Magnetic Alloys of Iron, Nickel, and Cobalt *

By G. W. ELMEN

The unexpected magnetic properties of certain alloys of iron and nickel discovered some 20 years ago led to a thorough study of the entire range of iron-nickel alloys. The results of this study were so encouraging that alloys of these metals with cobalt, the only other ferromagnetic metal, also were studied, as well as various alloys of these metals with small amounts of non-magnetic metals added. From the results of this extended investigation have emerged several alloys that are playing important parts in the continued advancement of electrical communication.

SOME alloys of iron, nickel, and cobalt have remarkable magnetic properties superior in many situations to those of the constituent metals. Many of these alloys have found wide use in the instrumentalities and circuits of electrical communication, and were developed primarily for that purpose. This paper reports the experience and techniques of the Bell Telephone System in the development and utilization of these materials.

The advantageous properties of these alloys were disclosed through exhaustive researches, during which the whole realm of combinations of these three metals was explored. That certain alloys of iron and nickel had unexpected properties at low flux densities had already been discovered in the Bell Telephone Laboratories. There was at that time no theoretical basis for predicting, or even explaining, the character of those alloys; and, therefore, a study was undertaken of the whole iron-nickel series. The results were so encouraging that combinations of these elements with cobalt likewise were studied; and finally those alloys of special interest were combined with varying amounts of non-magnetic metals. In the course of this investigation several thousand specimens were made and tested in a period extending over fifteen years.

Such an empirical investigation is time consuming and expensive, but in a field where so little theory was available for guidance it was the only certain means to determine the practical possibilities of these alloys. It has been justified by the large number of alloys it has developed for practical use in communication engineering. One of the first and most striking applications was to submarine telegraph cables. The largest field of application, however, has been in teleph-

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* Published in the December 1935 issue of *Electrical Engineering*, and scheduled for presentation at the Winter Convention of the A. I. E. E., New York City, January 28–31, 1936.

ony, where the requirements generally are very exacting, and where other advances have imposed rigid demands on the magnetic materials.

In telephone circuits, standards of transmission efficiency require that the magnetic materials used as circuit elements shall produce maximum magnetic effect with minimum energy loss and distortion of the transmitted currents. Translated into magnetic characteristics, this means that at low magnetizing forces the material shall have high permeability in combination with low hysteresis loss, and, in many situations, constancy of permeability over the operating range. In circuits for voice and carrier currents it is often necessary to reduce the intrinsic permeability of the material to obtain the required constancy and low losses in the apparatus. Furthermore, to minimize eddy currents, a high resistivity is required and the material must be structurally suitable for fabrication into thin laminations. For other uses, such as for signaling and switching mechanisms, the magnetic properties at medium and high flux densities determine the suitability of the material. High permeability and low coercive force make for improved sensitivity and speed of operation. Low coercive force is of special interest in marginal apparatus where the difference between the operating and releasing currents is small.

Preparation and Composition of the Alloys

A great many factors contribute to the final properties of an alloy. Among the most important of these are the purity of the elements used in the alloy, their preparation, and the heat-treatment. The magnetic properties attainable can be completely masked by the intrusion of small quantities of certain impurities or by improper heat-treatment. For iron the magnetic properties can be improved materially by removing extremely small quantities of carbon and other non-metallic elements through heat-treating * in an atmosphere of hydrogen and at temperatures close to the melting point. This method of purification also improves the magnetic properties for alloys of iron, nickel, and cobalt. For communication purposes, it has not been found expedient as yet to introduce this method of refinement in the commercial production of these alloys. The purity of the constituents is controlled by ordinary methods of chemical analysis, by methods of melting, and by annealing processes which do not increase the amounts of important

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* There is a rapidly growing technical literature relating to the effects of very small percentages of impurities on magnetic properties and the methods for their removal, with notable contributions by T. D. Yensen of the Westinghouse Electric and Manufacturing Company, W. E. Ruder of the General Electric Company, and P. P. Cioffi of the Bell Telephone Laboratories.

impurities. The magnetic properties recorded in this paper have therefore been confined mostly to those obtained on materials produced by standard metallurgical methods.

In the commercial method of producing these alloys the best grades of commercial iron, nickel, and cobalt are used. The melting is done in an electric furnace, and after the mechanical fabrication into suitable shapes these alloys are heat-treated to develop the desired magnetic properties.

Early in an investigation of these alloys it was found that some of them required special heat-treatments to develop the desired magnetic properties. For some the slow cooling incident to the ordinary process of annealing was not suitable, and a rapid cooling was necessary. For another group the slow cooling in the annealing process was not slow enough, and the best results were obtained when the alloys were held at a constant high temperature for a considerable time. It was evident that to determine the most suitable temperature of heating and rate of cooling for each alloy would require more time than was warranted in the exploratory work. Three methods of heat-treatment that, in a general way, would separate the alloys into groups, were developed. These heat-treatments are designated in this paper as "annealing," "quenching," and "baking."

The annealing process consists of heating the samples in closed containers to a temperature of 1,000 degrees centigrade, and cooling with the furnace. The cooling ordinarily requires 7 hours before room temperature is reached. This heat-treatment is primarily for the purpose of removing the effects of mechanical strains necessarily resulting from the rolling and stamping of the alloys into suitable shapes. All the alloys discussed in this paper received this heat-treatment before any of the more special processes were applied.

The quenching process consists of heating the alloys for a short time at 600 degrees centigrade, and cooling in air at room temperature for small samples with large surfaces, and in oil for larger samples. The rate of cooling attained by these methods is approximately 40 degrees centigrade per second. It has been found that the best rate of cooling for maximum permeability does not always develop the highest initial permeability. The difference, however, is not large, and often is masked by other variations in the manufacturing process.

The baking process consists of heating the alloys for 24 hours at 425 degrees centigrade, and then slowly cooling to room temperature. The rate of cooling does not affect the development of the magnetic properties unless it is so rapid as to introduce mechanical strains.

CLASSIFICATION OF THE ALLOYS

A convenient way of showing graphically the compositions of the alloys of iron, nickel, and cobalt is by means of the composition triangle in Fig. 1. The sides of this triangle represent the binary alloys of the three metals, and points inside the triangle, the ternary alloys.

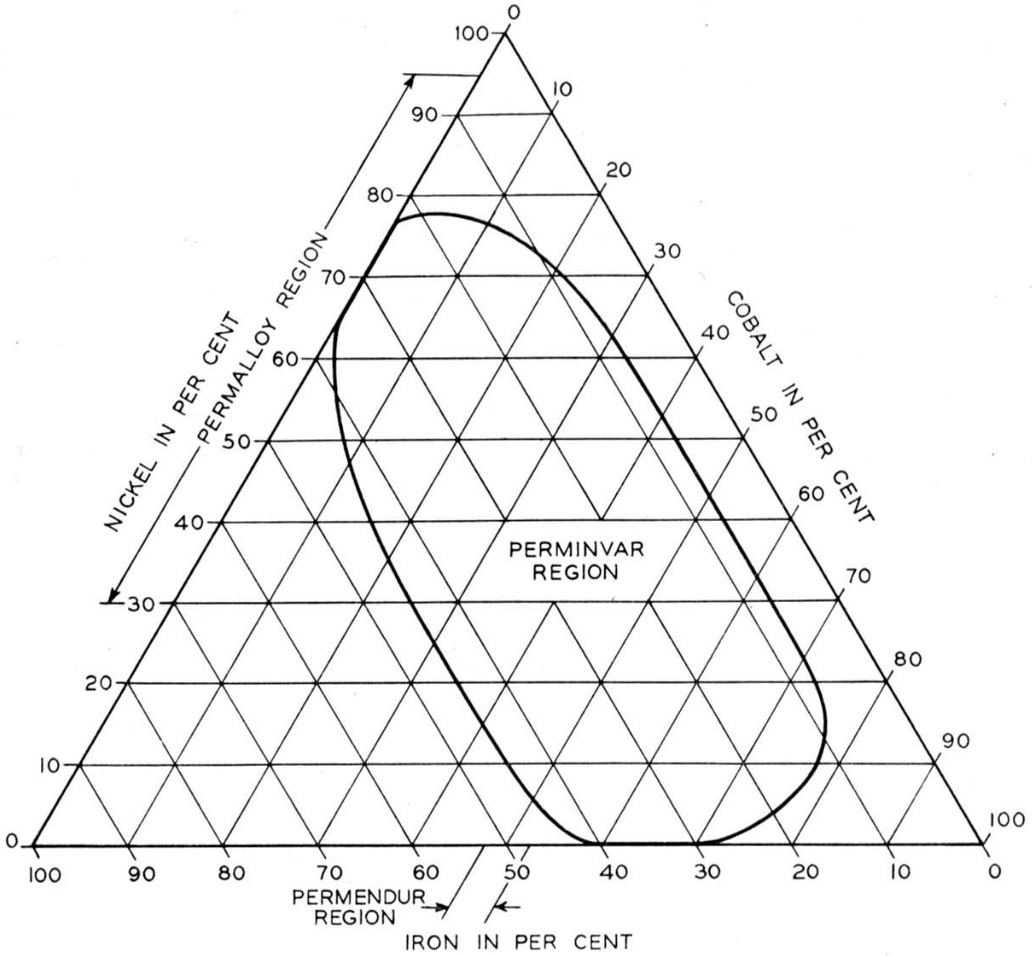

Fig. 1—Composition diagram for alloys of iron, nickel and cobalt.

