the elastic modulus which correspond closely to the anomalies in thermal expansion. At temperatures both below and above the limits of the transformation region these alloys behave normally—that is to say, the elasticity decreases with rising temperature—but during transformation rapid changes in the opposite direction occur, as indicated roughly by Figures 45 and 46—curve *A*, which are self-explanatory after what has already been said in Section V.

Table 13 gives the results found by Guillaume at room temperature for the elastic modulus of some nickel steels. Table 14 and Figure 47 show how the modulus has been found to change with the temperature. In the few cases investigated the temperature at which the elasticity of any given alloy reached its maximum value appeared to be about 10° C. below that at which ferromagnetic properties began to appear on cooling.

Cold working and annealing modify the elastic properties appreciably, so that the values given above must be regarded as holding strictly only for the particular specimens investigated. The elastic modulus of invar forged hot is about 15,000 kg/mm$^2$; drawn into a large rod it reaches 15,500 kg/mm$^2$; in a very hard drawn wire it may attain 16,000 kg/mm$^2$.

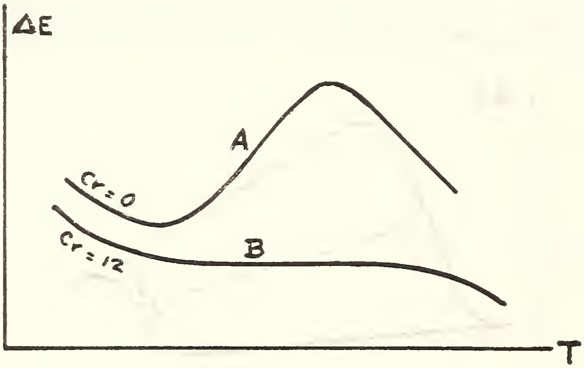


FIG. 46.—*Typical curves representing variations in the modulus of elasticity of a reversible nickel steel with temperature. (Guillaume.)*

Curve A represents the pure nickel-iron alloy; curve B the pure nickel-iron alloy containing a proportion of additions equivalent to 12 per cent chromium.

(*b*) VARIATION OF MODULUS OF ELASTICITY WITH NICKEL CONTENT.—The variations in the thermoelastic coefficient (temperature coefficient of elastic modulus) of pure ferronickels with nickel content are shown in curve *A* of Figure 48. The curve is seen to cross the zero coefficient line in two places—the first corresponding to 29 per cent nickel and the other at about 45 per cent nickel—and the curve reaches a maximum at about 36 per cent nickel. By application of the rule of corresponding states, the two zero values are seen to correspond to the maximum and minimum, respectively, of curve *A* (fig. 46), which represents the variations in the elastic modulus of a single alloy with temperature. It will also be seen that the variation of the thermoelastic coefficient in function of nickel content is very rapid in the neighborhood of the two zero values, and to cite a practical illustration of this fact the smallest errors in composition in the castings and even the lack of chemical homogeneity in the same casting would lead to appreciable variations in the thermoelastic coefficient of watch springs obtained from the same casting, the error in the watch movement attaining even a large value of the order of 25 seconds per 24 hours in the temperature interval 0–30° C.

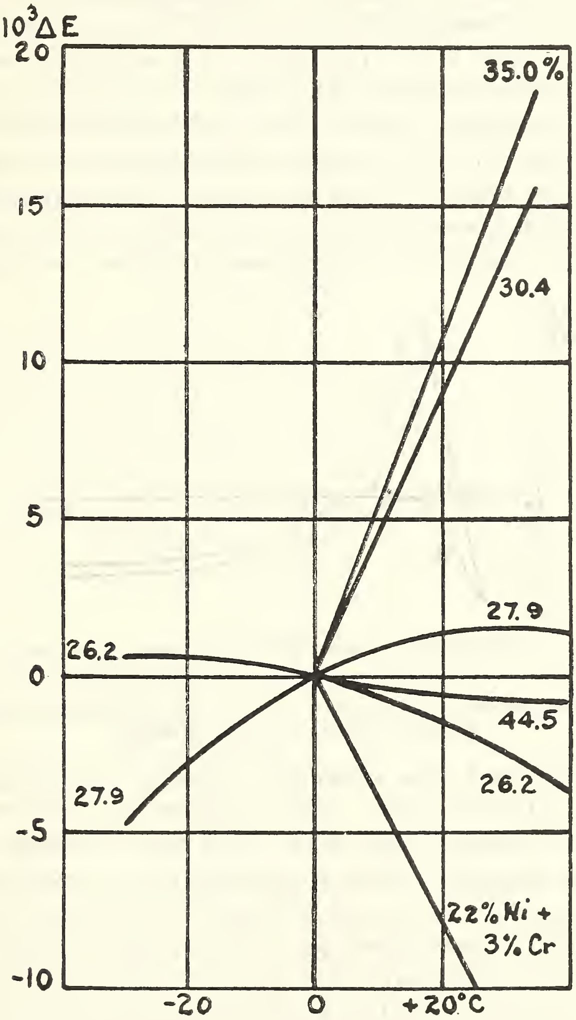


FIG. 47.—*Variations of the elastic moduli of nickel steels with temperature.* (*Guillaume.*)

(*c*) "Elinvar," an Alloy Having a Nonvariant Elastic Modulus.—Later, in connection with his studies on ferronickels to which additions had been made (see Sec. V), Guillaume (28, vol. 171, p. 83), observing the close analogy existing between the anomalies in thermal expansivity and thermoelastic coefficient of ferronickels and recognizing the fact that the addition of a third constituent to the alloy diminished the anomaly as well as progressively raising the minimum, predicted the existence of an alloy "elinvar" possessing a zero thermoelastic coefficient or invariable modulus of elasticity over an appreciable temperature range. This prediction was realized by the preparation of a 36 per cent nickel alloy to which about 12 per cent chromium, or its equivalent, where small quantities of manganese, tungsten, or carbon were used in addition to the chromium forming the balance of the additions, had been added. (The addition of a little manganese facilitates the forging of the alloy, while that of carbon raises the elastic limit, especially when accompanied by a hardening metal, as chromium, etc.) Curve *B* of Figure 48 shows the maximum value of thermoelastic coefficient of this alloy to have been so lowered that it is tangent to the zero axis, and at the same time the zero value is much less sensitive to the nickel content, as compared with the case pointed out above for pure ferronickels. Applying the rule of corresponding states, the successive values of the elastic modulus with temperature for this alloy will be represented by curve *B* of Figure 46, and here it will readily be seen that the modulus remains quite constant over a considerable range of temperature. Following a practical application of this

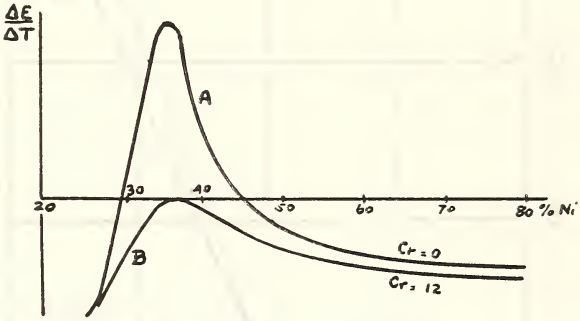


Fig. 48.—*Variations in the temperature-coefficient of modulus of elasticity of nickel steels with nickel content at 20° C. (Guillaume.)*

Curve A represents the pure nickel-iron alloys; curve B the pure nickel-iron alloys containing added elements equivalent to 12 per cent chromium.

improvement, results were obtained on compensating springs acting upon single metal balances, where the watch movements, giving a total difference of only a few seconds per 24 hours between 0 and 30° C., were, within half a second, a linear function of temperature. Guillaume has predicted the extension of the use of single metal balances in conjunction with springs of elinvar to high-grade watches and chronometers.

