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PROCEEDINGS OF THE IRE®

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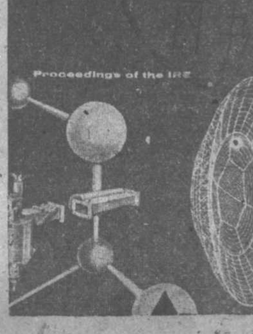

THE COVER—Connecting the klystron oscillator on the left and the antenna on the right is an isolator, one of a new family of microwave devices which utilize the magnetic properties of ferrites. The isolator consists of a slab of ferrite mounted inside a waveguide which has a permanent magnet strapped to the outside. The magnetized ferrite exhibits nonreciprocal properties at microwave frequencies, permitting transmitted waves to travel freely to the antenna but absorbing waves reflected back from the antenna. Ferrites derive their unusual properties from the spinning of electrons around axes which are oriented in a common direction, as depicted in the background. As the cover suggests, this special issue is concerned with both the fundamentals and the applications of ferrites.

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Joseph J. Gershon

Director, 1956–1957

Joseph J. Gershon received the B.S. degree in electrical engineering from Illinois Institute of Technology. From 1944 to 1945 he was with Ilg Electric Ventilating Company as electrical engineer in research and development. He entered DeVry Technical Institute in 1945 as instructor. Three months later he was given the assignment of developing a program in engineering mathematics and communications. Upon completion he organized a technology and design curriculum intended to follow the earlier courses, which later developed into a television design program.

In January of 1954 he was placed in charge of the resident school. At the present time he is revising the curriculum to more closely fit the changing needs of industry, by expanding the circuit analysis and mathematics in conjunction with new servomechanism and computer networks in the technology and design program.

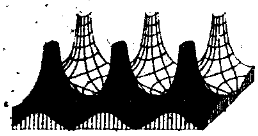
Mr. Gershon has been an active member of the executive committee of the Chicago Section since 1948. He served on most of the section committees and in several instances was chairman. He became Secretary of the Chicago Section in 1952 and in 1954–55 he was Section Chairman. His activity extended to the circuit theory symposiums held at the National Electronics Conferences.

Mr. Gershon also served as Sections Committee Chairman of the Professional Group on Circuit Theory for the past four years, and on its administrative committee, and on the Professional Groups Committee. He is now a member of the Nominations and Appointments Committees.

He is a registered professional engineer in the state of Illinois, and a member of Eta Kappa Nu, Tau Beta Pi, American Society for Engineering Education and the Armed Forces Communications and Electronic Association.

ADC 73/06

Poles and Zeros



Conference in Print. Lester Hogan describes the contents of this issue (p. 1233) so well that we have decided to omit *Scanning the Issue*. But it would be wrong to let the occasion pass without comment from the editorial chair, for this issue is special in more ways than Professor Hogan, in his modesty, is likely to admit. We have the opinion of an expert when Managing Editor Gannett says "This issue will stand up to any special issue we have ever published." Up to now there has been no place in the literature where an engineer can get a starting point on ferrites and their use at microwave frequencies. In this issue we are privileged to publish 26 papers in this area, ten of them of a tutorial nature—in essence the first textbook on the subject and no doubt the principal reference for years to come.

Compilations of this sort don't just happen; they require the most exacting preparation. In this case, it took three organizations to float the issue: the Air Force Cambridge Research Center, the IRE Professional Group on Microwave Theory and Techniques, and Harvard University. Last April these not-so-strange bedfellows sponsored a Conference on the Properties and Applications of Ferrites at Microwave Frequencies at Cambridge. Ten invited papers, plus a larger number of contributed papers, were presented. By good management and a little luck, they covered the subject in masterful fashion. It had been planned to publish the papers in the TRANSACTIONS of the PGMTT, but the Editorial Board requested the sponsors to make the papers available to the PROCEEDINGS, arguing that the subject matter was of such timeliness, fundamental importance and widespread utility that it should be presented to the profession at large.

This proposal having been accepted, the editorial work began. Professor Hogan agreed to organize the issue and to review the papers in detail. In this he was assisted by Howard Scharfman, Benjamin Lax, G. S. Heller and John Rowen. John Rowen made the further contribution of the ideas underlying the cover of this issue and checked the artist's sketches. These men, no less than the authors of the papers and the sponsor bodies, made possible this issue, for which every IRE member can be thankful.

An especially valuable aspect of the organization of the issue is the arrangement of the ten tutorial papers in such a way that, as Professor Hogan points out, the reader with no previous knowledge of the field should be able to prepare himself for intelligent research in this field.

New? The technology reported in this issue is new, as close to the frontier of solid-state physics as the semiconductors treated in the special issue of December, 1955. But the novelty is of a special sort, residing in the combination of properties of materials which were identified in the earliest stages of electrical science. The ferrites, as we know them today, combine high magnetic permeability with such high resistivity that eddy currents cannot interfere with their utility as concentrators and manipulators of high-frequency magnetic energy. The implications and second-order consequences of this basic concept occupy the two hundred-odd pages that follow.

The widespread amazement at the growing importance of solid-state materials in electronics cannot be supported by a sober view of the past. Far from being upstarts, the solid-state materials have always been the backbone of our art and the desire to understand them better has existed for fifty years. Omitting ordinary conductors and insulators, the historical sequence of solid-state technology in telephony and electronics runs approximately as follows: high retentivity magnets in the telephone receiver; surface states of carbon grains in the telephone transmitter; low-purity semiconductors in crystal detectors; tungsten and thoriated tungsten cathodes; the oxide cathode; phosphors; the photosensitive cathode; secondary emissive surfaces; high-purity semiconductors in crystal diodes; ferrites for megacycles; highest-purity semiconductors in transistors; ferrites for kilomegacycles.

Viewed in this perspective, the vacuum in the vacuum tube is almost an interloper. So viewed also, the solid-state materials are seen to be new only in the sophistication with which they are currently handled. Future progress would appear to be well indicated by the recent history of the development of ferrites for microwaves. These have been produced by bringing together traditionally separate properties, by the utmost patience in their preparation and refinement, and by more accurate and comprehensive knowledge of the internal processes which underly their external properties.
—D.G.F.

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Introduction to the Ferrites Issue

C. LESTER HOGAN

During the past decade we have witnessed a tremendous advance in the field of radio electronics through novel applications of solid-state materials. The most outstanding contributions have probably come from the class of materials known as semiconductors. However, within the past few years an increasing interest in the properties and applications of ferromagnetic materials has led to a whole new family of communications' devices which utilize the magnetic properties of matter. The rapid progress is due to many reasons. Probably the foremost is the development of a new class of ferromagnetic materials that have become known as ferrites. An important reason for this progress is the fact that a growing group of radio engineers have learned that a thorough understanding of the basic concepts of solid-state physics is essential to them if they are to be creative engineers in this new "solid-state electronics era."

Actually, it has been difficult for the communications engineer to obtain the background that he needs on the properties of ferromagnetic materials. To be sure, the information is in the literature (along with many concepts, theories, and experiments which are misleading or incorrect), but it has never been organized for the engineer in the way that information on semiconductors has been organized.

It was in appreciation of this need that this particular issue was conceived. Ten leading authorities have been invited to prepare review papers concerning various aspects of ferromagnetic materials and their applications. All have been prepared with the needs of the radio engineer in mind.

The issue starts with a general survey of the properties and applications of ferrites by C. Dale Owens. This article summarizes the basic properties of ferrites which have given them a unique position in the field of ferromagnetic materials. In addition, it discusses the major uses that engineers have found for these materials so far.

Following this general survey paper are four papers dealing specifically with various phases of the theory of ferromagnetism and ferromagnetic resonance that the engineer needs to know in order to understand the operation of the various devices which he uses. The first of these (Van Vleck) summarizes the present status of the physical theory of ferro- and ferri-magnetism. Then, there are three papers (Bloembergen, Suhl, Artman) dealing with various aspects of the theory of ferromagnetic resonance, which, of course, is the phenomenon upon which all microwave ferrite devices depend. Bloembergen is a tutorial review covering the linear theory, while Suhl is a tutorial paper on the nonlinear theory, which constitutes for the most part original work not previously published in any such extensive form.

The next six papers (Van Uitert; Fresh; Spencer, Ault, and Le Craw; Mullen; Sensiper; Tannenwald and Seavey) discuss the chemistry and general physical properties of ferrites along with the unique measuring techniques which have been found useful for measuring these properties.