In this diagram the alloys of special interest because of their magnetic properties are indicated, and, for convenience, each group in which the magnetic properties are similar has been given a specific name.

On the iron-nickel side of the triangle the permalloy region is indicated. In this group several compositions have been developed for commercial use in the Bell System. The method of identifying these alloys consists of prefixing a numeral indicating the per cent of nickel; for example, 45-permalloy contains 45 per cent nickel and 55 per cent iron. To some of these permalloys small amounts of other metals also are added. In designating ternary permalloys the same scheme is extended, so that the name gives everything except the iron content, and this is obtainable by difference. Thus, 3.8–78.5 Cr-permalloy contains 3.8 per cent chromium, 78.5 per cent nickel, and 17.7 per cent iron.

The perminvar region, enclosed by the curved line, contains those compositions that require baking to develop completely their characteristic magnetic properties. The specific compositions of these alloys are indicated by two prefixed numerals, the first indicating the nickel and the second the cobalt percentages, respectively. Thus the 45–25 perminvar alloy contains 45 per cent nickel, 25 per cent cobalt, and 30 per cent iron. Another alloy of the perminvar group, in which the nickel and cobalt percentages are the same as the alloy just mentioned, but which contains 7 per cent molybdenum and 23 per cent iron, is designated as 7–45–25 Mo-perminvar.

In the iron-cobalt series of alloys the composition 50 per cent iron and 50 per cent cobalt has been developed for commercial use. This is the permendur alloy, indicated in the triangular diagram in Fig. 1. This alloy is difficult to cold roll, but the addition of 1.7 per cent vanadium improves the mechanical properties and makes it sufficiently ductile to roll into thin sheets. The same system has been followed in designating this alloy as in the case of the permalloys. Thus 1.7 V-permendur is an alloy containing 1.7 per cent vanadium with iron and cobalt in equal proportions.

Table I lists the designations and compositions of those alloys, developed for particular purposes, which are discussed more fully in the remainder of this paper.

TABLE I

DESIGNATIONS AND COMPOSITIONS OF SOME MAGNETIC ALLOYS

Designation	Composition, Per Cent					
	Ni	Fe	Co	Cr	Mo	V
78.5 permalloy	78.5	21.5				
80 permalloy	80	20				
45 permalloy	45	55				
3.8–78.5 Cr-permalloy	78.5	17.7		3.8		
3.8–78.5 Mo-permalloy	78.5	17.7			3.8	
2–80 Mo-permalloy	80	18			2	
45–25 perminvar	45	30	25			
7–45–25 Mo-perminvar	45	23	25		7	
Permendur		50	50			
1.7 V-permendur		49.15	49.15			1.7

Ni = nickel; Fe = iron; Co = cobalt; Cr = chromium; Mo = molybdenum; V = vanadium.

In Figs. 2, 3, and 4 are shown the magnetization curves for low, medium, and high magnetizing forces for these alloys, except the 80 permalloy and the 1.7 V-permendur, for which the curves are substantially the same as for 78.5 permalloy and permendur, respectively. Curves for "Armco" iron and ordinary commercial 4 per cent silicon steel also are shown in these figures. All these materials were annealed, and in the case of the 78.5 permalloy and the perminvars the annealing was followed by quenching and baking, respectively. It may be seen from these curves that the permalloy group reaches almost saturation values long before the iron and silicon steel and the other alloys have reached the lower bend in the magnetization curve. With the exception of the 45-permalloy, which saturates at a fairly high value, the permalloys have low saturation induction and the permendur the highest. The permeability curves computed from these curves are plotted in Figs. 5 and 6. In Fig. 5, curves for the permalloy alloys are plotted at a smaller vertical scale than in Fig. 6 containing the curves for the other alloys.

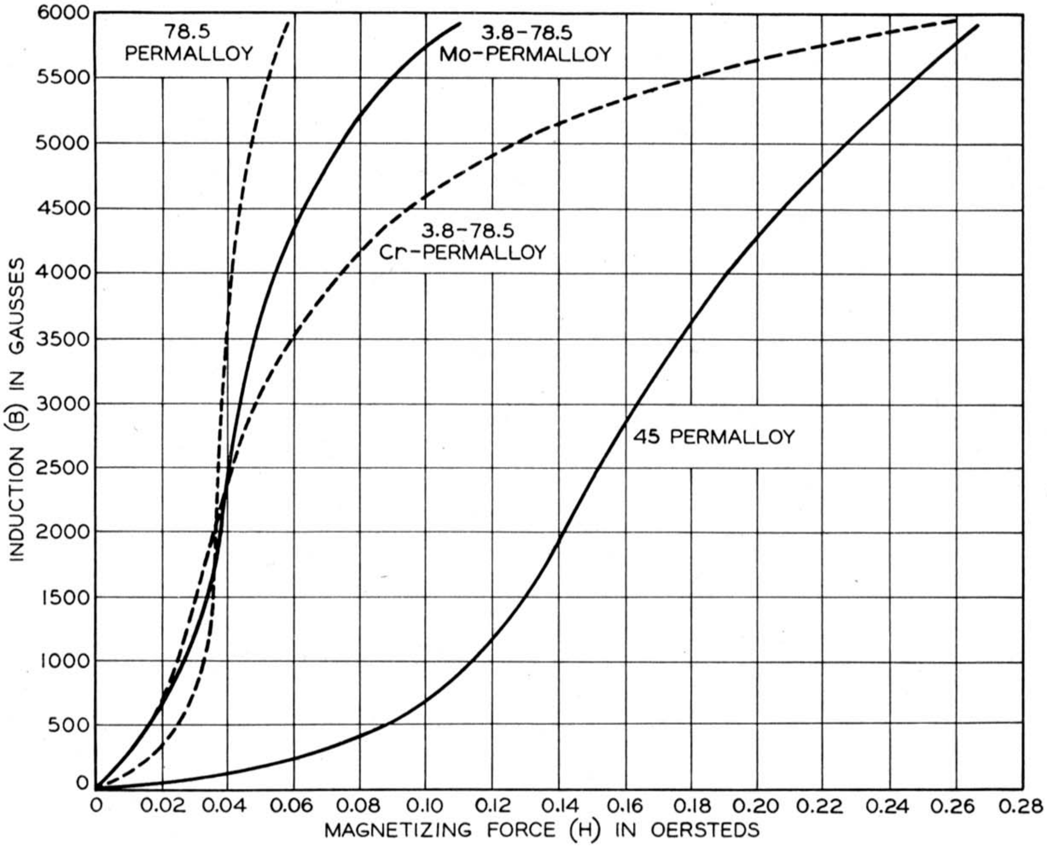

Fig. 2—Magnetization curves for several permalloys for flux densities less than 6,000 gausses.