Chevenard (11, vol. 171), in his work on the elasticity of torsion of ferronickels, has confirmed the principles set forth by Guillaume's results. The thermoelastic coefficient can be markedly modified by suitable thermal or mechanical treatment, and small discrepancies in the composition of the alloy can by this means be corrected.

### 4. DUCTILITY.

Like all other high-nickel steels invar is very ductile and very strong. It is easily rolled into sheets or drawn into wire, but it wears cutting tools rapidly. When annealed it can undergo large deformations without rupture, although experiments made very recently at the Bureau of Standards have shown that it is possible to draw very fine wire, 0.004 inch in diameter (B. & S. gage No. 38) only by quenching rather than by slow cooling from the annealing temperature.

### 5. POLISH.

After the surface layers, which are always a little cracked in rough bars of nickel steels, have been thoroughly removed the remaining metal is perfectly sound and takes a beautiful polish, showing no pits under a magnification of 80 diameters. Very regular lines a few microns wide may be ruled on these surfaces.

## X. RESISTANCE OF IRON-NICKEL ALLOYS TO CORROSION.

Resistance to attack by fresh and sea water and acid liquors increases with the proportion of nickel, and it has been stated that an alloy containing 18 per cent nickel may be regarded as being practically noncorrodible. Alloys containing 36 per cent are so resistant that a divided length standard may be left to itself for months in an atmosphere saturated with moisture without showing rust spots. In expansion measurements bars have remained hours in warm water and were never dried on removal from the bath. Afterwards they were placed in steam for a long time without showing deterioration of the fine lines ruled on the polished surfaces. Rough surfaces, on the other hand, became covered with a slightly adherent layer of rust on exposure to steam for a few days. It is important to avoid the commencement of an attack. A spot of ink produces a slight tarnish which increases after wetting. All the alloys are attacked by hydrochloric acid. A soldered joint improperly washed may start extensive corrosion.

To give one an idea of the much greater resistance offered by these alloys, as compared with that by ordinary carbon steels, to corrosion by hydrochloric acid, the results of a test very recently carried out at the bureau may be cited. The specimens of invar and electrolytic iron, the latter having previously been annealed at 500° C. for about 45 minutes, were immersed in a hydrochloric acid solution of one-half normal strength for three days for the invar specimens and 10 days for the electrolytic iron specimens. The faces of one specimen of each material were ground to a final finish as produced by quite coarse emery paper, while the faces of the other specimens were highly polished as for microscopic examination. The loss in weight, in milligrams, per square centimeter of surface exposed per day was found to be:

| | |
|---|---|
| Invar (36.13 per cent Ni and 0.08 per cent C) | 0.26 (ground). |
| | 0.24 (polished). |
| Electrolytic iron (0.028 per cent C) | 0.9 (ground). |
| | 0.8 (polished). |

While the resistance of invar to oxidation is very much greater than that of ordinary steel, nevertheless it is not perfect. Therefore it is prudent to cover an invar instrument with vaseline if it is to be left for a long time in a moist atmosphere. This precaution is necessary in tropical climates, where invar tapes and wires ought never to be left ungreased except during actual use. The slight rust spots which may appear in time can generally be removed by rubbing with a greasy rag.

## XI. SUMMARY OF PROPERTIES OF INVAR.

Invar is a nickel-steel containing about 36 per cent nickel, together with approximately 0.1 per cent of carbon and 0.5 per cent or less of manganese, with metallurgically negligible quantities of sulphur, phosphorus, and other elements. It is made either in the open-hearth, crucible, or electric furnace. It melts sharply at about 1,425° C. Above some 200° C. to its melting point invar may be considered to consist of a homogeneous solid solution of iron, nickel, and carbon. Below 200° C. and at a temperature dependent on its history and exact composition it undergoes a reversible transformation of such a nature that for any sample the transformation may be incomplete. This condition of thermochemical instability gives rise to both slowly changing and quickly changing values of its physical properties—changes which are particularly manifested in the expansion.

The alloy invar can be forged, rolled, turned, filed, and drawn into wires; and it takes a beautiful polish, giving an excellent surface on which fine lines may be ruled. In general, it should be worked slowly. It will withstand without spotting the corrosive action of water, even when immersed for several days. Its density is about 8.0 $gm/cm^3$, its electrical resistivity is of the order of 85 microhm–cm, or about eight times that of pure iron, and its temperature coefficient of electrical resistance about 0.0012 per ° C. It is ferromagnetic, but becomes paramagnetic in the neighborhood of 165° C.

The mean coefficient of linear expansion between 0 and 40° C. is of the order of one to two millionths for the ordinary invar, and samples have been prepared with even small negative coefficients. The amounts of carbon, manganese, and chromium present appear to exercise considerable influence on the expansion. Above 200° C. the expansion of invar is nearly that of Bessemer steel.

Invar is subject to changes in length of a "transitory" nature due to "after effects" following cooling from a high temperature and to changes in length following even slight alterations in temperature. For example, at 15° C. the elongation of 1 m is 0.07 to 0.08 $\mu$ per day after forging and 0.03 $\mu$ after annealing to 40° C. After a long rest at room temperatures (10 to 20° C.) the contraction setting in after bringing the metal to a higher temperature is completed in about one-half hour at 100° C. and only after several days at 40° C. The range of transitory length variations following temperature changes is given approximately by the formula—

$$\Delta L/L = -0.00325 . 10^{-6} t^2$$

which holds for temperatures between 0 and 100° C.

Invar also gradually elongates with time, forged and drawn material behaving somewhat differently in this respect, so that there is a determinable, seasonal correction to be applied to its length when used as a length standard. This effect or "progressive" change may be reduced, but not entirely eliminated, by special heat treatments consisting in an annealing process extending over several weeks carried out at successively decreasing temperatures.

Invar also shows marked magnetostriction phenomena, or changes of length accompanying changes in strong magnetic fields.

The invar from a single melt will not, in general, be of absolutely uniform properties throughout, the expansion variations not being more than $\pm 0.03 \times 10^{-6}$, so that, in determining lengths to one part in ten million, it appears safe to use the same expansion formula for all the pieces from a given melt.

The mechanical properties of invar are approximately as follows: Tensile strength, 50,000 to 100,000 lbs./in.$^2$, or 35 to 70 kg/mm$^2$; elastic limit, 30,000 to 70,000 lbs./in.$^2$, or 21 to 50 kg/mm$^2$; elongation, 25 to 50 per cent; reduction of area, 40 to 70 per cent; scleroscope hardness, 19; and Brinell hardness, 160.

