ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

STUDY, DEVELOPMENT, AND PRODUCTION OF FERROSPINELS APPLICABLE TO TUNING OF SEARCH RECEIVERS

QUARTERLY PROGRESS REPORT NO. 3, TASK ORDER NO. EDG-6
Period Covering April 1, 1953 to June 30, 1953

Electronic Defense Group
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TASK ORDER

Title: STUDY, DEVELOPMENT, AND PRODUCTION OF FERROSPINELS APPLICABLE TO TUNING OF SEARCH RECEIVERS

Purpose of Task:

To further the development of ferrospinels of different incremental permeabilities and low losses, with reference to specific applications of interest to the Signal Corps such as RF tuning units.

Procedure:

The approach to the general objective will include:

a. The preparation, under controlled conditions, of specimens of different compositions;

b. The measurement of parameters such as the incremental and initial permeabilities, the saturation inductance, the coercive force and the Q (figure of merit) at various frequencies;

c. The interpretation of these magnetic parameters in terms of the composition, reaction temperature, pressure and other conditions in the preparation of the samples;

d. The relationship of the solid state properties of the crystallite with the various measured magnetic parameters;

e. Theoretical explanations, where possible, for the relationships found in d. above.

Reports and Conferences:

a. Quarterly Task Order Reports shall be submitted reporting technical detail and progress under this Task Order;

b. Task Order Technical Reports of a final summary type are in general desirable and shall be prepared at the conclusion of investigations of each major phase. Such reports shall be prepared as decided in conference between the Electronic Defense Group and the Contracting Officer's Technical Representative in the Countermeasures Branch, Evans Signal Laboratory.

<u>Personnel</u>:

Electronic Defense Group:

Project Physicist: Mr. D. M. Grimes

Countermeasures Branch, Evans Signal Laboratory:

Project Engineer: Mr. Leon I. Mond

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Project Scientist: Dr. E. Both

<u>Comments</u>:

The classification of this Task Order as Unclassified shall not preclude the classification of individual reports according to the information they contain, as determined in conference with the Contracting Officer's Technical Representative.

M. KEISER
Chief, Countermeasures Branch
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Representative

ABSTRACT

Much of the long awaited equipment for the measurement of permeability has arrived. Experimental cores are being made under controlled conditions as rapidly as their properties can be analyzed.

A tentative expression for the incremental susceptibility is given based upon a Gaussian distribution of impurity centers.

The status of the specific heat, Hall coefficient, and magnetostriction measurements is described.

STUDY, DEVELOPMENT, AND PRODUCTION OF FERROSPINELS APPLICABLE TO TUNING OF SEARCH RECEIVERS

QUARTERLY PROGRESS REPORT NO. 3, TASK ORDER NO. EDG-6
Period Covering April 1, 1953 to June 30, 1953

1. PURPOSE

The purpose of this report is to summarize the progress made by Task Group 6 of the Electronic Defense Group from April 1, 1953 to June 30, 1953 on the Signal Corps Contract No. DA-36-039 sc-15358.

The purpose of the task is to further the development of ferrospinels of different incremental permeabilities and low losses, with reference to specific applications of interest to the Signal Corps such as r-f tuning units.

The proposed program of Task Group EDG-6 was outlined in previous progress reports. Only those items will now be reported which have been worked on during the period.

2. PUBLICATIONS AND REPORTS

Mr. D. M. Grimes gave a paper entitled "Reversible Susceptibility in Ferrimagnetic Materials," at the Washington meeting of the American Physical Society held April 30, May 1 and 2. Mr. B. Hershenov also attended the meeting.

3. GENERAL STATUS OF THE PROGRAM (D. M. Grimes)

The past quarter's work has been the most fruitful to date, and we anticipate increased progress during the coming quarter. Most of the necessary equipment for our measurements has now arrived. The apparatus is being placed into an integrated cycle of manufacture and quality measurement and control.

We could not find a commercially available oven which met all of our specifications. The closest approach seemed to be a Harper HL-6 which was ordered early in the quarter and arrived June 29. In the meantime we have been using the same oven as previously described with an autotransformer placed in the input circuit to obtain less temperature fluctuation during firing.