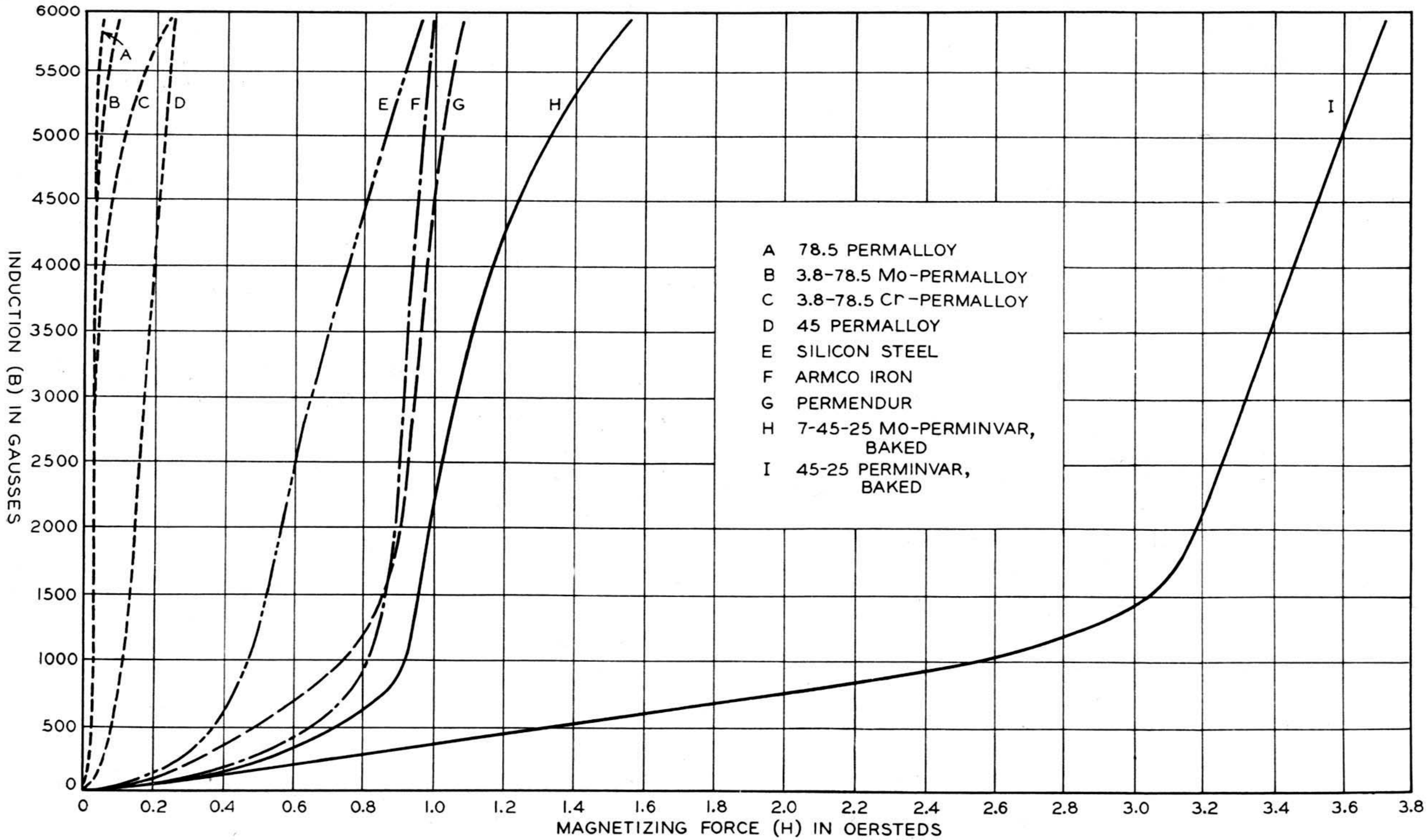

Fig. 3—Magnetization curves for permalloys, perminvars, and permendur.

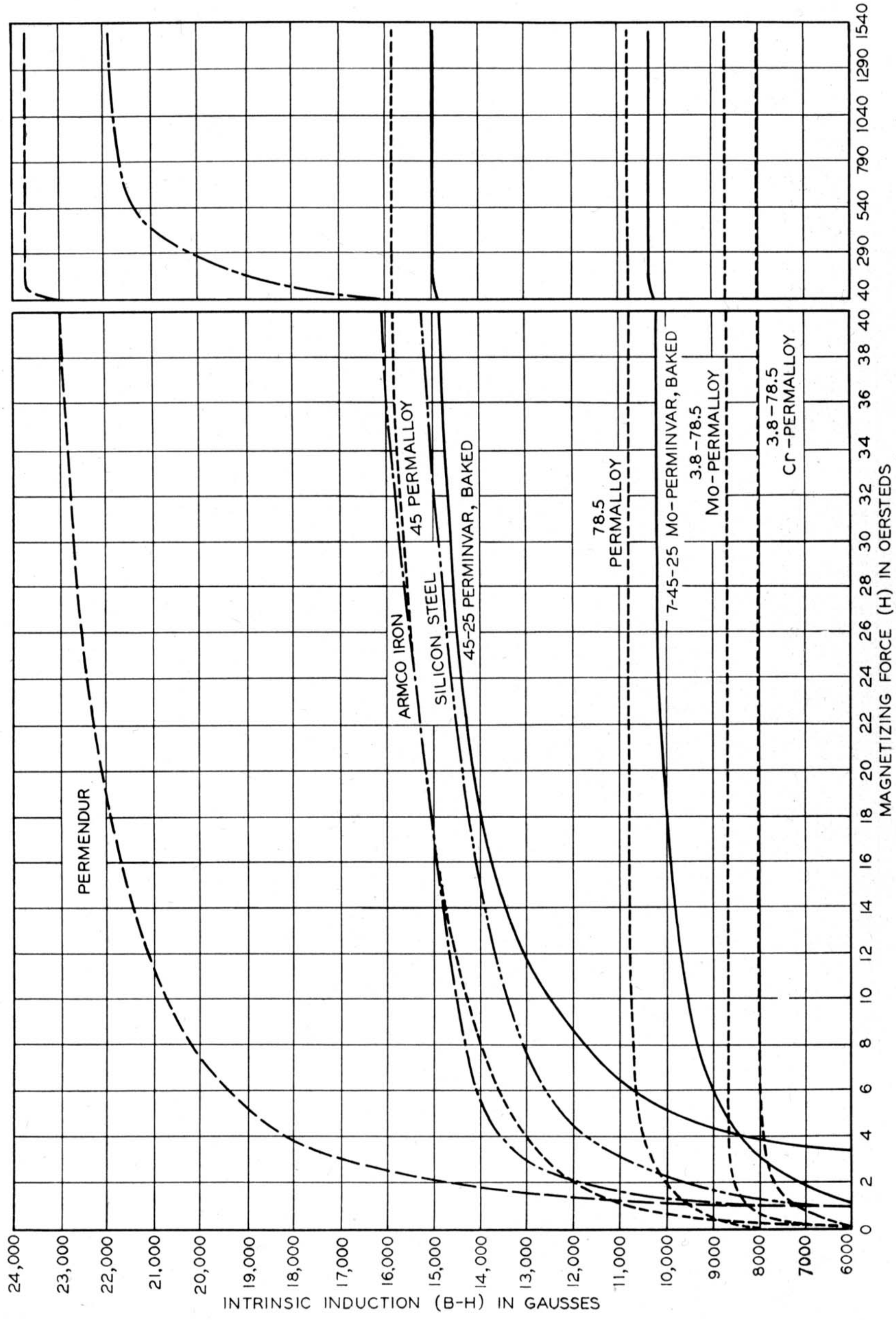

Fig. 4—Magnetization curves for permalloys, perminvars, and permendur.

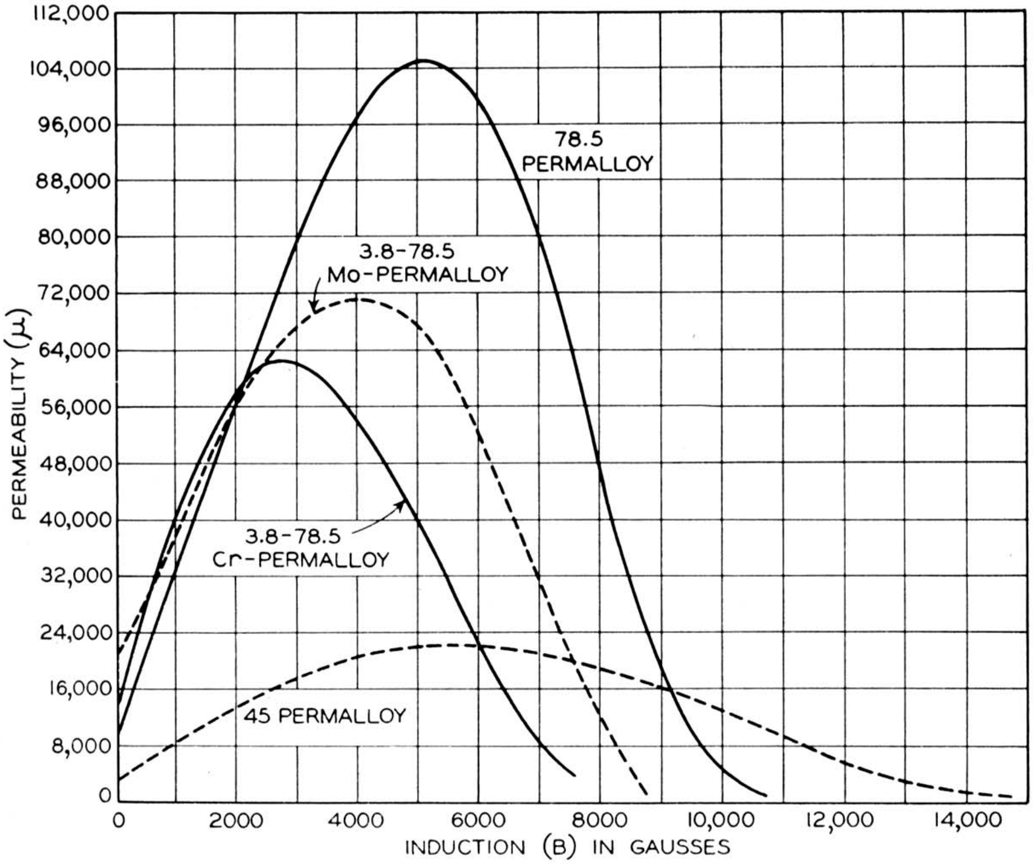

Fig. 5—Permeability curves for permalloys.