The final fifteen papers deal with the theory and art of microwave ferrite devices. Those by Hogan, Lax, Heller, and Kales are tutorial reviews on various phases of the subject, while the remainder of the issue deals with original contributions either to the theory, or art, of microwave ferrite devices. These papers should give the reader an appreciation of the tremendous activity which is now taking place.

Only the serious student who is devoting a major share of his time to this field will find it worthwhile to attempt to digest all the material here. The less serious reader should be able to pick those fields of greatest interest to him by the titles of the articles. The ten tutorial review papers (Owens, Van Vleck, Bloembergen, Suhl, Van Uitert, Fresh, Hogan, Lax, Heller, and Kales) were selected and arranged so that a reader with no previous knowledge would be able to prepare himself for intelligent research in this ever-expanding field.

A Survey of the Properties and Applications of Ferrites Below Microwave Frequencies*

C. DALE OWENS†, SENIOR MEMBER, IRE

Summary—**A review of the properties, applications, and engineering significance of ferrites below microwave frequencies is presented. The survey includes a discussion of the nature of ferrites, their magnetic and electrical properties, the use of the μQ product as a design index of efficiency, core losses, and the effects of air gaps. This is followed by a discussion of the use of ferrites in a wide variety of applications. A Bibliography is also included.**

INTRODUCTION

THE PRACTICAL achievement of modern magnetic ferrites was announced just 10 years ago. They are ceramic-like materials, with permeabilities ranging up to several thousand combined with specific electrical resistivities over a million times those of metals. Laminating or powdering is not necessary, as it is with metals, in order to limit eddy currents to permissible values. The impact of this development on both engineering applications and on the basic understanding of magnetism has been very great. This paper will review the properties, applications, and engineering significance of ferrites below microwave frequencies.

Today, large numbers of persons are engaged in the study, manufacture, improvement, and use of ferrites. These include research scientists, students, technicians, and engineers working directly with ferrites. In addition others are working to improve the basic oxide materials, to design and build processing equipment, such as furnaces or grinding machines, and to develop new test equipment to meet the specific requirements for the controlled manufacture and application of ferrites. Ferrites now are in everyday use in inductors and transformers for carrier telephony, in flyback transformers, deflection coils, and inductance adjustment slugs in tv sets, and in antennas and IF transformers in radio sets. They are uniquely suitable for miniaturized inductors and pulse transformers demanded for transistorized circuits. The rapid development of ferrites for the new fields of computer circuits and microwave components promises an even greater effect on the daily lives of engineers and the public in the near future.

The work on ferrites comprises a very extensive activity in the field of magnetism, and is the subject of many symposia and large numbers of articles. It is an integral part of the advance in solid state and atomic physics. Ferrite is a member of the semiconductor family, which includes diodes, transistors, and solar cells. It is intriguing to consider this modern ferrite as a rebuilt version of lodestone, the first magnetic material discovered by man, and a possible forerunner of future new magnetic materials synthesized directly from performance specifications prepared by design engineers. Fig. 1 outlines on a time scale some of the major steps in the development of magnetic materials.

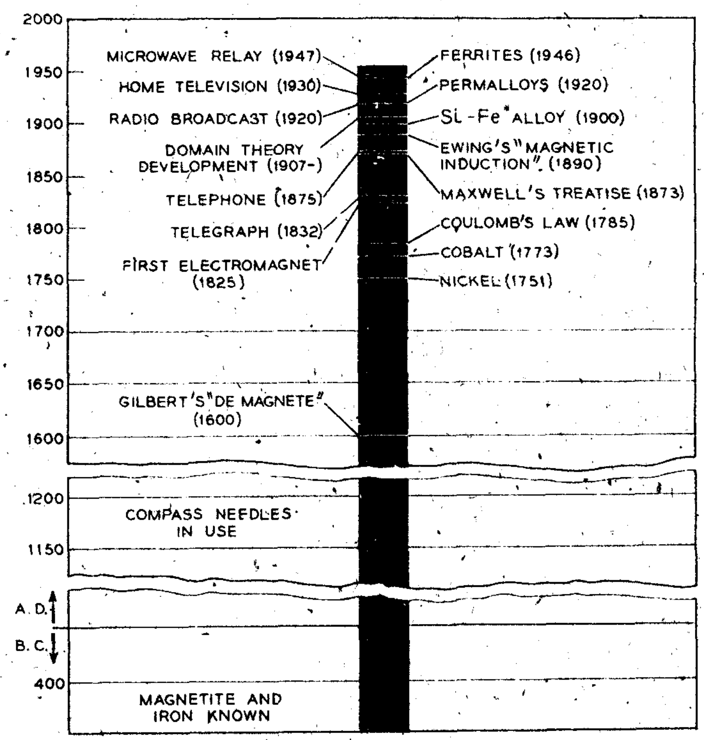


Fig. 1—Time scales of some magnetic discoveries and fields of use.

The modern ferrite development is timely. The emphasis on carrier, radio, and tv frequencies and on miniaturization has brought increasing demands for reduction of core losses. A point of diminishing return for effort and cost in further laminating and powdering metals appears to have been reached. Although sporadic efforts to develop ferromagnetic nonmetals have gone on for 50 years, the stimulating need has developed only in recent years. The advantages of the combined high permeability and high resistivity announced by Phillips in 1946 were apparent immediately to engineers designing inductors and transformers for communication use.

* Original manuscript received by the IRE, July 25, 1956.
† Merrimack Valley Lab., Bell Telephone Labs., Inc., North Andover, Mass.

An unexpected increase in core losses accompanied by a decrease in permeability was discovered in ferrites at frequencies far below those calculated to produce troublesome eddy currents. This led to intensive investigations of magnetic mechanisms and to new insight into magnetic theory. Domain wall movement, dimensional resonance, and ferromagnetic resonance were studied as mechanisms contributing to core loss. Very high "apparent" dielectric constants were measured on some of the ferrites in connection with dimensional resonance studies. The investigation of ferromagnetic resonance led to the discovery that ferrites were transparent to microwaves under proper conditions and produced Faraday rotation of the microwaves with very low losses. This is the phenomenon on which the gyrator and revolutionary new components for waveguides are based.

In turn, the studies of magnesium-manganese compositions most suitable for microwaves showed tendencies of some of the materials to have rectangular loops, that is, a high ratio of remanence to saturation. Development studies have provided cores suitable for memories and magnetic switches in computers and data processing circuits.

A study of why the saturation magnetization of ferrites is lower than that calculated from the simple addition of all the atomic moments led to the new concept of *ferrimagnetism*. The saturation moment of ferrites is explained as the resultant of two interplacing lattices of metal atoms with opposing magnetic moments.

The story of ferrites is one of mutual teamwork and stimulation in research, engineering applications, theory manufacture, and measurements.

The Nature of Ferrites

As a simple explanation, the modern ferrite may be described as a material derived from lodestone, or magnetite ($Fe^{++}O.Fe_2^{+++}O_3$) by substituting other metal atoms in place of the divalent iron (Fe^{++}). If these atoms are divalent and about the same diameter as iron atoms, the basic spinel type crystal structure of magnetite can be preserved, and greatly increased values of permeability and resistivity can be obtained. The properties of the ferrite are dependent upon the kinds of metal atoms and their proportions and geometric arrangement among the interstices of the close packed cubic array of oxygen atoms in the spinel structure. Suitable atoms to replace iron include manganese, magnesium, nickel, copper, cobalt, zinc, and cadmium. If the divalent iron is entirely replaced by zinc or cadmium alone, a nonmagnetic material is obtained. If it is replaced by one of the other atoms, the resulting material is magnetic, but the permeability seldom exceeds 100 and the hysteresis losses are high. These types of materials have been known for many years.

However, if the divalent iron in magnetite is partially replaced by zinc and partially by manganese, for example, the requirements for high permeability (and low hysteresis loss) are met. These are that the crystal be easy to magnetize in all directions (*i.e.*, have low crystal anisotropy) and that the change in dimensions with magnetization (magnetostriction) be small.[1]

The ferrites most commonly are manufactured from finely divided metal oxide powders, which are intimately mixed, pressed to shape, and then sintered. The process is similar to that for producing ceramics. As with ceramics, alternate processes are adaptable to ferrites. Ferrite compositions may be prepared by coprecipitation of the constituents from solution. For long rods or shapes which do not lend themselves to pressing from powder, casting or extrusion from a slip can be employed. Ferrite parts shrink some 10 to 20 per cent during firing. Fig. 2 illustrates some of the shapes and sizes of parts which have been produced. The final magnetic and electrical properties are highly dependent upon many factors which affect the arrangement of metal atoms in the crystal structure and the chemical homogeneity of the sintered compact. This includes the purity and "activity" of the constituent oxides, the heat treatment, and the atmosphere in which the parts are sintered and cooled. Ferrites of higher quality and new and more uniform properties are being achieved commercially as these factors are brought under better control.