The following statement gives a diagrammatic survey showing the nickel content of the iron-nickel alloys at which the maxima and minima determined for the various physical properties occur, and also the nickel content of certain alloys which because of their peculiar physical properties have found industrial application.

| Nickel (Per cent) | |
|---|---|
| 70 | Magnetic transformation attains its maximum temperature value. |
| 60 | |
| 56 | Same expansivity as steel (0.000011), but more stable and less subject to corrosion. Used in industrial measuring machines to avoid temperature corrections. |
| 50 | Suitable for use under special conditions in the construction of electromagnetic equipment. |
| 46 | Platinite—same coefficient of expansion as that of platinum (0.000009) and nearly same as that of glass. Maximum magnetostrictive effects (40–45 per cent Ni). |
| 42 | Length standards: Preferred to invar on account of greater stability and resistance to oxidation. Coefficient of expansion appreciably less than that of platinum. |
| 40 | 35–38 per cent Ni alloys: Very resistant to shock. May be used in machine parts designed to receive violent shocks. |
| 36 | Invar—Minimum true coefficient of linear expansion=0.0000012 per °C. at 20° C.<br>Elinvar—(With 12 per cent Cr.)=invariable modulus of elasticity and low coefficient of expansion.<br>Minimum thermoelectric power (35 per cent Ni).<br>Maximum specific heat (35 per cent Ni)=0.123 cal.-g for 25°–100° C.<br>Minimum thermal conductivity (35 per cent Ni)=0.025 c g s units.<br>Maximum thermoelastic coefficient (35 per cent Ni).<br>Maximum electrical resistance (32–35 per cent Ni)=about 85 microhms. |
| 30 | |
| | 20–30 per cent Ni alloys: Nonmagnetic on cooling at normal rates. Used for nonmagnetic parts requiring strength and toughness. |
| | Ferronickel (25 per cent Ni): High electrical resistance. Used for rheostats and electrical heaters. |
| 20 | 18–20 per cent Ni alloys with 0.2 per cent C.: Maximum tensile strength, 175,000 lbs./in.²; maximum elastic limit, 100,000 lbs./in.²; minimum elongation, 21 per cent; minimum reduction of area, 7 per cent. |
| 18 | 18 per cent Ni alloys: Practically incorrodible in fresh and sea water and acid liquors. |
| 15 | Maximum Brinell hardness, 15 per cent Ni, and Scleroscope hardness, 12–19 per cent Ni. |
| 10 | |
| | 0–5 per cent Ni: Structural steels. |
| 0 | |

## XII. APPLICATION OF SPECIAL NICKEL STEELS AND ALLOYS.

### 1. LOW NICKEL STEELS.

The applications of nickel steels depend naturally upon their properties or to the group (see Sec. IX) to which they belong, and the properties of each group suggest possible applications of those steels within that group. The steels of the first group, usually containing less than 5 per cent nickel, have a high elastic limit and high tensile strength. They are used for armor plate, guns, large axles, automobile parts, and structural purposes. To illustrate the American practice followed with respect to commercial or structural nickel steels, the ranges of composition and tensile properties called for these steels in the specifications prepared by the American Society for Testing Materials and by the Society of Automotive Engineers are given in Table 16.

### 2. INTERMEDIATE AND HIGH NICKEL STEELS.

Steels with a larger nickel content are very hard, take a good polish, resist oxidation, and have a higher elastic limit and tensile strength than carbon steels of the same hardness, so they may replace carbon steels where hardness is the property desired.

(*a*) 20–40 PER CENT NICKEL ALLOYS.—Within the range of compositions from 20 to 30 per cent nickel, the ferronickel alloys may readily be obtained in a nonmagnetic condition by cooling at normal rates from rolling or forging temperatures. They are used in this connection for the production of nonmagnetic parts requiring strength and toughness. (Table 1 gives some values of the magnetic properties of ferronickel alloys.) The high electrical resistance of 25 per cent nickel steel has also been of commercial importance. The steel called ferronickel is employed as electrical resistance wire in the construction of rheostats and electrical heaters. Steels with 25 to 40 per cent nickel and 0.3 to 0.5 per cent carbon are quite tough and strong because of their austenitic structure, have a low thermal expansivity, and are very resistant to corrosion in air, fresh or sea water. Because of these qualifications they are much used for gas engines, valves, and spindles, for ignition and boiler tubes, for valve stems on sea-water pumps. The alloys may be rolled and forged, but are not so readily machined as ordinary steel. They will have the following average tensile properties in the natural, unheat-treated state.

**Tensile Properties of High Nickel Steel (Bullens).**

| Steel. | Tensile strength. | Yield point. | Elongation in 2 inches. | Reduction of area. |
|---|---|---|---|---|
| | Lbs./in.$^2$ | Lbs./in.$^2$ | Per cent. | Per cent. |
| 25–28 per cent Ni (0.3–0.5 per cent carbon) | 85,000–92,000 | 35,000–50,000 | 30–35 | 50–60 |
| 30–35 per cent Ni | 85,000–95,000 | 40,000–50,000 | 30–40 | 40–60 |
| 35–38 per cent Ni | 100,000–115,000 | 64,000–78,000 | 25–35 | 50 |

Further increase of nickel lowers the elastic limit and tensile strength, but greatly increases the elongation. Nickel steels of the third group are very resistant to shock and may be used in machine parts which are designed to receive violent shocks. Steels of this group cover a wide range of expansion coefficients and anomalous variations of the elastic modulus. They are used in the manufacture of clocks, watches, and scientific instruments, and also for measures of length, measuring tapes, etc.

(*b*) INVAR.—Invar is being used extensively for length measures. It has proved to be an excellent material for tapes. The United States Coast and Geodetic Survey has found invar tapes far superior to steel tapes, it being possible to measure a base line more rapidly and with greater accuracy than with steel tapes. The advantage arises mainly from the low expansion of invar, measurements being made in daylight with very small corrections for temperature. This bureau has found that invar tapes which have been properly manufactured vary less than one part in 500,000 after six months' use in the field. There have been cases where invar tapes changed length between calibrations, but in practically every instance the cause could be traced to lack of proper treatment during the production or use of the tape.

French investigators have constructed length measures of invar in the form of wires instead of tapes. Tapes are more trouble to handle in a breeze, but wires twist and introduce errors in measurement which are not evident. The United States Coast and Geodetic Survey has found that wind caused little delay in the use of tapes, while the errors due to twist in wires were appreciable.

The low expansion of invar has been used to advantage in the construction of instruments requiring fixed distances between points to be independent of temperature, such as the bar between microscopes of a comparator for length standards.

The application of invar and related nickel steels to the construction of clocks and watches has resulted in a great increase in the accuracy of instruments for measuring time. Invar, or a nickel steel with a low expansion coefficient, has made possible the compensated clock pendulum without mercury, resulting in convenient design and greater accuracy. The use of nickel steel with a low coefficient of expansion in balance wheels of chronometers has made possible good compensation over a fairly wide range of temperature instead of for two definite temperatures. Clocks with torsion pendulums require little driving power and are constructed to run 400 days on a single winding. Compensation is obtained by making the torsion pendulum of nickel steel.