The permeability for alternating current of small constant amplitude as a function of superposed d.-c. magnetizing force is shown in Fig. 7 for some of the alloys. In most apparatus where both alternating and direct current are involved, this "butterfly curve" must be relatively flat over the expected range of d.-c. excitation. The important magnetic constants for these alloys are given in table II.

PERMALLOYS

In Fig. 8 the initial and maximum permeabilities and the coercive force and resistivities are plotted for quenched alloys of the iron-nickel series. These curves show the remarkable variations in magnetic properties with composition in this series of alloys. The permalloy region includes alloys between 30 and 95 per cent nickel, as indicated in Fig. 1. Some of the alloys in this region, particularly from 50 to 85 per cent nickel, require rapid cooling to develop the magnetic properties indicated in the curves. If they are merely annealed, both the maximum and the initial permeabilities are much lower. The greatest effect in reducing the permeabilities by slow cooling appears to be for

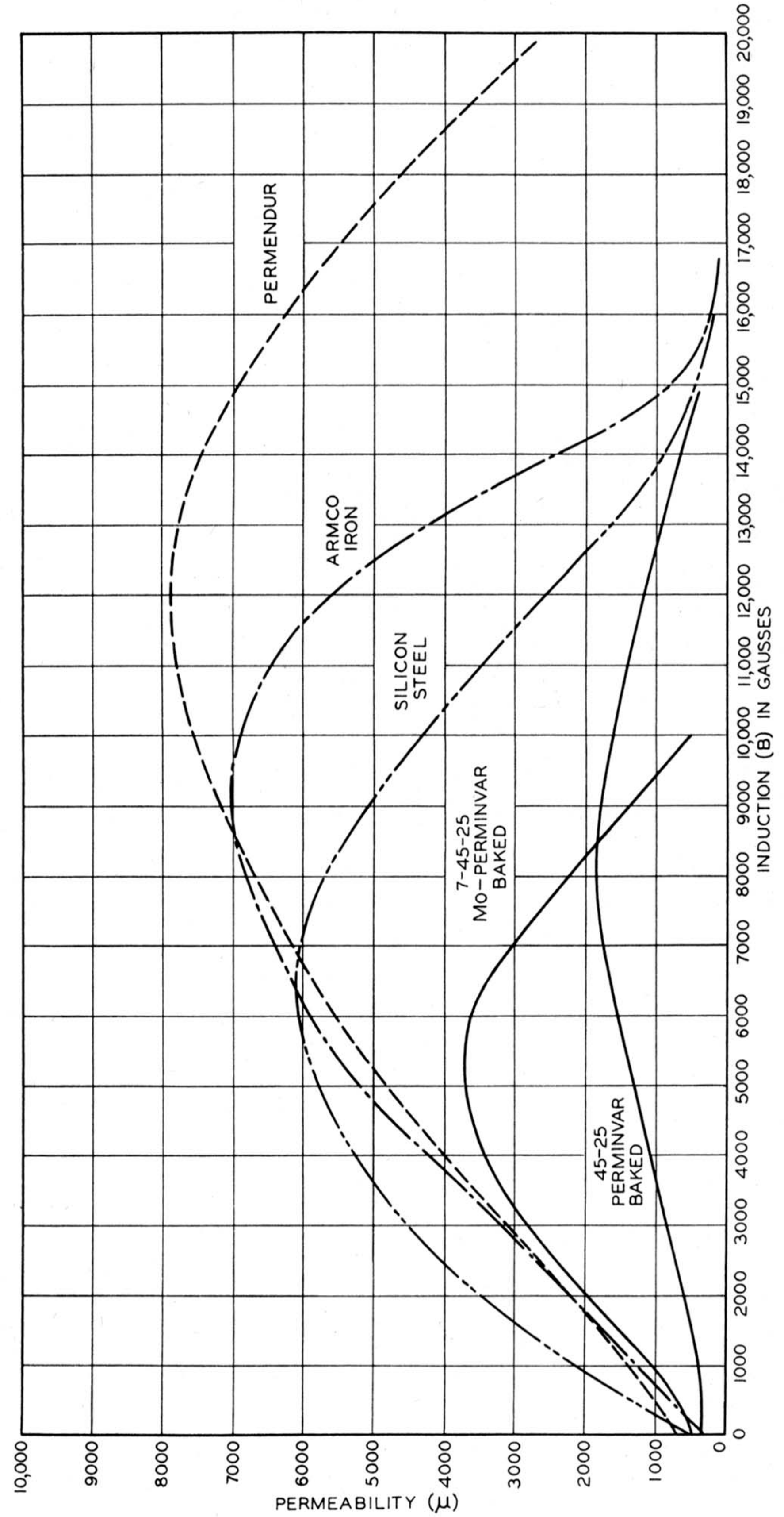

Fig. 6—Permeability curves for perminvars and permendur.

TABLE II

Magnetic Constants for Alloys Discussed in This Paper

Material	μ_0	μ_m	$W_{H=\infty}$	B_r	H_c	$(B-H)_{H=\infty}$	ρ
"Armco" iron	250	7,000	5,000	13,000	1.0	22,000	11
4% silicon-steel	600	6,000	3,500	12,000	0.5	20,000	50
78.5 permalloy, quenched	10,000	105,000	200	6,000	0.05	10,700	16
45 permalloy	2,700	23,000	1,200	8,000	0.3	16,000	45
3.8–78.5 Cr-permalloy	12,000	62,000	200	4,500	0.05	8,000	65
3.8–78.5 Mo-permalloy	20,000	75,000	200	5,000	0.05	8,500	55
45–25 perminvar, baked	400	2,000	2,500	3,000	1.2	15,500	19
7–45–25 Mo-perminvar, baked	550	3,700	2,600	4,300	0.65	10,300	80
Permendur	700	7,900	6,000	14,000	1.0	24,000	6

Here μ_0 and μ_m are the initial and maximum permeabilities, respectively; $W_{H=\infty}$ is the hysteresis loss in ergs per cubic centimeter per cycle for saturation value of flux density; B_r is the residual induction in gausses; H_c is the coercive force in oersteds; $(B - H)_{H=\infty}$ is the saturation value of the intrinsic induction in gausses; ρ is the resistivity in microhms-centimeter.

the alloys containing between 70 and 80 per cent nickel; for example, 78.5 permalloy with a standard anneal has its initial permeability reduced to 1,200. If the alloy is baked for several hundred hours this permeability can be reduced still further to about 500. There is a very rapid decrease in the coercive force as the nickel increases above 27 per cent, and the lowest values are reached in the region between 70 and 80 per cent nickel. The resistivity increases rapidly just below the permalloy region, and reaches maximum at about 31 per cent nickel. It should be noted that the large changes in the coercive force and the resistivity are at the lower end of the permalloy region, while the highest permeabilities are developed in the alloys containing between 75 and 80 per cent nickel.