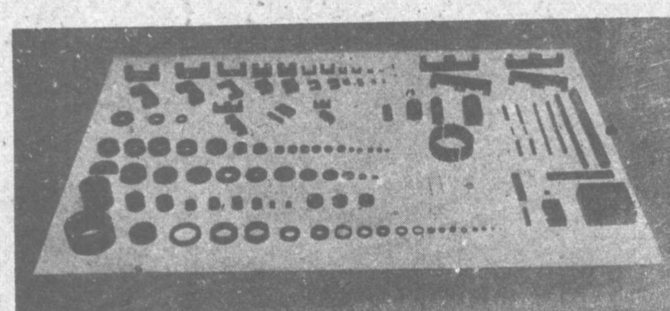
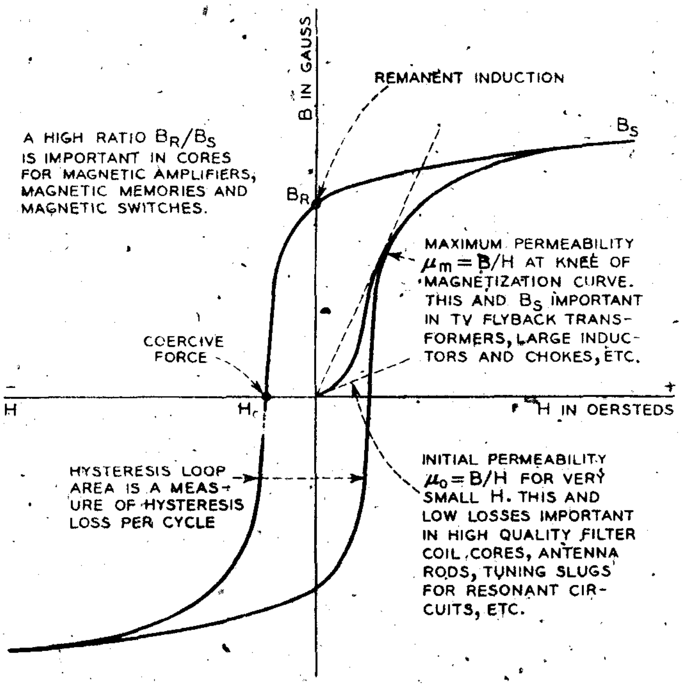


Fig. 2—Various shapes and sizes of ferrite cores.

The Magnetic and Electrical Properties of Ferrites

The magnetic properties of a material are defined by the way the flux density B is related to the applied magnetic field H (see Fig. 3), and by the losses resulting from changing magnetic fields. There are almost unlimited variations in composition and heat treatment possible among the ferrites giving rise to a large and

[1] Crystals containing metal atoms substantially larger in diameter than iron atoms, as when the divalent iron is replaced by barium, are found to be hexagonal in structure. They exhibit high crystal anisotropy and high coercive force, up to 3000 oersteds intrinsic value. This is the basis of the development of ferrite type permanent magnets with high resistivity, suitable for use in high frequency fields. The high coercive force makes it particularly useful for disk magnets.



THE PLOT OF INDUCTION B VERSUS MAGNETIZING FORCE H GIVES THE CHARACTERISTIC HYSTERESIS LOOP FOR A MAGNETIC MATERIAL. WHEN THE MAGNETIZING FIELD H IS RAPIDLY CHANGED AS IN AC APPLICATIONS, THE CHANGING FLUX DENSITY B GENERATES A VOLTAGE WHICH PRODUCES CURRENTS, AND ENERGY LOSSES, IN CONDUCTING AND DIELECTRIC PATHS.

Fig. 3

versatile family of materials. The ranges of values obtained for several characteristics are shown in Fig. 4, and compared to those of iron and other magnetic materials. Certain typical combinations of properties are indicated by letter designations. It will be observed that many of the characteristics such as Curie temperature T_c, coercive force H_c, maximum permeability μ_m and resistivity ρ show a general correlation, direct or inverse, with the initial permeability μ_0.

The initial permeability μ_0 of ferrites varies from around 5 for magnetite to over 6000 for a nickel zinc ferrite of the type designated A in Fig. 4. While these values are not particularly impressive compared to those which can be obtained in metals, the significant factor is that they are combined with resistivities many orders of magnitude greater. The dc resistivities of ferrites, except for magnetite with 0.01 ohm-centimeter, range from 10 ohm-centimeters to values as high as 10^8 ohm-centimeters. These compare with values of 10×10^{-6} ohm-centimeters for iron to around 100×10^{-6} ohm-centimeters for some of the metal alloys.

A comparison of the hysteresis loops of iron, molybdenum permalloy, and a ferrite are shown in Fig. 5. The ferrite corresponds to type B in Fig. 4. The saturation flux density B_s is relatively low for all the ferrites, ranging from about 1500 to less than 5000. This imposes

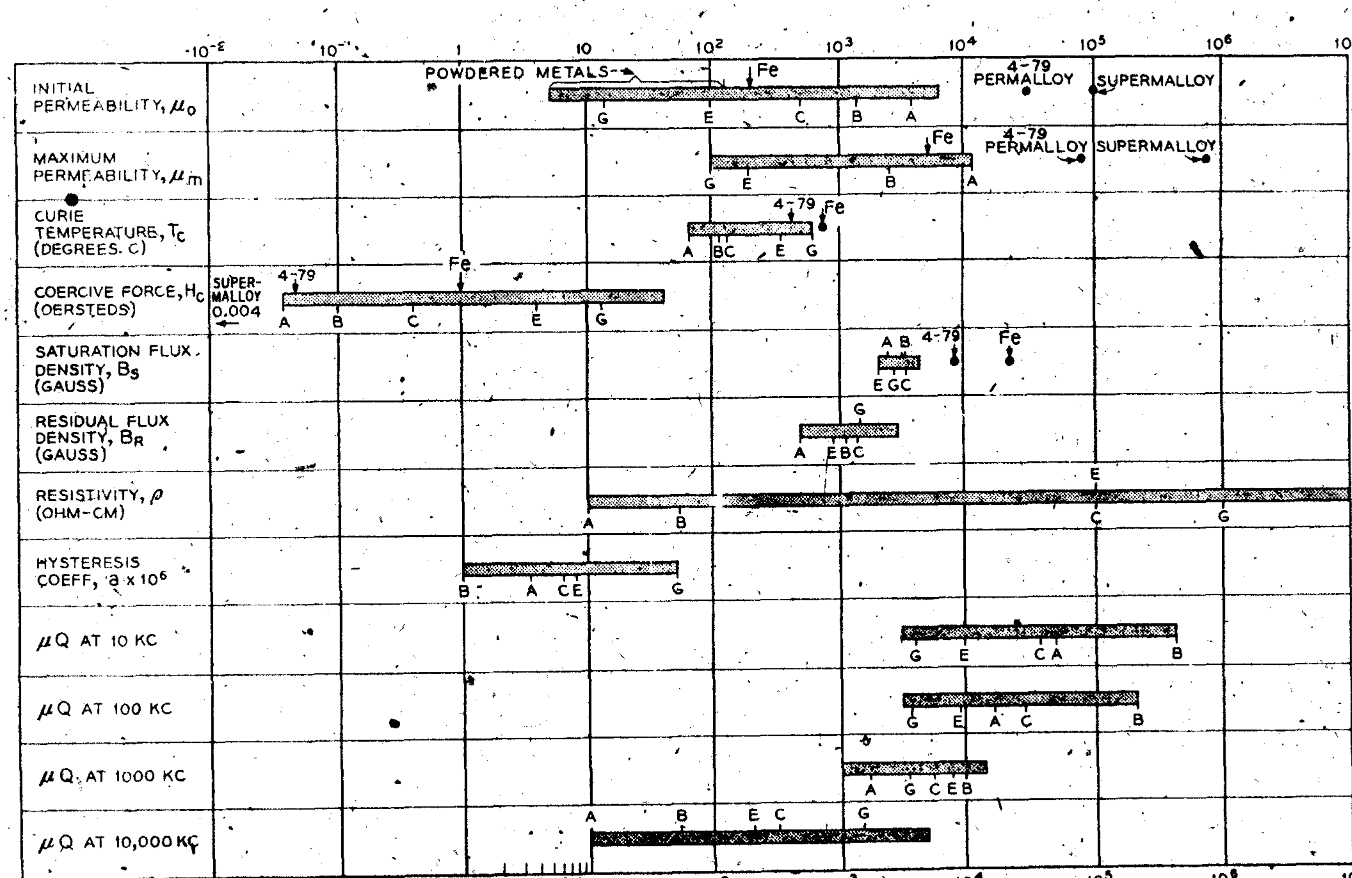


Fig. 4—Ranges of properties obtained in ferrites compared to properties of iron and permalloys. Letters designate certain typical ferrites. A) NiZn. B) MnZn. C), E) NiZn, often with additional elements Mg, Mn, Co, or Cu. G) Ni.