(*c*) Elinvar.—The development of the alloy "elinvar," already referred to in Section IX, 3 *c*, possessing an invariable elastic modulus has extended the possibilities of the use of single metal balances in high-grade watches and chronometers, thus securing a large degree of compensation in a quite cheap manner.

(*d*) Platinite.—Platinite, a nickel steel with about 46 per cent nickel and the same expansion as platinum, approximately $9 \times 10^{-6}$ per °C., was formerly used in place of platinum for sealing in leads in electric light bulbs, but not being found wholly suitable for the purpose has, as the bureau understands, been substituted by a compound wire with a 38 per cent nickel steel core incased in copper and sometimes coated with platinum. The nickel-steel core if free will expand less than the glass and the copper more, so that each resists the other and the wire as a whole will have the desired rate of expansion.

(*e*) 50 or More Per Cent Nickel Alloys.—Yensen (75) made a thorough study of the electrical and magnetic properties of pure iron-nickel alloys prepared by melting in vacuo. (See fig. 18.) He found that alloys containing approximately 50 per cent nickel can be forged and worked, and that they have the following average electrical and magnetic properties which may be compared with those of pure iron and nickel.

| Metal. | Flux density $H=100$ gausses. | Saturation value. | Hysteresis loss $B=10,000$. | Electrical resistivity. |
|---|---|---|---|---|
| | | Gausses. | Ergs/cm/cycle. | Microhm-cm. |
| Pure iron | 18,500 | 22,500 | 1,100 | 11 |
| 50 per cent alloy | 15,500 | 15,500 | 800 | 45 |
| Pure nickel | 6,000 | 6,000 | 25,000 | 8 |

As the 50 per cent alloys are relatively incorrodible, they should be of value under special conditions in the construction of electromagnetic equipment. Another interesting magnetic characteristic of this alloy is the fact that the *B H* curve up to $B = 2{,}000$ to 4,000 gausses is nearly linear, which makes it of value for certain electromagnetic meters. Industrial measuring machines constructed of 56 per cent nickel steel avoid temperature corrections in testing the dimensions of steel gauges and machine parts, since this alloy has about the same thermal expansivity as ordinary steel. In addition, it is more stable and less subject to corrosion.

Certain parts of machinery used in commercial liquid air plants, such as valves of expansion engines, are subjected to relatively violent shocks and, therefore, any metal used for such parts should possess sufficient strength and ductility to withstand these shocks at even very low temperatures. Chevenard (77) has reported the results of a study made on this problem and which led to the development of the iron-nickel alloy, "AMF," patented in 1918 (in France) and manufactured by the Société Anonyme de Commentry-Fourchambault et Decazeville. The composition of this alloy appears to run about as follows: 55 to 60 per cent nickel, 1 to 3 per cent manganese, and 0.2 to 0.4 per cent carbon. Ordinary steels, even the softest ones, are extremely brittle at liquid air temperatures, while nickel and ferronickels with more than 40 per cent nickel are ductile at all temperatures. The presence of carbon and manganese within certain percentage limits was found not to affect this property. Fragility at very low temperatures appears to be a specific property of iron in its two allotropic states since all alloys rich in iron are found to be brittle, as is shown by the fact that the resilience of steels with the iron in the alpha state reaches a minimum at below $-100°$ C., and that of austenitic steels containing more than 60 per cent iron (in the gamma state) shows a similar diminution. Chevenard states that at liquid air temperatures ($-190°$ C.) the previously annealed "AMF" alloy has about the following tensile properties: Tensile strength, 114,000 lbs./in.$^2$ (80 kg/mm$^2$); elastic limit, 57,000 lbs./in.$^2$ (40 kg/mm$^2$); elongation, 40 per cent; reduction of area, 55 per cent; Fremont impact value, greater than 45 kg/cm$^2$. In cooling down from room temperature to $-190°$ C. the tensile strength and elastic limit are sensibly increased—about 20 to 30 per cent over that at room temperature, while the elongation and reduction of area decrease a little—about 10 to 20 per cent of the values for room temperature. If the mechanical parts are required to resist particularly intense strains, the elastic limit of the alloy may be increased by slight working; that is, by finishing the hot-working operation at a dark red heat. Chevenard also states that the results of this study have been supported by practical tests extending over about 10 years and by the fact that no accidental ruptures of valves in the expansion valves of Claude machines had so far been met with in service.

(*f*) "BAROS" ALLOY.—This alloy, containing about 90 per cent nickel and 10 per cent chromium and already referred to in greater detail near the end of Section I, because of its almost exact reversibility in expansion, its average expansibility being nearly the same as that of the iron alloys under investigation, its very slight oxidibility, and its mean calorific capacity being almost equal to that of steel, has been used in measuring apparatuses; for example, as a standard length bar in a dilatometer employed by Chevenard (10, vol. 14) for the study of iron alloys, more as a means of detecting differential values than of determining precise expansions.

## XIII. SOURCES OF SUPPLY FOR VARIOUS NICKEL STEELS.

The alloys sold under the trade-marks "Invar," "Elinvar," "Dilver," "Adr," and "Platinite"[11] are protected by patents and are manufactured only by the Société Anonyme de Commentry-Fourchambault et Decazeville, 84 rue de Lille, Paris ($7^e$). This company, which has been the pioneer in the scientific development of high-nickel steels, manufactures on order pieces of any desired composition, pattern, or size.

Steels containing from 1.5 to 95 per cent nickel are manufactured in America for a great variety of purposes; for example, gun tubes and other gun parts, engine and locomotive forgings, pneumatic hammers and air drills, turbine blades, gas-engine valves, ignition tubes, spark plugs, axles, shafts, steering knuckles, gears, and other parts of automobiles, airplanes, machinery subjected to severe stresses, thermostats, and balance wheels for watches.

The following firms have informed this bureau that they are makers of nickel steels:

Carpenter Steel Co., Reading, Pa., makes steels with 25 to 30 per cent nickel, but does not make steel of specified low thermal expansivity.

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[11] Invar, expansion coefficient between −100 and +200° C., almost zero; Elinvar, modulus of elasticity practically invariable at ordinary temperatures; Dilver, expansion coefficient nearly that of ordinary glass or $8 \times 10^{-6}$ per °C.; Adr, whose total expansion from 0 to 500° C. is less than that of all ordinary metals and is used particularly in the construction of rotary distributors; Platinite, expansion coefficient nearly that of platinum.

Crucible Steel Co. of America, Pittsburgh, Pa., 5 to 95 per cent nickel; material furnished in hot rolled bars or sheets, in cold drawn rounds and shapes, and in cold rolled strips; expansivity to specifications.

Driver-Harris Co., Harrison, N. J., Invar composition special nickel steel on order in form of straight rods, strips, and sheet.

Midvale Steel & Ordnance Co., Philadelphia, Pa., 1.5 to 95 per cent nickel; chrome-nickel steels; expansivity to specifications. Can supply these steels in cold drawn flats, rounds and squares, in any size and also hexagons and octagons in certain sizes.