45-Permalloy

One of the alloys developed for commercial use is 45-permalloy. This attains a saturation flux density as high as any of the permalloys. At 40 oersteds the flux density is 16,000 gausses, substantially the same as for "Armco" iron, and considerably higher than for ordinary silicon steel (Fig. 4). The initial and maximum permeabilities (under standard practice of heat-treating) are 2,700 and 23,000, respectively (Fig. 5 and Table II). For cores requiring flux densities between 8,000 and 12,000 gausses this alloy is specially useful. The resistivity of the alloy is 45 microhms-centimeter, which is high enough to make it superior for use in cores in a.-c. circuits. The higher permeability at

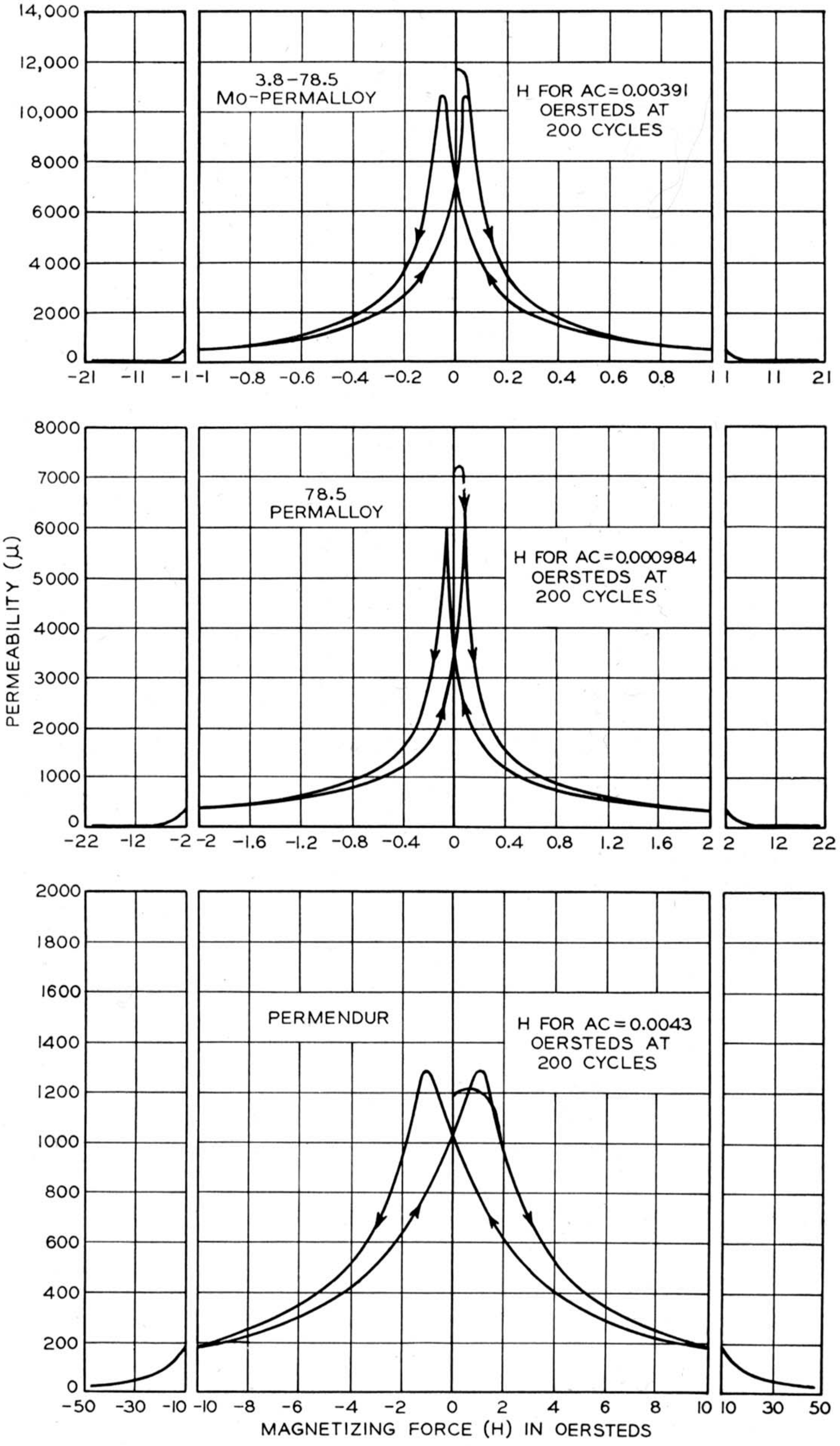

Fig. 7—Effect of superposed d.-c. fields on the a.-c. permeability of permalloys and permendurs. Annealed.—*Continued on page 125*