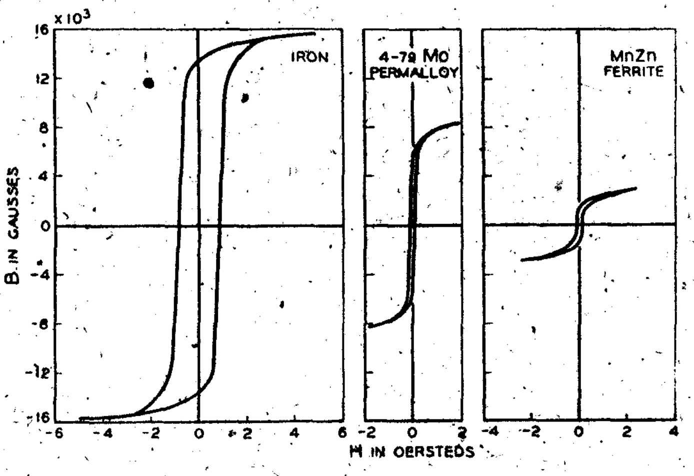


Fig. 5—Hysteresis loops of iron, 4-79 molybdenum permalloy and a MnZn ferrite.

a limitation on their use in power transformers or devices operating at high flux levels. A large variety of loop shapes are obtained with the ferrites, including those which are highly rectangular.

Another of the significant characteristics of ferrite is the low Curie temperature found in the high permeability materials. The Curie temperature is the temperature above which thermal agitation overcomes the alignment of magnetic moments and causes the material to become paramagnetic. It is typical of most magnetic materials that the initial permeability increases with rising temperature to a peak value just below the Curie temperature. This is shown in Fig. 6 for iron and

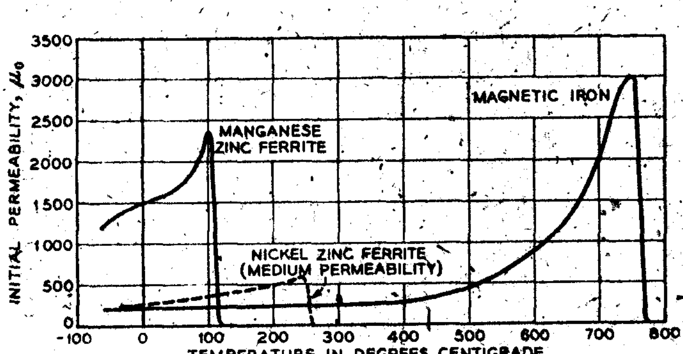


Fig. 6—Change of permeability with temperature for magnetic iron, a MnZn and a NiZn ferrite.

ferrite. The high permeability realized in some of the ferrites is due largely to the fact that they have Curie temperatures near room temperature and are used near the peak permeability. This condition tends to produce high sensitivity of permeability and other properties to temperature variations. The effect of temperature on the hysteresis loop of a nickel zinc ferrite with a permeability of 800 is shown in Fig. 7.

Material μQ Product as a Useful Index

In the appraisal of magnetic materials for design applications, especially for precision inductors, low

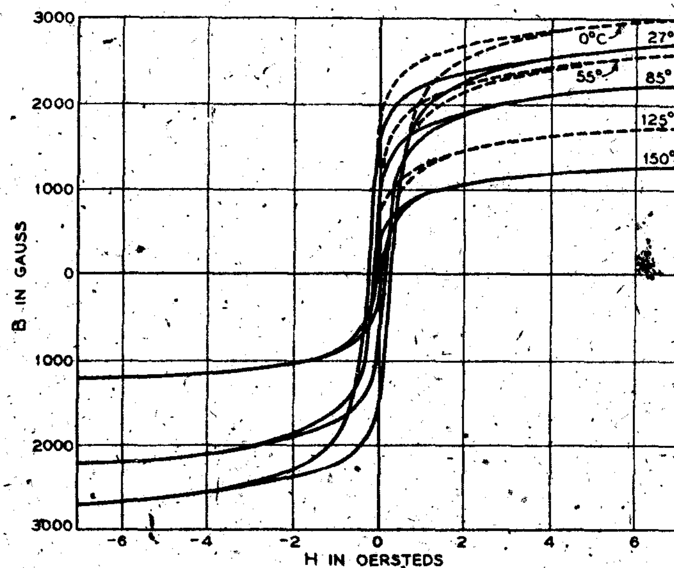


Fig. 7—Effect of temperature on the hysteresis loop of a NiZn ferrite with a permeability of 800.

losses and small changes of permeability and losses with frequency, flux density, temperature, and time are often of more importance than the actual value of permeability. The μQ product of a material, sometimes written $\mu_m Q_m$, has been found to be a useful index of efficiency for design applications. In this product, μ is the permeability and the material $Q(=2\pi fL/R_m)$ represents the reactance of a winding on a core per unit of core loss, as indicated in Fig. 8. The term R_m is the effective series resistance arising from core loss in the material. It is easy to see that a high value of μQ is desired. A higher value of μ will produce a larger amount of inductance L per turn, which can be used to provide a more efficient coil or a smaller coil of the same efficiency. A high value of μ also reduces leakage flux and improves the shielding when the core material surrounds the winding. A higher value of material Q means less loss per cycle per henry.

Fig. 8—Representation of core loss R_m as a series resistance. R_c = winding resistance; R_m = effective series resistance due to magnetic core; L_s = series inductance; $R_s = R_c + R_m$ = effective resistance of inductor;

$$\text{inductor } Q = \frac{2\pi f L_s}{R_c + R_m} = \frac{2\pi f L_s}{R_s};$$

material $Q = 2\pi f L_s / R_m$

where f = frequency in cps.

In a practical inductor design, the inductor $Q(=2\pi fL/R_s)$ which can be obtained is proportional to $\sqrt{\mu Q}$ of the material. In a transformer, a core material with a higher μQ results in a proportionally smaller shunt loss across the transformer windings. Fig. 9 shows the improvement of the μQ product over the years, reaching a peak in the recent ferrites.

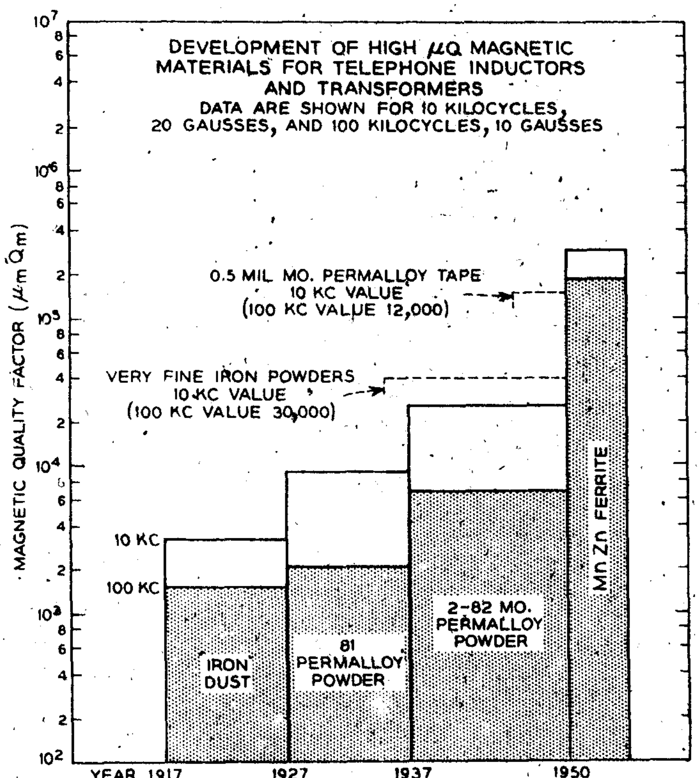


Fig. 9—Improvements in the μQ product over the years.