Simonds Manufacturing Co., Lockport, N. Y., Invar and high nickel steels on order in form of billets or bars.

The dealers listed below also have informed the bureau that they can supply nickel steels of minimum thermal expansivity:

Bausch & Lomb Optical Co., Rochester, N. Y., Invar rods, sheet, flat, T section.

H. Boker & Co. (Inc.), 101–103 Duane St., New York, N. Y., German product sold under trade name of "Stoic Metal," an alloy similar to Invar in general chemical composition and having a negligible coefficient of expansion; furnished in rod, sheet, wire, and tape.

Keuffel & Esser Co., Hoboken, N. J., Invar tapes.

Société Genevoise, Geneva, Switzerland (represented in U. S. A. by R. Y. Ferner, 1410 H Street, NW., Washington, D. C.), Invar in the form of tapes or ribbon as thin as 0.3 mm and 6 to 30 mm in width, rectangular or square sections up to 40 mm width, round bars either drawn and white polished or black in diameters of 5 mm up, and clock pendulums; meter and yard standards, scales and graduated tapes of invar, 42 per cent or 58 per cent nickel steels. Invar furnished in three classes, differing in the guaranteed degree of coefficient of expansion per degree centigrade as follows: (*a*) less than $0.8 \times 10^{-6}$, (*b*) 1.0 to $1.6 \times 10^{-6}$, and (*c*) may be as high as $2.5 \times 10^{-6}$. The coefficient of expansion per degree centigrade of the 42 per cent nickel steel is $8 \times 10^{-6}$ and that of the 58 per cent nickel steel 10 to $11 \times 10^{-6}$.

No general statement regarding the quotations for the 36 per cent nickel steel manufactured in America can be made, inasmuch as the material would, in view of the small demand for it, have to be made on special order under rather highly specialized conditions, and consequently the price would necessarily be governed by these and other factors. The makers offer no guarantees other than which may be assumed from the composition of the alloy in meeting the exacting requirements of precise measuring instruments. One maker has, however, stated that minimum expansivity is attained with very fair results by cold drawing and quenching followed by prolonged aging, although they are not willing to guarantee to meet extremely difficult requirements.

## TABLE 1.—Magnetic Properties of Ferronickels.

| Per cent Ni. | Hegg (1910). | | | | | Curie constants C (Weiss and Foëx, 1911). |
|---|---|---|---|---|---|---|
| | Density D, in grams per cubic centimeter. | Transformation temperatures centigrade (Curie points). | | Saturation values at 0° absolute magnetic moment per unit mass( $B-H)_0$. | | |
| | | $\theta$ or $\theta_1$ | $\theta_2$ | $\sigma^\circ$ | $=4\pi\sigma_0$D | |
| | | Degrees. | Degrees. | | | |
| 0 | 7.875 | 758 | ........... | 223.2 | 22 090 | 0.072 |
| 10 | 7.89 | 730 | 532 | 221.0 | 21 910 | .0577 |
| 20 | 8.02 | 625 | 218 | 210.8 | 21 240 | .0460 |
| 30 | 8.06 | 533 | 127 | 203.6 | 20 620 | .0315 |
| 40 | 7.63? | 365 | ........... | 184.2 | 17 660 | .0251 |
| 50 | 8.05 | 527 | ........... | 169.2 | 17 120 | .0227 |
| 60 | 8.29 | 599 | ........... | 146.8 | 15 290 | .0185 |
| 70 | 8.39 | 613 | ........... | 127.1 | 13 400 | .0157 |
| 80 | 8.52 | 562 | ........... | 103.1 | 11 040 | .0126 |
| 90 | 8.60 | 480 | ........... | 80.6 | 8710 | .0100 |
| 100 | 8.86 | 374 | ........... | 58.8 | 6550 | .0056 |

## TABLE 2.—Change in Electrical Resistance with Temperature (Guillaume).

| Per cent Ni. | Mean coefficients of variation between 0 and t° C. | Per cent Ni. | Mean coefficients of variation between 0 and t° C. |
|---|---|---|---|
| 22.0+3 Cr | (784−0.13 t) $10^{-6}$ | 30.4 | (897−0.43 t) $10^{-6}$ |
| 26.2 | (844+0.01 t) $10^{-6}$ | 35.0 | (1561−1.69 t) $10^{-6}$ |
| 28.7 | (700−0.20 t) $10^{-6}$ | 35.7 | (1161−1.68 t) $10^{-6}$ |

## TABLE 3.—Electrical Resistivity of Pure Ferronickels, in Microhm-cm.

| Per cent Ni. | Yensen (1920).[1] | | Burgess and Aston (1910).[2] | Ruer and Schüz (1910).[3] |
|---|---|---|---|---|
| | Without additions. | With additions (given in parenthesis). | | |
| 0 | ........... | ........... | 12.1 | 12 |
| 0.27 | ........... | ........... | 13.1 | ........... |
| 0.50 | 11.5 | 12.7 (0.2 Si) | ........... | ........... |
| 0.56 | ........... | ........... | 15.4 | ........... |
| 1.00 | 12.7 | 14.3 (0.2 Si) | ........... | ........... |
| 1.07 | ........... | ........... | 16.9 | ........... |
| 1.48 | 13.8 | 15.1 (0.2 Si) | ........... | ........... |
| 1.93 | ........... | ........... | 16.4 | ........... |
| 1.96 | 14.9 | 16.5 (0.2 Si) | ........... | ........... |
| 2.44 | 16.1 | 18.0 (0.2 Si) | ........... | ........... |
| 2.84 | 17.1 | ........... | ........... | ........... |
| 2.90 | ........... | 19.1 (0.2 Si) | ........... | ........... |
| 3.85 | 19.4 | 20.7 (0.2 Si) | ........... | ........... |
| 4.62 | 20.3 | ........... | ........... | ........... |
| 4.76 | ........... | 21.4 (0.2 Si) | ........... | ........... |
| 5.0 | ........... | ........... | ........... | 29 |
| 5.67 | 22.0 | 25.8 (0.2 Si) | ........... | ........... |
| 7.00 | ........... | 25.7 (0.2 Si) | ........... | ........... |
| 7.05 | ........... | ........... | 26.9 | ........... |
| 7.33 | 24.8 | ........... | ........... | ........... |