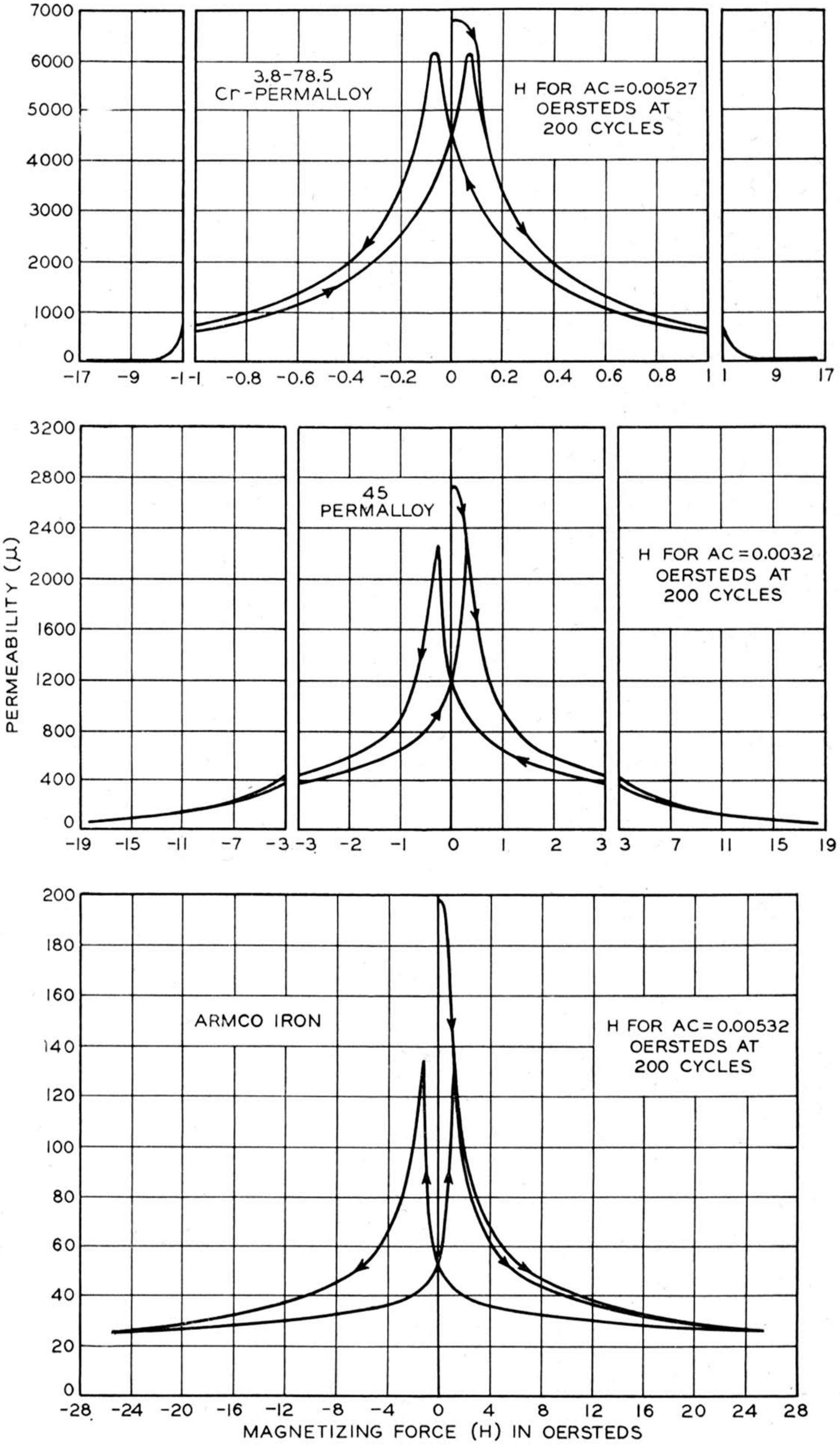

FIG. 7—*Continued from page 124*

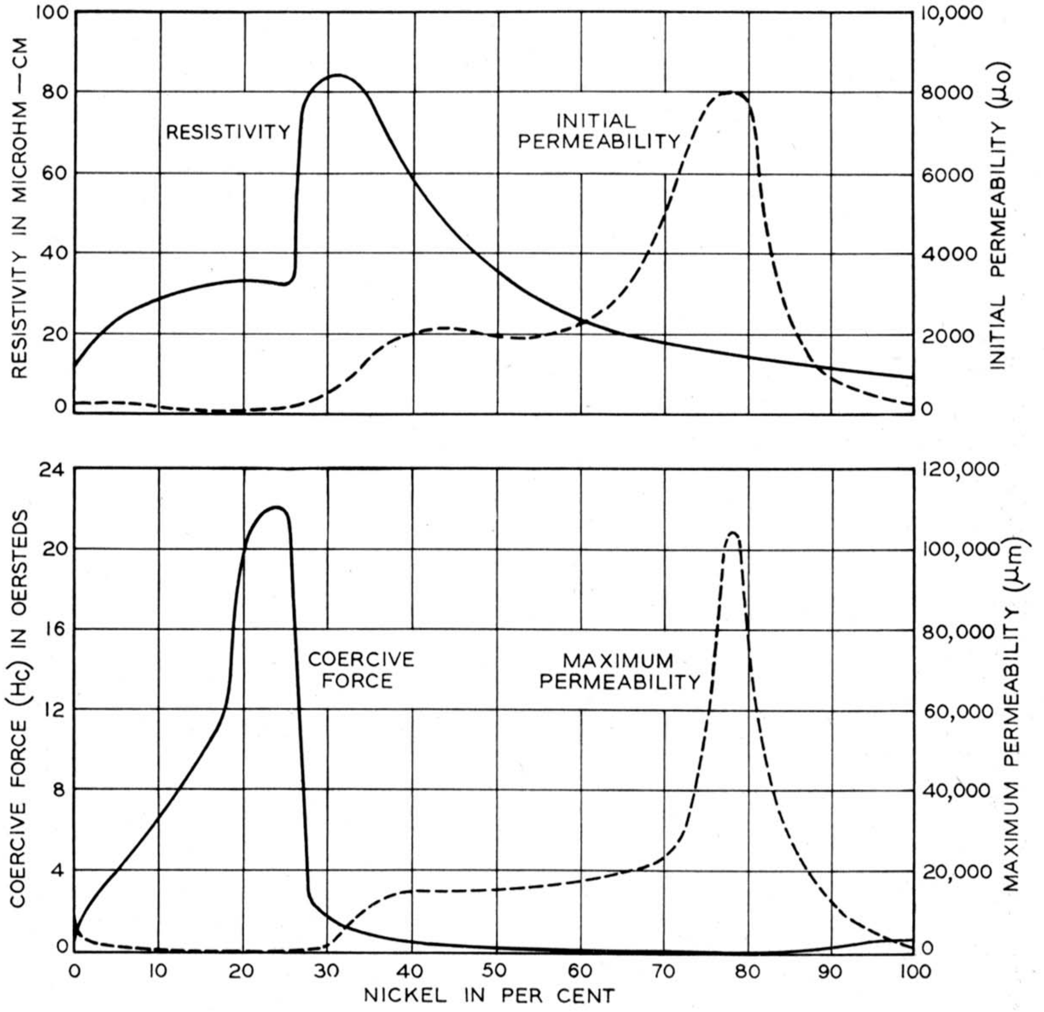

Fig. 8—Resistivity, initial and maximum permeabilities, and coercive force of iron-nickel alloys.

fairly high values of superposed d.-c. field, shown in Fig. 7, also favors its use for some purposes.

78.5-Permalloy

Another alloy long used in the telephone plant is 78.5 permalloy. Quenching develops a higher maximum permeability in this than in any of the other permalloys. Initial and maximum permeabilities of 10,000 and 105,000 readily are developed. The hysteresis loss and the coercive force of quenched 78.5 permalloy are minimum. The saturation flux density of this alloy is between 10,000 and 11,000 gausses, and it is reached with a very low magnetizing force. The rapid rise in the flux density of this alloy for small increments in the magnetizing force and the low saturation flux density are shown in Figs. 2, 3, and 4.

Initial and maximum permeabilities of 78.5 permalloy are improved by elimination of impurities and also by special care in the quenching process. As stated earlier, the rates of cooling required to develop the highest initial permeability differ from those for the highest maximum.

Chromium Permalloy and Molybdenum Permalloy

When other metals are added to permalloys their resistivities, in general, are increased. In research work at the Bell laboratories chromium and molybdenum mostly were used. It was found that with these elements a desirable combination of high resistivity and high initial permeability could be obtained. The variation in resistivity, keeping the nickel content constant at 78.5 per cent, is shown in Fig. 9. Chromium increases the resistivities somewhat more than molybdenum for a given addition, but the difference is not very large. The 3.8–78.5 Cr-permalloy has a resistivity of 65 microhms-centimeter, as compared with 55 for the 3.8–78.5 Mo-permalloy.

Figure 9 also illustrates the manner in which additions of these metals affect the initial permeability and the sensitivity of the permeability to rate of cooling. The solid line curves are for the annealed and the broken-line curves for the quenched specimens. For the quenched alloys the highest permeabilities are obtained when the added chromium and molybdenum are 2.4 per cent and 1.6 per cent, respectively. For this cooling rate the chromium permalloy seems to develop a slightly higher initial permeability. The difference, however, is small, and a greater spread between different samples has been observed. For the annealed alloys the largest value of initial permeability is obtained with molybdenum permalloy. For 3.8 Mo-permalloy an initial permeability of 20,000 is obtained. With the same heat-treatment the initial permeability of the corresponding chromium alloy is 12,000. It is surprising to note that small additions of these non-magnetic metals increase the initial permeability to values considerably higher than that for quenched 78.5 permalloy. Beyond 5 per cent this improvement ceases. All additions decrease the saturation induction values and the maximum permeabilities.

Several of these alloys have been developed for commercial use. Of these the most important are 2–80 Cr-permalloy, 3.8–78.5 Cr-permalloy, and 3.8–78.5 Mo-permalloy.

PERMINVAR

The distinctive magnetic properties of the perminvars are constancy of permeability at low flux densities, a low hysteresis loss in the same