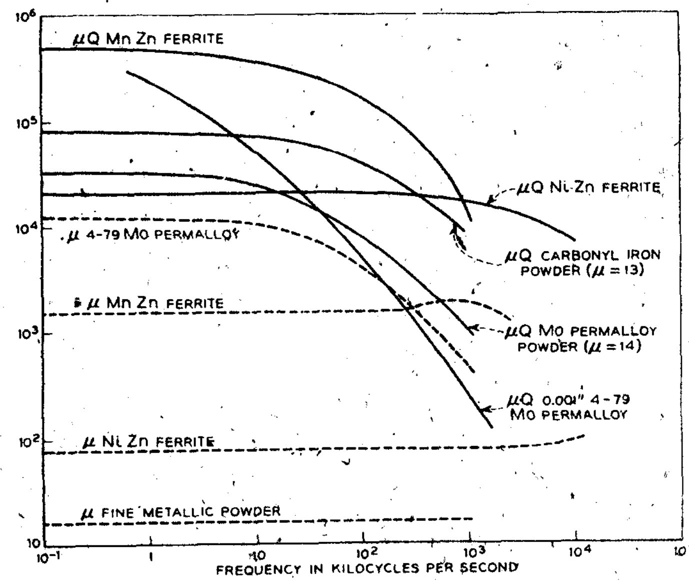


Fig. 10—Change of μQ with frequency for ferrites and other materials.

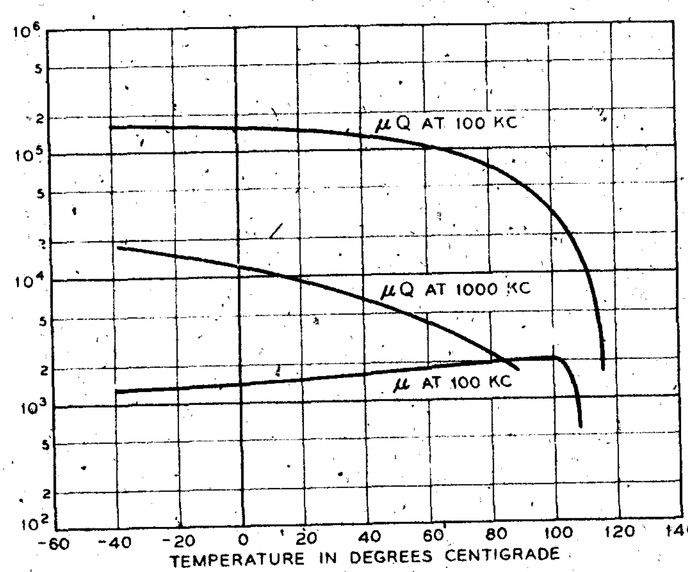


Fig. 11—Change of μ and μQ with temperature for a MnZn ferrite.

The μQ product of a material may be determined on a solid core but will remain practically unchanged if an air gap is cut in the core to reduce μ. In a design with an assembled core structure containing air gaps, when the air gap is correctly chosen, the core loss per henry can be made equal to the dc resistance per henry and the inductor Q can be optimized. It is found that the optimum value of permeability as well as the optimum inductor Q is proportional to the $\sqrt{\mu Q}$ of the core material.

The variation of μ and μQ with frequency, temperature, and flux density are shown in Figs. 10–12 to illustrate the behavior of typical ferrites. The μ and μQ begin to decline very rapidly above a certain "critical" frequency which depends on the permeability. Because of the high resistivities of ferrites this cannot be attributed to bulk eddy current effects. The values of the μQ products will be observed to drop off with increasing temperatures and flux densities and to "disappear" at the Curie temperature and at the saturation flux density.

Core Loss in Ferrites

Core loss data on metal laminations and powders can be expressed in terms of an eddy current coefficient e, hysteresis coefficient a, and residual coefficient c related by the Legg equation:

$$R_m = e\mu f^2 L + a\mu B_m f L + c\mu f L$$

where R_m is the effective series resistance in ohms, f is in cycles, the inductance L is in henrys, and B_m is the peak flux density in gausses. This equation is inadequate for use with ferrites except at frequencies well below the

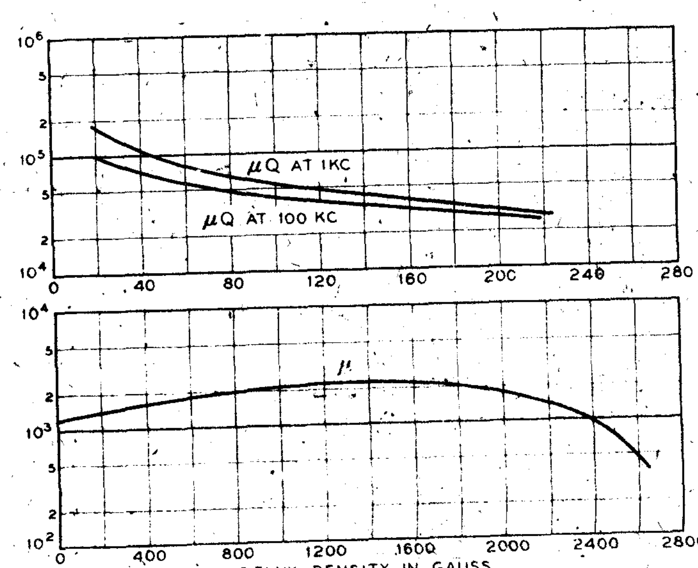


Fig. 12—Change of μ and μQ with flux density for a MnZ...

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critical frequency at which μQ begins to decrease rapidly. This is often arbitrarily taken as the frequency at which Q decreases to 10. Above this frequency in ferrites the residual term increases faster than the first power of frequency and becomes predominant. The coefficient c then becomes frequency dependent.[2]

The theoretical physicist has been challenged by the frequency characteristics of ferrites and has vigorously hunted the mechanisms responsible for the residual losses, no longer masked by eddy currents. He has been almost too successful in that there are several plausible mechanisms, possibly with overlapping effects. The explanations are largely an extension of the theory of domain behavior in magnetic bodies. They deal with the basic response of the magnetic moments of spinning electrons when applied fields are superimposed upon their natural crystal environment. The high frequency losses in ferrites are attributed to domain wall resonance or relaxation, ferromagnetic resonance, and dimensional resonance. Briefly, these are described as follows.

Domain Wall Resonance or Relaxation

The domain wall is the region between domains in which the direction of the magnetic moments of the electron spins is in a state of transition from the direction of one domain to that of the other. Because of the angular momentum of the spinning electrons (inertia), crystal forces (elasticity), and damping factors (loss), the domain wall can exhibit resonance like an RLC circuit at certain critical frequencies or will "relax" if the damping is critical.

Ferromagnetic Resonance

This occurs when the frequency of the applied ac field and the precession frequency of the spinning electrons correspond. The precession frequency is a function of the steady field aligning the electron spins. This phenomenon is usually observed at 4000–24,000 megacycles when the material is saturated by a strong applied dc field. The effect is a sharp peak in the absorption loss curve and a resonance in the permeability curve. However several investigators have pointed out that ferromagnetic resonance could occur under the influence of a self-contained crystal anisotropy field even at frequencies as low as a few megacycles, in a ferrite in which permeability depends upon rotations of the spins as a whole instead of by growth of domains through wall movement. The resonance effects would be expected to be very broad under these conditions and could account for the type of dispersion of permeability and μQ observed at frequencies of one to one hundred megacycles.