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

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

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

**TABLE 3.—Electrical Resistivity of Pure Ferronickels, in Microhm-cm.—Continued.**

| Per cent Ni. | Yensen (1920). | | Burgess and Aston (1910). | Ruer and Schüz (1910). |
|---|---|---|---|---|
| | Without additions. | With additions (given in parenthesis). | | |
| 8.00 | 25.2 | 26.2 (0.1 Mn) | | |
| 8.17 | | | 26.7 | |
| 9.52 | | 29.6 (0.2 Si) | | |
| 9.61 | 27.1 | | | |
| 10.0 | | 28.9 (0.2 Si+0.1 Mn) | | 31 |
| 10.20 | | | 28.6 | |
| 11.29 | | | 29.4 | |
| 12.07 | | | 30.3 | |
| 13.11 | | | 34.8 | |
| 14.92 | 29.8 | | | |
| 15.0 | | 31.0 (0.2 Si) | | 39 |
| 19.21 | | | 36.2 | |
| 20.0 | | | | 39 |
| 22.11 | | | 38.7 | |
| 25.0 | | | | 40 |
| 25.20 | | | 63.2 | |
| 26.40 | | | 65.5 | |
| 28.42 | | | 82.0 | |
| 30.0 | | 82.0 (0.2 Si) | | 87 |
| 34.5 | | 81.3 (0.2 Si) | | |
| 34.81 | 80.4 | | | |
| 35.0 | | | | 94 |
| 35.09 | | | 81.1 | |
| 40.0 | | | | 81 |
| 45.0 | | | | 48 |
| 47.8 | | | 44.7 | |
| 50.0 | | 42.8 (0.75 Mn) | | 43 |
| 50.0 | | 45.6 (1.0 Mn) | | |
| 55.0 | | | | 41 |
| 60.0 | | | | 30 |
| 65.0 | | | | 27 |
| 70.0 | | | | 27 |
| 75.0 | | | | 19 |
| 75.06 | | | 22.1 | |
| 80.0 | | | | 18 |
| 85.0 | | | | 20 |
| 90.0 | | | | 22 |
| 95.0 | | | | 19 |
| 100.0 | | | [4] 12.4 | 9 |

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

**TABLE 4.—Electrical and Thermal Properties of Pure Ferronickels (L. H. Ingersoll and others).**

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

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[1] Values for pure iron and pure nickel taken from measurements of Jäger and Dieselhorst.

**TABLE 5.—Expansion of Nickel Steels—Mean Coefficients of Linear Expansion Between 0° and t° C.; Applicable Between 0° and 38° (Guillaume).**

| Per cent Ni. | Mean coefficients of linear expansion×10⁶. | Per cent Ni. | Mean coefficients of linear expansion×10⁶. |
|---|---|---|---|
| 0 | 10.354+0.00523 t | 44.4 | 8.508−0.00251 t |
| 5.0 | 10.529+0.00580 t | 48.7 | 9.901−0.00067 t |
| 19.0 | 11.427+0.00362 t | 50.7 | 9.824+0.00243 t |
| 26.2 | 13.103+0.02123 t | 53.2 | 10.045+0.00031 t |
| 27.9 | 11.288+0.02889 t | 70.3 | 11.890+0.00387 t |
| 28.7 | 10.387+0.03004 t | 100.0 | 12.661+0.00550 t |
| 30.4 | 4.570+0.01194 t | 12.2+1 Cr | 11.714+0.00508 t |
| 31.4 | 3.395+0.00885 t | 16.8+1 Cr | 11.436+0.00170 t |
| 34.6 | 1.373+0.00237 t | 16.2+2.5 Cr | 19.496+0.00432 t |
| 35.6 | 0.877+0.00127 t | 21.3+3 Cr | 18.180+0.00426 t |
| 37.3 | 3.457−0.00647 t | 34.8+1.5 Cr | 3.580−0.00132 t |
| 39.4 | 5.357−0.00448 t | 35.7+1.7 Cr | 3.373+0.00165 t |
| 43.6 | 7.992−0.00273 t | 36.4+0.9 Cr | 4.433−0.00392 t |

TABLE 6.—Expansion of Nickel Steels—True Coefficients of Linear Expansion at t° C. (Guillaume).

| Per cent Ni. | Limits of application. | True coefficients of linear expansion×$10^6$. |
|---|---|---|
| | Degrees. | |
| 30.4 | 0–110 | 4.570+0.0235 (t–0) |
| | 110–164 | 7.15 +0.104 (t–110) |
| | 164–220 | 12.60 +0.008 (t–164) |
| 31.4 | 0–122 | 3.395+0.0150 (t–0) |
| | 122–182 | 5.25 +0.128 (t–122) |
| | 182–220 | 13.00 +0.036 (t–182) |
| 34.6 | 0–142 | 1.373+0.0047 (t–0) |
| | 142–220 | 2.05 +0.065 (t–142) |
| 37.3 | 0–150 | 3.457–0.0072 (t–0) |
| | 150–220 | 2.37 +0.011 (t–150) |

TABLE 7.—Elongations on Heat Treating a 35.5 Per Cent Nickel Steel Bar (Guillaume).

| Temperature, °C. | Time. | Elongations in microns per meter— | | | | |
|---|---|---|---|---|---|---|
| | | Total. | At 100°. | At 60°. | At 40°. | At 6°–20°. |
| | Hours. | | | | | |
| 150 | 40 | 8.1 | | | | |
| 100 | 1 | 12.2 | 4.1 | | | |
| 100 | 7 | 19.3 | 11.2 | | | |
| 100 | 47 | 25.3 | 17.2 | | | |
| 100 | 79 | 28.1 | 20.0 | | | |
| 60 | 45 | 33.8 | | 5.7 | | |
| 60 | 111 | 36.7 | | 8.6 | | |
| 60 | 202 | 39.7 | | 11.6 | | |
| 60 | 318 | 40.5 | | 12.4 | | |
| 40 | 88 | 42.7 | | | 2.2 | |
| 40 | 229 | 44.3 | | | 3.8 | |
| 40 | 395 | 46.1 | | | 5.6 | |
| 40 | 509 | 46.7 | | | 6.2 | |
| 40 | 698 | 47.0 | | | 6.5 | |
| | Days. | | | | | |
| 11 | 3 | 47.5 | | | | 0.5 |
| 11 | 17 | 47.4 | | | | 0.4 |
| 11 | 33 | 48.8 | | | | 1.8 |
| 11–18 | 74 | 49.3 | | | | 2.3 |
| 18–20 | 118 | 50.0 | | | | 3.0 |
| 20–14 | 176 | 51.6 | | | | 4.6 |
| 14–8 | 244 | 52.6 | | | | 5.6 |
| 6–8 | 300 | 52.8 | | | | 5.8 |
| 6–8 | 333 | 53.5 | | | | 6.5 |
| 8–9 | 375 | 53.1 | | | | 6.1 |

**TABLE 8.—Elongations on Heat Treating a 35.5 Per cent Nickel Steel Bar (Guillaume).**

| Temperature, °C. | Time. | Elongations in μ per meter. | |
|---|---|---|---|
| | | Total. | At 6° to 20°. |
| | Hours. | | |
| 100 | 4 | 12.3 | ........ |
| 100 | 21 | 22.4 | ........ |
| 100 | 71 | 26.7 | ........ |
| 100 | 118 | 26.7 | ........ |
| 100 | 150 | 28.1 | ........ |
| 10 | 5 | 28.3 | 0.2 |
| 10 | 14 | 28.7 | 0.6 |
| 10 | 30 | 29.5 | 1.4 |
| 10–11 | 54 | 30.2 | 2.1 |
| 10–15 | 92 | 32.0 | 3.9 |
| 16–20 | 145 | 32.8 | 4.7 |
| 20–14 | 223 | 35.3 | 7.2 |
| 14–8 | 343 | 35.8 | 8.7 |
| 6–8 | 385 | 37.7 | 9.6 |