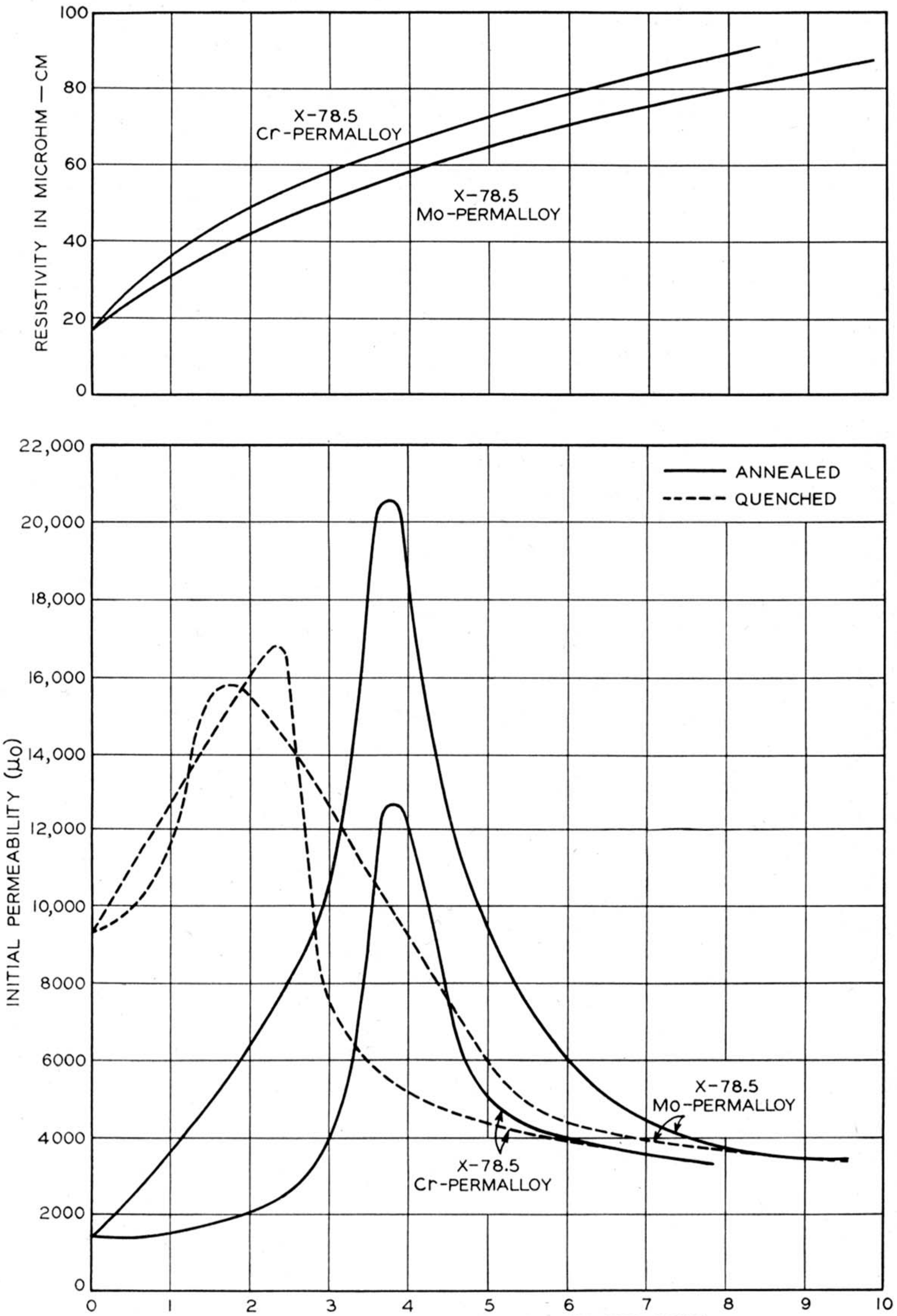

Fig. 9—Resistivity and initial permeability of 78.5 permalloy with chromium or molybdenum replacing part of the iron. In the curve designations, *X* indicates the percentage of chromium (Cr) or molybdenum (Mo) as read from the abscissa.

range, and, for medium flux densities, a characteristic constriction in the middle of the hysteresis loop. In some alloys this constriction is so extreme that the coercive force vanishes, making the two branches of the loop coincide when the magnetizing force is reduced to zero, in spite of the considerable hysteresis loss involved in the entire cycle. At high flux densities this constriction disappears and the loops have normal shapes.

The degree to which these properties can be developed depends on the composition and the heat-treatment. For the most typical alloys slow cooling in the annealing process produces this effect to a certain degree. Baking for 24 hours in the 400–500 degree (centigrade) temperature range brings most alloys into a stable condition in which no further baking materially will affect the magnetic properties.

As indicated in Fig. 1, some of the binary alloys tend toward the perminvar characteristics with long baking. Of the permalloys a considerable proportion of those that must be quenched to develop the desirable magnetic properties show perminvar characteristics when they are baked.

45–25 Perminvar

The perminvar characteristics have been developed most intensely in 45–25 perminvar. The magnetization curve in Fig. 3, and the permeability curve in Fig. 6, illustrate this fact. The constancy of permeability at low magnetizing forces and the necessity of "baking" to attain this condition are illustrated in one of the sections of Fig. 10, where the permeabilities are plotted for the quenched and baked conditions. The permeability of the quenched alloy begins to change at very low magnetizing forces, but that of the baked alloy, though lower, remains constant for magnetizing forces up to 3 oersteds.

Hysteresis loops for this alloy in the two conditions are shown in Fig. 10 for maximum flux densities of less than 1,000 and more than 5,000 gausses. For the baked alloy the hysteresis loops for maximum flux densities less than 1,000 gausses cannot be measured by ordinary ballistic methods, because the two sides of the loop coincide in a straight line. For loops with higher maximum flux densities the area begins to appear, but the two branches of the loop still meet at the origin. Although the coercive force is sensibly zero for the baked alloy until the maximum flux density exceeds 5,000 gausses, the hysteresis loss represented by the loop may become considerably greater than that for the quenched alloy.

7–45–25 Mo-Perminvar

The extremely low hysteresis loss and constancy of permeability at low flux densities makes 45–25 perminvar a suitable material for

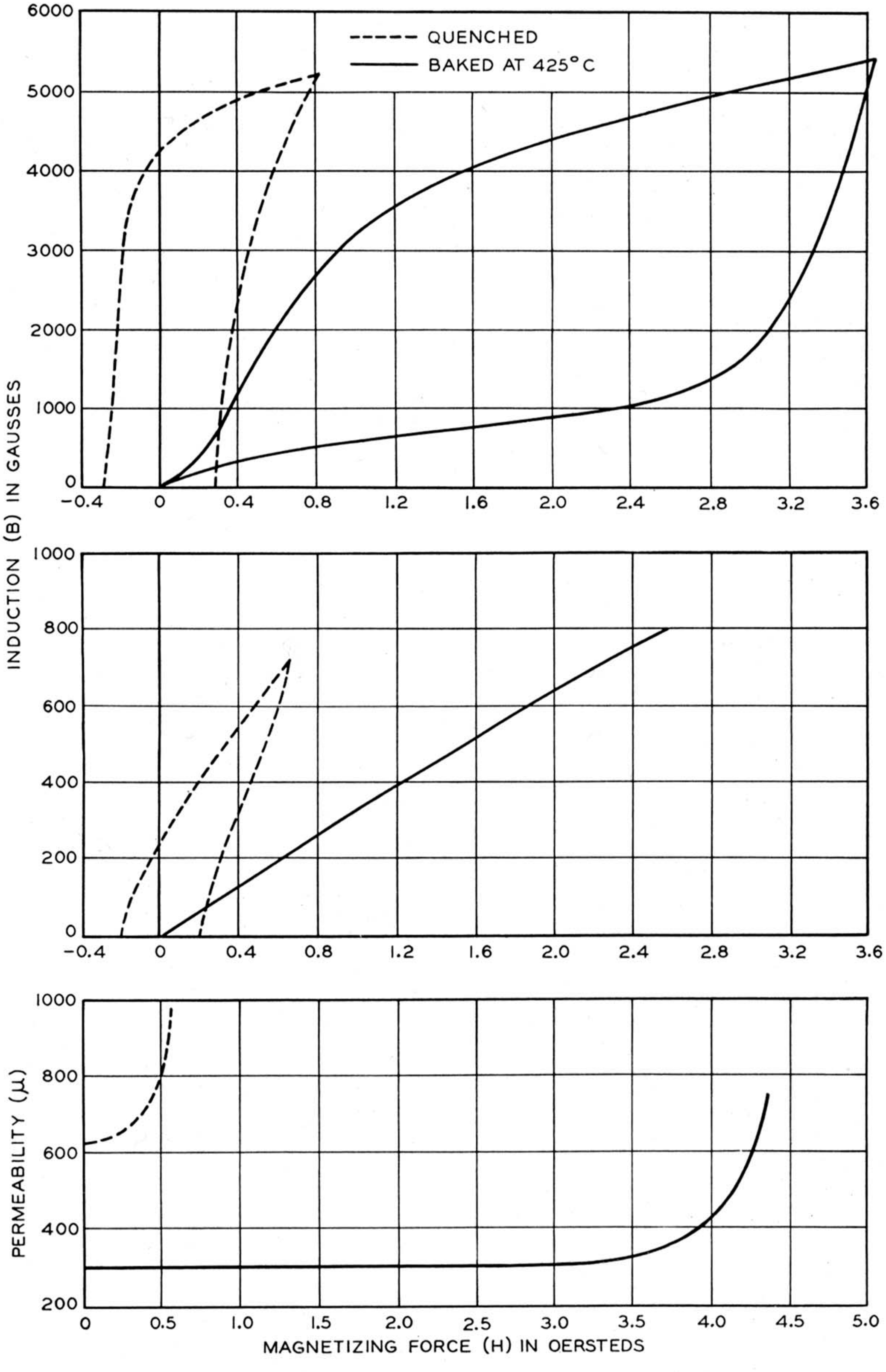

Fig. 10—Hysteresis loops and permeability curves for 45-25 perminvar.

applications where distortion and energy loss are fatal to good quality of transmission. The resistivity of this alloy is only 18 microhms-centimeter, but it can be increased without serious sacrifice of the low hysteresis characteristic by adding molybdenum. The alloy chosen for commercial use is 7–45–25 Mo-perminvar, having a resistivity of 80 microhms-centimeter.

The manner in which molybdenum affects the magnetic properties is illustrated in Figs. 3, 4, and 6. The permeability is not quite so independent of the magnetizing force as for the alloy without molybdenum, nor is the hysteresis loss quite so low. The initial permeability for the alloy baked the customary 24 hours is somewhat higher. When baked for a longer period the magnetic characteristics tend more toward those of 45–25 perminvar.