[2] When the complex notation is used for permeability, $\mu = \mu' - j\mu''$, a loss angle $\tan \delta = \mu''/\mu'$ is commonly used. Here μ' is the usual permeability and μ'' is the loss per cycle. The following relationships exist:

$$\mu Q = \frac{\mu'}{\tan \delta} = \frac{(\mu')^2}{\mu''} = \frac{2\pi}{ef + aB_m + c}.$$

Dimensional Resonance

This is a cavity-type electromagnetic resonance which can occur in cores in which a dimension of the core corresponds to a half wavelength of an electromagnetic wave propagated through the material. The "apparent" dielectric constant k of manganese zinc ferrite with a permeability of 1000 may be as high as 100,000 at 100 kc. This value drops with frequency to a constant value of the order of 10 at a few megacycles. This suggests that the high measured values of dielectric constant may arise from a granular structure of ferrite, of more conducting regions separated by high resistance films. The apparent dielectric constants in most nickel zinc ferrites are of the order of 1000 at low frequencies, except for very low permeability types, in which the dielectric constant may be less than 100. The dielectric Q is low, of the order of 1. Since the velocity of propagation of an electromagnetic wave is equal to $3 \times 10^{10}/\sqrt{\mu k}$ centimeters per second, the velocity will be 1×10^7 centimeters per second for $\mu = 1000$ and $k = 9000$. A half wavelength would be 5 centimeters at one megacycle, or 1 centimeter at 5 megacycles.

Effects of Air Gaps

An air gap in a magnetic circuit reduces the instability of permeability due to mechanical or magnetic shock or temperature changes below that experienced on a continuous ring core. In ferrite cores for precision, high quality components, air gaps are used for improving stability as well as for obtaining optimum values of Q, previously discussed. The following equation relates the effective permeability μ_e of the core containing an air gap to the intrinsic permeability μ of the ferrite parts neglecting leakage.

$$\mu_e = \frac{\mu}{r(\mu - 1) + 1}$$

where r is the ratio of the air gap length l_a to the total mean length l_t of magnetic flux in the core assembly. The differential of the above equation can be written in the following form relating the percentage change in μ_e to the percentage change in μ:

$$\frac{d\mu_e}{\mu_e} = \frac{d\mu}{\mu} \frac{\mu_e}{\mu} (1 - r).$$

If the value of μ is 1000 and the air gap is 1 per cent of the total flux path, then the value of μ_e will be 91 and the percentage change in μ_e will be only 9 per cent that of μ.

In some structures it is desired to assemble the core from parts but to retain a high permeability. It can be determined from the above relationship that the air gap ratio cannot exceed 0.01 per cent if the core permeability is to be greater than 90 per cent of the intrinsic ferrite permeability (of around 1000). If the flux path is 2.0 inches the total air gap would need to be less than 0.2 mil, or 0.1 mil each for two air gaps. This type of accuracy can be achieved through grinding and polishing the ferrite mating surfaces.

Other Characteristics

Like magnetic materials in general, ferrites show a decrease in permeability with increasing values of superimposed dc fields, and show a residual change after removal of the steady field. These effects are reduced by the use of an air gap. Some ferrites undergo shifts in permeability after ac demagnetization at high flux levels or after the materials are heated just through the Curie temperature and recooled to room temperature. Other ferrites, particularly extruded rod, have been found to be sensitive to vibration. This effect may be enhanced after the material has been subjected to a strong ac or dc magnetic field. Since these latter phenomena probably are functions of impurities, porosity, imperfections, and domain structure, ferrites can exhibit widely varying properties and representative samples should be checked carefully prior to application in designs requiring the highest stability.

Ferrites have about the hardness of quartz and are machined to size or provided with flat mating surfaces when required, by grinding operations under a water coolant. Diamond tools are often used. Cutting and machining also can be done satisfactorily with a supersonic machine tool. Mechanical polishing and lapping can be done in conventional ways when a smooth surface is needed.

Magnetostriction in the common polycrystalline ferrites is negative. The change in length when magnetized to saturation ranges from -0.5 parts per million to -22 parts per million. Because of the high resistivities, they are of interest for delay lines and magnetostrictive oscillators. It is a matter of interest that the highest value of magnetostriction so far measured on a magnetic material, 800×10^{-6}, was on a single crystal of cobalt ferrite in the [100] direction, after a magnetic anneal.

A number of investigators have grown single crystals of ferrites. These have been useful for studying domain wall motion and loss mechanisms. Initial permeabilities as high as 5000 have been measured on single crystals of Fe_3O_4, as compared to less than 10 in the polycrystalline form. No commercial applications involving single crystals are known to the author.

Applications of Ferrites

Ferrites have a large and increasing number of applications because component and circuit engineers have found them advantageous in accomplishing specific objectives. In some cases, ferrites yield higher efficiency, smaller volume, lower costs, greater uniformity, or easier manufacture than can be obtained with other materials. In others, including the microwave field, the unique properties of ferrites permit accomplishments not feasible with any other known material. Table I (opposite) summarizes the principal design applications, the most important component characteristics, and the properties of ferrites on which they depend. The applications fall roughly into categories determined by the material properties used:

1) *Linear B-H*, low flux level, high stability.
2) *Nonlinear B-H*, medium to high flux levels.
3) *Highly nonlinear B-H*, rectangular loop.
4) *Microwave properties*, ferromagnetic resonance, Faraday rotation.
5) *Magnetostriction.*

The microwave applications are included in the table for completeness but will not be covered in the discussion which follows on several typical ferrite designs. A recent article by Duncan and Stone [66] surveys ferrite applications in inductor design rather comprehensively, particularly those in the linear *B-H* region. Various methods of inductance adjustment are discussed, including wide range methods for tuners.

Filter Inductors

The high μQ product of ferrites over the frequency range of 50 kc to 150 kc has led to their extensive use in filter inductors for band-pass filters in carrier telephone circuits. Precise inductance adjustment, high inductor Q, and good stability are necessary for the function of separating channels. Such coils are normally of the pot type construction in which the cores are assembled using a center post, two end plates, and an outside ring. An alternate assembly uses two cups either with integral posts or a separate post. The principal air gap is provided by shortening the posts. With a proper magnitude of air gap built in, the permeability can be made correct for an optimum value of Q. Movable magnetic details which shorten or shunt the air gap have been incorporated for inductance adjustment. This eliminates the need for close factory adjustment, permits alignment of equipment after assembly, and eliminates trimmers. In the pot type cores described, the ferrite material provides an effective shield around the form winding. Permeabilities ranging from 35 to 100 are used most commonly to obtain the desired Q and required stability.

A completed filter coil is shown in Fig. 13 (p. 1242). Here, with a volume of 1.5 cubic inches, a Q of 500 is obtained at 100 kc. The core consists of manganese zinc ferrite with an intrinsic permeability of 1500. A coil wound on a molybdenum permalloy powder ring and previously used for a similar purpose had more than six times the volume but only one-half the Q. Furthermore, it could not be adjusted after final assembly. The ferrite coil can be adjusted over a range of plus or minus fifteen per cent by means of a movable cylindrical core shown in Fig. 13.

In experimental models on this structure, inductor Q's in excess of 1000 at 100 kc have been obtained. The manner in which distributed capacitance tends to reduce Q becomes an important consideration under these conditions.

TABLE I

A SUMMARY OF FERRITE APPLICATIONS

Type of component	Typical frequency	Characteristic sought	Favorable ferrite properties	Typical ferrite μ_0	Desired improvements
A. Linear B-H, low flux density					
Filter inductors	100 kc	High Q, precision, stability, low modulation	High μQ, low hysteresis, convenient core shapes	MnZn 1000–2500	Higher μQ, lower temperature coefficient
IF transformers	465 kc	High Q, stability, adjustability	High μQ, shapes	NiZn* 100–200	Higher μQ to higher frequencies better stability to temperature and to magnetic and mechanical shock
Antenna cores	1000 kc	Moderate Q, stability	High μQ; rod shapes		
Wide band transformers	to 15 mc	Reproducability of transmission characteristics	High μ, low losses, assembled core structures	Mn Zn 1000–2500 NiZn* >500	Very uniform magnetic and mechanical properties
Adjustable inductors	Various	Adjustment ±20 per cent	High μ, shapes	MnZn NiZn*	
Tuners	Various	Adjustment >10/1	Various mechanical structures, μ variation in dc field		
Miniature inductors	Various	Moderate Q, small size	Cup shapes	MnZn >1000 Ni Zn* >1000	Higher saturation, less loss at moderate Bm
Loading coils	Voice	Stability, low modulations, low leakage flux	High μQ		Lower sensitivity to dc fields Lower hysteresis loss
B. Nonlinear B-H, medium to high flux densities					
Flyback transformers	15–100 kc	Low loss, moderate size		MnZn >750 NiZn* >750	Higher saturation, lower losses Higher curie temperatures
Deflection yokes					
Miniature transformers	Pulse	Small size, easy mounting	High μ, cup shapes	NiZn 4000	Higher saturation
Carrier power transformers	Various				
Choke coils					
Suppression beads		High resistive impedance	High loss above critical frequency	MnZn >500 NiZn* >500	
Recording heads			Mechanical rigidity, low loss	NiZn, MnZn	Higher saturation, nonabrasive surface
C. Highly nonlinear, rectangular loop					
Memory cores	Pulse	Two identifiable stable states, fast flux reversal	Small rings practical reasonable rectangularity	MgMn	Higher degree of rectangularity, stability, uniformity, low cost
Switching cores	Pulse	Fast flux reversal, high output	Reasonable rectangularity	MgMn	High saturation for high output
Multiaperture cores					
Magnetic amplifiers					
D. Microwave properties					
Isolators, attenuators, circulators, switches, modulators			Faraday rotation Ferromagnetic resonance	MgMn*	
E. Magnetostriction and other properties					
Delay lines					
Filters and oscillators					
Temperature controls		Sensitivity to temperature	Low curie temperature Temperature sensitivity		

* May contain additional elements such as Mg, Mn, Co, Cu, Al.