**TABLE 9.—Length Variations in Hot-Forged Bars of Invar (Guillaume).**

| Number. | Nickel. | Treatment of bar. | Elongation in millionths. | True coefficients of linear expansion at 20° C. $\times 10^6$. |
|---|---|---|---|---|
| | Per cent. | | | |
| 1 | 35.2 | Forged hot | ........ | 1.27 |
| | | 4,536 days at room temperature | 38 | 1.32 |
| 2 | 35.5 | Forged hot | ........ | 1.21 |
| | | Skin removed; 150 hours at 100°, 4,820 days at room temperature | 65 | 1.32 |
| 3 | 35.5 | Forged hot | ........ | 1.18 |
| | | Skin removed; 40 hours at 150°, gradually cooled in 50 days to 40°, 4,802 days at room temperature | 66 | 1.31 |
| 4 | 35.5 | Forged hot; 55 hours at 100°, 150 hours at 60° | ........ | 1.67 |
| | | 62 hours at 100°; cooled in 73 days to 25°, 4,015 days at room temperature | 34 | 1.73 |
| 5 | 35.6 | Quenched; 55 hours at 100°, 187 hours at 60° | ........ | 1.36 |
| | | 4,564 days at room temperature | 26 | 1.42 |
| 6 | 35.5 | Quenched; 55 hours at 100°, 189 hours at 60° | ........ | 1.28 |
| | | 479 hours at 60°, 856 hours at 40°, 690 days at room temperature, planed to H-section | ........ | 1.31 |
| | | 4,145 days at room temperature | ........ | 1.32 |
| 7 | 35.5 | Forged hot; 66 hours at 100° | ........ | 1.30 |
| | | 739 hours at 60°, cooled in 102 days to 25°, planed to H-section, 320 days to room temperature | ........ | 1.35 |
| | | 4,145 days at room temperature | ........ | 1.33 |
| 8 | 43.0 | Forged hot | ........ | 7.33 |
| | | 108 hours at 100°, 4,496 days at room temperature | ........ | 7.47 |

**TABLE 10.—Elongation of Invar with Time After Cooling Three Months from 100° to 25° C. (Benoît and Guillaume).**

| Days after completion of treatment. | Elongation in microns per meter. | Days after completion of treatment. | Elongation in microns per meter. | Days after completion of treatment. | Elongation in microns per meter. |
|---|---|---|---|---|---|
| 0 | 0.0 | 1,000 | 6.6 | 2,000 | 9.3 |
| 100 | 1.5 | 1,100 | 6.9 | 2,100 | 9.5 |
| 200 | 2.5 | 1,200 | 7.2 | 2,200 | 9.7 |
| 300 | 3.2 | 1,300 | 7.5 | 2,300 | 9.8 |
| 400 | 3.9 | 1,400 | 7.8 | 2,400 | 10.0 |
| 500 | 4.4 | 1,500 | 8.1 | 2,500 | 10.2 |
| 600 | 4.9 | 1,600 | 8.4 | 2,600 | 10.3 |
| 700 | 5.4 | 1,700 | 8.7 | 2,700 | 10.5 |
| 800 | 5.8 | 1,800 | 8.9 | 2,800 | 10.6 |
| 900 | 6.2 | 1,900 | 9.1 | 2,900 | 10.8 |

**TABLE 11.—Temporary Length Variations of Invar Following Rapid Change in Temperature $\Delta L/L = -0.00325\times10^{-6}t^2$ (Benoît and Guillaume).**

| Temperature, °C. | $10^6\Delta L/L$ Starting from— | | Temperature, °C. | $10^6\Delta L/L$ Starting from— | | Temperature, °C. | $10^6\Delta L/L$ Starting from— | |
|---|---|---|---|---|---|---|---|---|
| | 0° | 15° | | 0° | 15° | | 0° | 15° |
| | Microns per meter. | | | Microns per meter. | | | Microns per meter. | |
| 0 | 0.0 | +0.7 | 10 | −0.3 | +0.4 | 20 | −1.3 | −0.6 |
| 1 | 0.0 | +0.7 | 11 | −0.4 | +0.3 | 21 | −1.4 | −0.7 |
| 2 | 0.0 | +0.7 | 12 | −0.4 | +0.3 | 22 | −1.5 | −0.8 |
| 3 | 0.0 | +0.7 | 13 | −0.5 | +0.2 | 23 | −1.7 | −1.0 |
| 4 | 0.0 | +0.7 | 14 | −0.6 | +0.1 | 24 | −1.8 | −1.1 |
| 5 | −0.1 | +0.6 | 15 | −0.7 | +0.0 | 25 | −2.0 | −1.3 |
| 6 | −0.1 | +0.6 | 16 | −0.8 | −0.1 | 26 | −2.2 | −1.5 |
| 7 | −0.1 | +0.6 | 17 | −0.9 | −0.2 | 27 | −2.3 | −1.6 |
| 8 | −0.2 | +0.5 | 18 | −1.0 | −0.3 | 28 | −2.5 | −1.8 |
| 9 | −0.2 | +0.5 | 19 | −1.1 | −0.4 | 29 | −2.7 | −2.0 |

**TABLE 12.—Densities of Nickel Steels (Guillaume).**

| Per cent Ni. | Density in grams pre cubic centimeter. | Per cent Ni. | Density in grams per cubic centimeter. | Per cent Ni. | Density in grams per cubic centimeter. | Per cent Ni. | Density in grams per cubic centimeter. |
|---|---|---|---|---|---|---|---|
| 5.0 | 7.787 | 24.1 [2] | 8.014 | 34.6 | 8.066 | 100.0 | 8.750 |
| 15.0 | 7.903 | 26.2 | 8.096 | 37.2 | 8.005 | 12.2 Ni+1 Cr | 7.892 |
| 19.0 | 7.913 | 30.4 | 8.049 | 39.4 | 8.076 | | |
| 24.1 [1] | 8.111 | 31.4 | 8.008 | 44.3 | 8.120 | | |

[1] Nonmagnetic.

[2] Magnetic, but transformation apparently incomplete.

### TABLE 13.—Elastic Moduli of Nickel Steels (Guillaume).

| Per cent Ni. | Modulus of elasticity in metric[1] tons per square millimeter. | Per cent Ni. | Modulus of elasticity in metric[1] tons per square millimeter. | Per cent Ni. | Modulus of elasticity in metric[1] tons per square millimeter. |
|---|---|---|---|---|---|
| 5.0 | 21.7 | 31.4 | 15.5 | 12.2+1 Cr | 19.0 |
| 15.0 | 19.1 | 34.6 | 15.4 | 16.2+2.5 Cr | 19.6 |
| 19.0 | 17.7 | 35.2 | 14.9 | 16.8+1 Cr | 18.3 |
| 24.1[2] | 19.3 | 37.2 | 14.6 | 34.8+1.5 Cr | 15.5 |
| 24.1[3] | 17.4 | 39.4 | 15.1 | 35.7+1.7 Cr | 15.7 |
| 26.2 | 18.5 | 44.3 | 16.3 | 36.4+0.9 Cr | 15.7 |
| 27.9 | 18.1 | 70.0 | 19.8 | | |
| 30.4 | 16.0 | 100.0 | 21.6 | | |

[1] A metric ton is 1,000 kg. [2] Nonmagnetic. [3] Magnetic; transformation apparently incomplete.