Permendur

An alloy in the iron-cobalt series used in communication apparatus is permendur. The typical composition is 50 per cent iron, 50 per cent cobalt. The outstanding magnetic property of this alloy is high permeability in the range of flux densities between 12,000 and 23,000 gausses (Figs. 4 and 6). The high permeability of this alloy "endures" to higher flux densities than does the permeability of any other magnetic material. Its initial permeability is about 700, though values as high as 1,300 have been observed for some samples. In addition to the high permeability at high flux densities permendur also has a relatively flat "butterfly" curve, as may be seen in Fig. 7. For a superposed d.-c. magnetizing force of 10 oersteds the a.-c. permeability of "Armco" iron is 40, as compared with 200 for permendur.

1.7 V-Permendur

Permendur is difficult to roll into sheets, because of its brittleness. To overcome this difficulty 1.7 per cent vanadium is added. With this addition it may be rolled into sheets as thin as a few thousandths of an inch. This amount of vanadium affects the magnetic properties only slightly, although larger amounts decrease the permeability at high flux densities.

Another improvement incident to the addition of vanadium is a fourfold increase of resistivity from its value of 6 microhms-centimeter for simple permendur. Permendur, it may be noted, has the lowest resistivity of the iron-cobalt series.

Laboratory Results

As stated hereinbefore, all the alloys that have been discussed have been made on a factory scale for some use in the telephone plant.

This paper, however, would be incomplete without mention of some of the remarkable magnetic properties obtained in laboratory samples. In table III some of these magnetic achievements are tabulated. The special treatments given these specimens are noted also in this table.

TABLE III

SOME REMARKABLE MAGNETIC PROPERTIES OBTAINED IN LABORATORY SPECIMENS *

Material	μ_0	μ_m	H for μ_m	H_c	Heat Treatment
"Armco" iron	20,000[1]	340,000[1]	0.021	0.03[1]	18 hr. at 1,480 deg. C., followed by 18 hr. at 880 deg. C., both in hydrogen
45 permalloy	11,000	227,000	0.025	0.0145	Melted in vacuum; electrolytic iron and electrolytic nickel; 18 hr. at 1,300 deg. C. in hydrogen
65 permalloy	2,500	610,000[2]	0.0148	0.012[2]	18 hr. at 1,400 deg. C. in hydrogen; heated to 650 deg. C. 1 hr., cooled in magnetic field of 16 oersteds in hydrogen
78.5 permalloy	13,000[3]	405,000[3]	0.0101	0.0153	$2\frac{3}{8}$ x 2 x 0.109 in. tape; annealed; wrapped in 2 layers of 3 mil. tape and quenched from 600 deg. C. in tap water
3.8–78.5 Mo-permalloy	34,000[1]	140,000[1]	0.025[1]		1,400 deg. C. in hydrogen
Permendur	1,000	37,000	0.22	0.20	940 deg. C. in hydrogen for 18 hr., slowly cooled to room temperature
Permendur	1,300	29,000	0.27		940 deg. C. in hydrogen, 6 hr.; slowly cooled to room temperature
45–25 perminvar		189,000	0.052	0.059	Heated to 1,000 deg. C. in hydrogen, reheated to 700 deg. C. and cooled in hydrogen in a magnetic field of 14 oersteds

For explanation of symbols in headings see footnote to table II.

* Except as noted, the values in this table have not previously been published.

ENGINEERING APPLICATIONS

One of the first uses of the permalloys was for continuous loading of a telegraph cable between New York and the Azores laid in 1924. For this project 78.5 permalloy was used in the form of a 0.125 by 0.006 inch tape wrapped helically on a stranded copper conductor. The average initial permeability of this alloy in the laid cable was 2,300, considerably less than can be obtained under the best conditions of heat-treatment and absence of strains. With this loading, the speed of transmitting messages was increased fivefold.[4] By the time a second cable project was undertaken the chromium permalloys had been developed, and 2–80 Cr-permalloy was selected. This alloy has a resistivity of 45 microhms-centimeter, and the initial permeability of the loading on the laid cable was in the neighborhood of 3,700. The increase in permeability and in resistivity increased materially the message carrying capacity.[5]

The largest use of permalloys in the telephone plant has been in cores of loading coils,[6] where the alloy is used in the form of compressed insulated dust. Iron dust cores had been standard for these coils.[7] The lower magnetic losses of permalloy dust, however, permitted utilizing higher core permeabilities. This has resulted in a very material decrease in the size of loading coils. For a high grade loading coil core made from iron dust the effective core permeability at low flux densities had to be limited to 33. The first permalloy used for loading coil cores was 80 permalloy. The insulated and compressed core was designed for an effective permeability of 75—more than double that for the iron dust. Development work on an improved compressed magnetic dust core in which molybdenum is used, is now approaching completion. It is expected that the new material will have a substantially higher permeability than that of the 80-permalloy dust cores, and that it will have intrinsically superior eddy current and hysteresis loss characteristics. By virtue of these properties, it will be practicable to make a further substantial reduction in the size of loading coils without sacrifice in service standards. The decrease in the size of the cores with improvement in the core material is illustrated in Fig. 11.

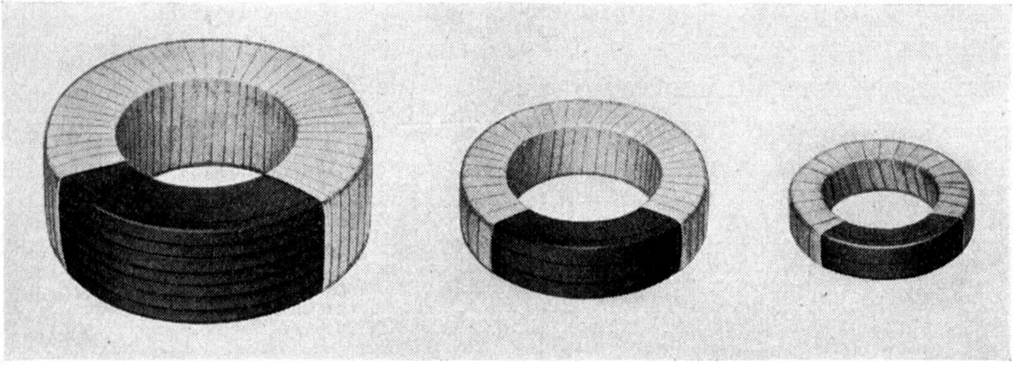

Fig. 11—Equivalent cores for loading coils. Iron dust core (left); permalloy dust core (center); molybdenum permalloy dust core (right).

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[4] For all numbered references see list at end of paper.

In d.-c. apparatus where high permeability and low coercivity are of importance, and where high resistivity does not add to the usefulness of the core material, 78.5 permalloy is suitable. It is used in certain relay structures, usually of marginal type, in which the difference between operating and releasing currents is small.

For audio transformers, for retardation coils, and for other apparatus in which high permeability and high specific resistance must be combined, both 3.8–78.5 Cr-permalloy and 3.8–80 Mo-permalloy have been used. The former has slightly higher resistivity, but the latter has higher initial permeability and is more ductile.

While the initial and maximum permeabilities of 45-permalloy are not as high as those of 78.5-permalloy, the higher flux densities attained by the former and its higher resistivity favor its use for certain types of relays and transformers where high flux densities are required. It is used also in some instances for cores of coils that require high a.-c. permeability when d.-c. magnetizing forces are superposed.

The magnetic characteristics of the perminvars make them especially suitable for use in circuit elements in which distortion and energy loss must be a minimum; but their relatively high cost, and the advisability of avoiding high magnetization throughout the life of the apparatus, have prevented their extensive use in telephone plant. One use for which perminvar is especially suitable is the loading of long submarine telephone cables. Here a high resistivity is very desirable, which has been shown to be obtainable in the 7–45–25 Mo-perminvar. The increase in resistivity resulting from the addition of molybdenum more than offsets the accompanying increase in hysteresis loss, and results in a continuous loading material satisfactory for certain types of loaded cables.

Permendur was developed for use in apparatus where very high flux densities are desired. For a moderate magnetizing force flux densities of 18,000 and 23,000 gausses readily are obtained. It is used for cores and pole pieces in loud speakers, certain telephone receivers, light valves, and similar apparatus.

It may be seen from this survey that there is a great variety of magnetic materials with widely different properties from which an engineer may choose in designing magnetic elements in which magnetic flux changes are essential. Already these alloys have an important place in telephone plant. However, iron and silicon steel still are used extensively, and will continue to hold their own on a cost basis for some purposes. There is no doubt, however, that alloys of iron, nickel, and cobalt will continue to supplant iron and silicon steel in many places where circuits and apparatus are redesigned to take full advantage of their magnetic properties.

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