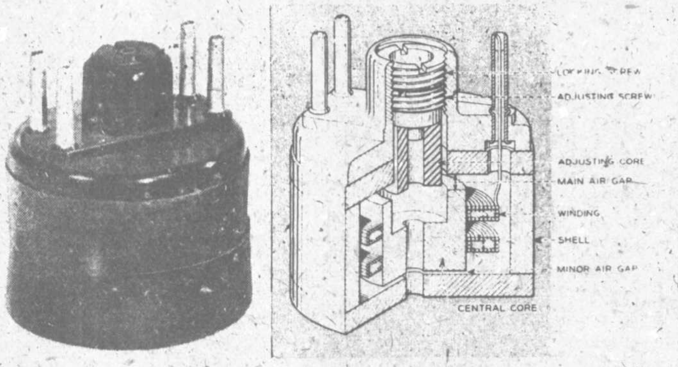

Fig. 13—A high-Q adjustable filter inductor.

Wide-Band Transformers

High permeability ferrites, in core assemblies made up of C's or E's, are being used in wide-band high frequency transformers. A precision transformer of this type (Fig. 14) is used in line amplifiers in the L-3 coaxial

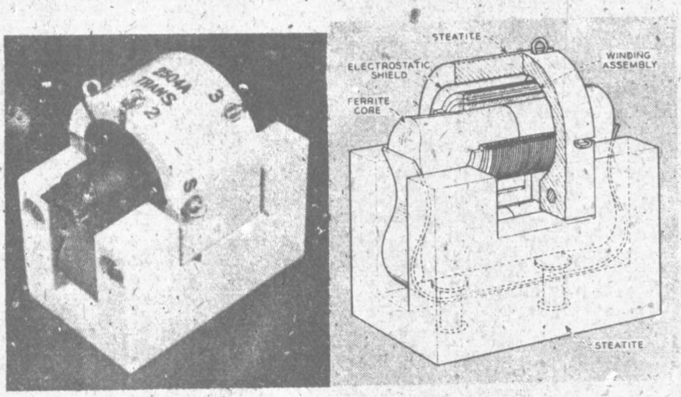

Fig. 14—A wide-band transmission transformer.

cable system in which the video band extends up to 8.4 megacycles. Here two C-shaped cores are assembled into two precise windings plated on optical quartz forms. The assembly is held to very close dimensions in order to control leakage inductance and parasitic capacitances and thereby the over-all transmission characteristics. Such close mechanical and electrical tolerances would not be possible with windings on toroidal cores. The permeability of the ferrite is high enough to provide the inductance necessary for transmission at low frequencies with the relatively small number of turns required to provide good high frequency response. With carefully ground mating surfaces, the loss in permeability due to air gaps is only about ten per cent.

Antenna Cores

Extruded rods of ferrite are utilized for antenna cores for broadcast radio receivers. These are usually one quarter to three quarter inch in diameter, in lengths ranging from two to eight inches. A winding is applied, normally distributed over the length of the core, to form an inductive antenna. The number of flux linkages is increased through the effective permeability of the core. The length to diameter ratio of the rod needs to be large in order to reduce demagnetizing effects and thus realize as much as possible of the intrinsic permeability of the ferrite. This generally has led to the extrusion of rods. For a given ratio of length to diameter, the sensitivity of the antenna is increased by enlarging both length and diameter. Sizes of portable radio cabinets and costs of the core material have influenced the production of cores toward the sizes noted above. The ferrite material should have moderately high Q over the broadcast frequency band to provide needed selectivity. It should be stable with respect to temperature changes, residual magnetic shock from high ac or dc magnetization, or mechanical vibration to prevent inductance changes large enough to cause detuning. Improvements in these respects have been achieved recently by new compositions and manufacturing techniques.

Miniature Components

The ferrites are finding more and more applications in a growing field for miniature inductors and transformers. The pot type structure is well suited for the efficient utilization of space. Two cups are commonly used and assembled around a winding. Terminal plates or pigtail leads are attached and the assembly is molded in plastic. Fig. 15 shows such an inductor assembly. The

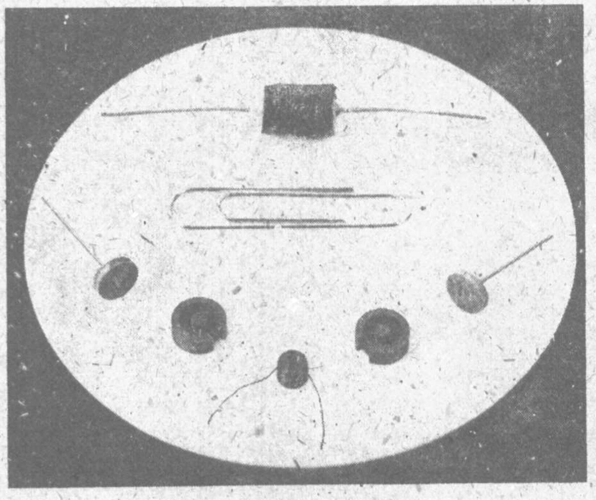

Fig. 15—A miniature inductor.

low power levels common with transistorized circuits are favorable to the use of ferrites in a similar structure in pulse transformers. In this case, high permeability materials, such as nickel zinc ferrite with 4000 permeability, or a manganese zinc ferrite with a permeability greater than 1000 are most suitable. The temperature rise in transistor circuits usually is low enough to permit the use of high permeability materials having low Curie temperatures.

Flyback Transformers and Deflection Yokes

Undoubtedly the largest use of ferrite measured in terms of pounds of material has been in flyback transformers for television circuits. They were first used in 1948. *C*-shaped cores are used in practically all designs, with a small air gap for reducing the variability caused by the presence of dc fields. Fig. 16 shows a flyback transformer assembled on ferrite cores with legs of square cross section. An evolution in the design of cores from square legs to hexagonal legs to round legs has been taking place. The round leg is helpful in reducing high voltage corona and has been made desirable by the progressive increase in flyback voltages from 10 kv up to 25 kv as larger picture tubes have been used. The manufacture has been made practical through the development of new die structures and pressing techniques.

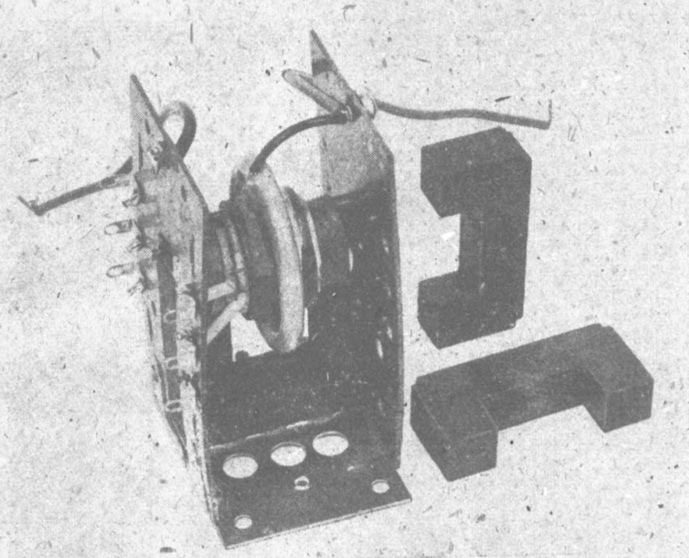

Fig. 16—A television flyback transformer.