### TABLE 14.—Change in Elastic Modulus with Temperature (Guillaume).

| Per cent Ni. | Magnetic state. | Coefficient of elasticity in metric tons per square millimete at t °C. |
|---|---|---|
| 22.0+3 Cr | Not magnetic | $19.67\ (1-394\times10^{-6}\ t)$. |
| 26.2 | Very slightly magnetic | $18.54\ [1-(51.6t+0.95\ t^2)\ 10^{-6}]$. |
| 27.9 | Slightly magnetic | $18.06\ [1+(104.t-1.72\ t^2)\ 10^{-6}]$. |
| 30.4 | Magnetic | $15.96\ (1+389\times10^{-6}\ t)$. |
| 35.0 | Very magnetic | $15.04\ (1+464\times10^{-6}\ t)$. |
| 44.5 | do | $16.40\ [1-(43.6\ t-0.62\ t^2)\ 10^{-6}]$. |

### TABLE 15.—Nickel Steels from Midvale Steel Co.

| No. | Composition. | | | Treatment. | Physical properties. | | | |
|---|---|---|---|---|---|---|---|---|
| | C | Mn | Ni | | T. S. | E. L. | Ext. | Cont. |
| 1 | 0.20 | 1.50 | 26.00 | A | 78 500 | 12 000 | 50.0 | 70.7 |
| | | | | C | 76 000 | 15 000 | 49.5 | 70.5 |
| 2 | .15 | 1.50 | 30.00 | A | 90 000 | 27 000 | 39.5 | 69.7 |
| | | | | B | 84 500 | 28 000 | 46.5 | 68.5 |
| | | | | C | 81 500 | 23 000 | 44.2 | 70.5 |
| 3 | .40 | 2.00 | 30.00 | A | 105 000 | 45 000 | 47.0 | 66.6 |
| | | | | B | 101 500 | 35 000 | 46.7 | 66.4 |
| | | | | C | 91 000 | 25 000 | 45.7 | 69.3 |
| 4 | .12 | 2.30 | 32.27 | A | 82 000 | 30 000 | 37.5 | 65.6 |
| | | | | B | 77 500 | 22 000 | 43.0 | 66.2 |
| | | | | C | 73 000 | 18 600 | 39.5 | 64.7 |
| 5 | .22 | 1.50 | 35.05 | A | 89 000 | 30 000 | 40.6 | 67.5 |
| | | | | B | 85 000 | 30 000 | 42.0 | 67.3 |
| | | | | C | 82 000 | 27 500 | 41.0 | 65.0 |
| 6 | .08 | .50 | 36.00 | A | 76 500 | 36 500 | 36.3 | 65.6 |
| | | | | B | 72 500 | 24 000 | 39.2 | 67.5 |
| | | | | C | 70 500 | 20 000 | 38.0 | 58.3 |
| 7 | .37 | 1.50 | 45.00 | A | 107 000 | 40 000 | 40.0 | 51.1 |
| | | | | B | 94 500 | 35 000 | 43.7 | 51.1 |
| | | | | C | 73 000 | 19 500 | 38.0 | 46.3 |
| 8 | .35 | 1.50 | 43.00 | Cold drawn | 100 000 | 52 500 | 16.2 | 46.0 |
| 9 | .17 | 1.25 | 50.66 | A | 99 000 | 48 500 | 38.5 | 67.7 |

Treatment A is the bar as rolled; B, the bar after being annealed (i. e., slowly cooled) from above 790° C.; C, the bar quenched, but not drawn, from above 760° C. The exact temperatures are not given.

## TABLE 16.—Standard Specifications for Structural Nickel Steel (Serial Designation: A8-21).

[A. S. T. M. Standards, 1921, p. 69.]

### CHEMICAL COMPOSITION.

| | Structural steel. | Rivet steel. |
|---|---|---|
| | Per cent. | Per cent. |
| C | Not over 0.45 | Not over 0.30. |
| Mn | Not over .70 | Not over .60. |
| P acid | Not over .05 | Not over .04. |
| P basic | Not over .04 | Not over .03. |
| S | Not over .05 | Not over .045. |
| Ni | Not under 3.25 | Not under 3.25. |

### TENSILE TESTS.

| Properties considered. | Rivet steel. | Plates, shapes, and bars. | Eyebar flats and rollers [2] unannealed. | Eyebar flats [1] and pins [2] annealed. |
|---|---|---|---|---|
| Tensile strength, pounds per square inch | 70,000–80,000 | 85,000–100,000 | 95,000–110,000 | 90,000–105,000 |
| Yield point, minimum, pounds per square inch. | 45,000 | 50,000 | 55,000 | 52,000 |
| Elongation in 8 inches, minimum, per cent. | $\frac{1,500,000}{\text{Tens. Str.}}$ | [3] $\frac{1,500,000}{\text{Tens. Str.}}$ | [3] $\frac{1,500,000}{\text{Tens. Str.}}$ | 20 |
| Elongation in 2 inches, minimum, per cent. | | | 16 | 20 |
| Reduction of area, minimum, per cent. | 40 | 25 | 25 | 35 |

[1] Tests of annealed specimens of eyebar flats should be made for information only.

[2] Elongation shall be measured in 2 inches.

[3] For plates, shapes, and unannealed bars over 1 inch in thickness a deduction from the percentage of elongation specified in the above table of 0.25 per cent shall be made for each one thirty-second inch of the specified thickness above 1 inch to a minimum of 14 per cent.

[S. A. E. Standard Specifications for Nickel Steels, March, 1922.]

### CHEMICAL COMPOSITION.

| S. A. E. steel No. | Carbon, range. | Manganese, range. | Phosphorus, maximum. | Sulphur, maximum. | Nickel, range. |
|---|---|---|---|---|---|
| 2315 | 0.10–0.20 | 0.30–0.60 | 0.04 | 0.045 | 3.25–3.75 |
| 2320 | .15– .25 | .50– .80 | .04 | .045 | 3.25–3.75 |
| 2330 | .25– .35 | .50– .80 | .04 | .045 | 3.25–3.75 |
| 2335 | .30– .40 | .50– .80 | .04 | .045 | 3.25–3.75 |
| 2340 | .35– .45 | .50– .80 | .04 | .045 | 3.25–3.75 |
| 2345 | .40– .50 | .50– .80 | .04 | .045 | 3.25–3.75 |
| 2350 | .45– .55 | .50– .80 | .04 | .045 | 3.25–3.75 |
| 2512 | max. .17 | .30– .60 | .04 | .045 | 4.50–5.25 |

NOTE.—The heat treatment given the steel to obtain the desired physical properties would depend upon the kind of service required of the steel. (See the S. A. E. Standard Iron and Steel Specifications for the various heat treatments recommended, though not to be considered in any way a part of the standard specifications.)

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