These cores must have low losses at operating flux levels up to as high as 1500 gausses at the 15.75 kc scanning frequency and at flyback frequencies up to 100 kc. Low losses are not only important from the standpoint of reducing size and cost of the transformer itself but also to permit reductions in the size of the power supply. The Curie temperature must be high enough so that losses do not rise excessively at operating temperatures. Increased permeabilities combined with higher saturation have been obtained in manganese zinc ferrites fired to high density and have contributed to reductions in size and cost.

Cores for deflection yokes in tv sets quite generally are made of ferrite materials. They are pressed as halves or quadrants of a circular ring for assembly around the neck of the picture tube. The material properties are less critical in yoke applications than in flyback transformers.

Magnetic Memories and Switches

One of the fastest growing and potentially large applications for ferrite cores is for memory and switching uses in digital computers and data processing circuits. This application involves the use of microsecond pulses for transmitting, storing, and reading information expressed in a binary code.

Rectangular hysteresis loop properties are required to provide two identifiable stable states of remanent magnetization and to provide a highly nonlinear *B-H* relationship so the state of magnetization can be definitely and quickly changed. The degree of rectangularity and the uniformity and stability of characteristics have a direct bearing upon the number of cores which can be used reliably in a memory, and hence upon the storage capacity of the memory. The values of coercive force determine how rapidly the information can be handled.

Cores of magnesium manganese ferrite now are being produced with a good degree of rectangularity. Uniformity is being sought through control of composition and processing and by an elaborate selection procedure. Ferrite cores have several inherent advantages. They can be formed into tiny rings down to 0.050 inch diameter in automatic presses. The cost of the raw materials is low. Ferrite cores are chemically and mechanically stable and are practically indestructible, except for actual mechanical breakage. In common with other magnetic cores, once triggered to a stable state, they will retain their magnetization indefinitely without further power consumption.

The properties of rectangular loop ferrite cores in relation to certain circuit operations may be understood by reference to Fig. 17.

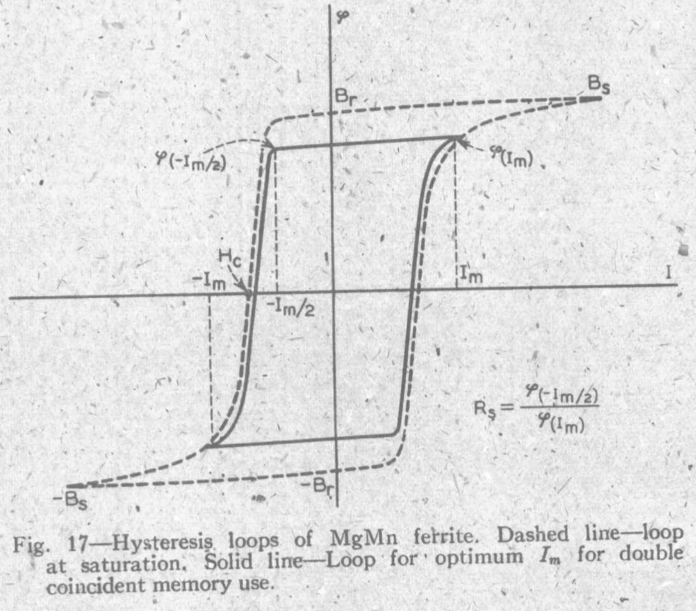

Fig. 17—Hysteresis loops of MgMn ferrite. Dashed line—loop at saturation. Solid line—Loop for optimum I_m for double coincident memory use.

When the material is magnetized by an applied field in the plus direction, it will retain the larger part of its magnetization when the applied field is removed. It is said to be "set" at plus B_r. If the rectangularity were perfect, B_r would be equal to the saturation flux density B_s. There would be no further change in the state of magnetization due to additional plus fields of any magnitude or to any negative field smaller in magnitude than minus H_c. However, if a negative pulse larger than minus H_c is applied the magnetization will be reversed and the core will remain set at minus B_r when the field is removed. For the latter case, the total flux change occurring in the core during reversal will be $2\ B_r$. The changing flux will induce a voltage in a "read-out" winding on the core and thus provide a method of detecting when the state of magnetization is changed by a current pulse.

If an array of cores is wired as shown in Fig. 18 any core in the group can be magnetized independently of the others by dividing the total magnetizing current equally between two windings. If the current is properly chosen, the one half current in either winding alone will be insufficient to magnetize or reverse a core, but the two half currents will be large enough to magnetize or switch the one core located at the intersection of the two wires. This provides the basis for setting each core in the array in a plus or minus state of magnetization to correspond to a binary code. The information can be read out by scanning the array with unidirectional half current pulses applied to the horizontal and vertical wires in a proper time sequence and noting which cores give a flux reversal when subjected to both currents simultaneously. The flux change is detected through the read-out winding which can be common to all cores. This action is indicated in Fig. 18.

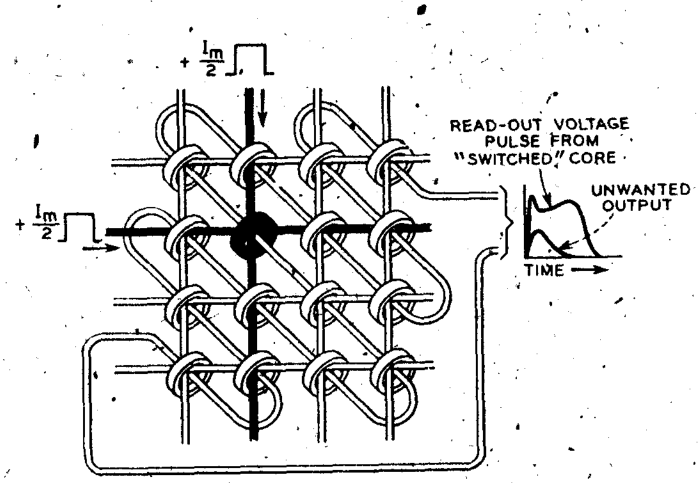

Fig. 18—An array of ferrite cores wired for double coincident memory use.

The above describes a single plane double coincident current memory in which the elements of each "word" are read out in sequence. Many planes may be operated in parallel, in which case whole words can be read out at once by locating each element of the word in a different plane. Each plane would have its own read-out winding. Also it is possible to divide the current into more than two parts and operate the array as a multiple coincident system by threading the appropriate number of driving windings in each core. Practical difficulties multiply due to departure of available materials from true rectangularity.

Magnetic cores also have important uses in the logic and switching circuits which direct and control the flow of information in and out of the memories and through the various processing operations. Fast operation is desired, which requires rapid switching and the generation of voltage pulses large enough to actuate succeeding cores.

Two highly important characteristics in a rectangular loop core are a large flux reversal and a short switching time t_w for a low applied drive. The latter indicates a low coercive force H_c, since a core will not switch until the applied pulse drive NI exceeds the coercive force. We may write

$$NI_0 = CH_c$$

where NI_0 is the minimum pulse drive required to switch the core and C is a constant (between 1 and 2) which depends upon the "inertia" of the magnetic domains to change direction and hence upon the characteristics of the core material. The switching time is related to the drive by the following expression:

$$t_w = \frac{k}{NI - NI_0}$$

where k is a constant applicable over a certain range of $(NI - NI_0)$ and is related to the damping or loss mechanisms in the core material. Much study is in progress on the magnetic mechanisms involved in switching behavior, but not all phenomena have been correlated as yet.

Departure from rectangularity causes unwanted output voltages to be generated when cores are subjected to pulses not intended to set or switch the core. This is due to some change in flux as the magnetization is driven from remanence to saturation of the same sign, or by a half pulse in the opposite direction from remanence. The latter condition can produce demagnetization of the core if the minor loop runs down onto the rounded corner of the major loop. Demagnetization effects are minimized by improving the rectangularity of the loop, by careful selection of the optimum current and associated one half current drives, as well as by arranging to have each half pulse followed by a pulse in the opposite direction to prevent progressive demagnetization steps. The temperature coefficient of the material and changes in ambient temperature must be such that the optimum point of operation is not shifted appreciably.

In memory planes, the noise or unwanted voltage pulses can be caused to cancel by wiring the series pickup winding so that outputs from one half of the cores will oppose the others. This solution requires that all the cores have exactly the same characteristics.

Since ideal rectangularity has not been obtained and since a high degree of uniformity is needed to compensate for nonrectangularity, a heavy responsibility is placed upon manufacturing control and testing. This

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