The permeability-frequency spectrum of the cores furnished by Mr. G. Dewitz of the C.G.S. Laboratories and the backlog of those of our own manufacture are now being measured. The progress made in each frequency range depends directly upon the date the measuring equipment was received. The actual equipment used in each frequency range will be described in the following sections. The more fundamental measurements, i.e., Hall coefficient, have been temporarily delayed until the backlog of permeability measurements have been taken. The dielectric constant frequency spectrum is also being delayed until the permeability measurements have been made.

We shall, both in this and future reports, give the permeability and losses in terms of the real and imaginary parts of the permeability. These are simply related to the coil Q and the loss factor as follows.

For a toroid of cross sectional area A and mean magnetic radius $\bar{r}$,

$$H = \frac{NI}{5\bar{r}} \qquad (1)$$

Assume I is sinusoidal so $I = I_o e^{j\omega t}$. Then

$$E = \frac{N d\phi}{dt} \times 10^{-8} = NA \frac{dB}{dt} \times 10^{-8} = NA\mu \frac{dH}{dt} \times 10^{-8} = je^{j\omega t} \frac{N^2 I_o}{5\bar{r}} A\mu\omega \times 10^{-8} \qquad (2)$$

$$= (R + j\omega L)\, I_o\, e^{j\omega t} \qquad (2')$$

We now define: $\mu = \mu_1 - j\mu_2$. Thus, upon substituting in (2) and equating (2) and (2'),

$$\mu_1 = \frac{5\bar{r} \times 10^8}{A\, N^2}\, L$$

$$\mu_2 = \frac{5\bar{r} \times 10^8}{A\,\omega\, N^2}\, R \qquad (3)$$

Q is, as usual, defined as $\omega L/R$. Tan δ is given by $R/\omega L$. Thus from (3)

$$\frac{1}{\tan\delta} = Q = \frac{\mu_1}{\mu_2} \quad . \qquad (4)$$

One other way of measuring the quality of a core is by giving its "loss factor," which we shall call σ.

$$\sigma = \frac{1}{\mu_1 Q} = \frac{\mu_2}{\mu_1^2} \quad . \qquad (5)$$

With the cores we have manufactured to date we have been attempting to learn how to control some major factors in production, i.e., gross physical appearance, large deviations in μ_1 and μ_2, by heat treatment, mixing, etc. At the moment we are running a test to see if the addition of V_2O_5 to the basic oxides will furnish the oxygen necessary to replace that normally lost during the firing process.

For the experimental check of the theory of reversible susceptibility, all necessary data have been gathered above room temperature. The B-H loops and the μ_{rp}-H butterfly loops have also been taken down to -70°C. We feel, however, that some of the transverse permeability measurements need to be rechecked. For this purpose a new magnet has been designed and is now being constructed.

Regarding the discrepancy described in Quarterly Progress Report No. 2 between the coercive force using D.C. and the 60-cycle drive, further tests on the 60-cycle method showed it to be more accurate than the involved error. We now feel that the difference is real and must have a magnetic origin.

Work was started during the quarter on an extension of the reversible susceptibility theory to include the incremental susceptibility. It is our aim to explain, at least qualitatively, the above-mentioned coercive force difference of the basis of this extension.

4. FACTUAL DATA

4.1 Theory of Incremental Susceptibility (D. M. Grimes)

A statistical method of obtaining the reversible susceptibility was discussed in some detail in Quarterly Progress Report No. 2, Task Order No. EDG-6, April 1953, and in Technical Report No. 8, August 1952. On the basis of this development it is possible to predict the normalized small signal susceptibility of ferromagnetic materials as a function of the normalized magnetization. These equations are applicable when considering the susceptibility variation of a coil placed in a tuned circuit handling low level signals only. An example would be the employment of an incredutor in the r-f section of a receiver.

The question now arises, how will the susceptibility vary when the magnitude of the r-f signal becomes large enough so that Barkhausen jumps appreciably contribute to the r-f susceptibility, i.e., the variation is no longer purely reversible? This situation may occur when a magnetic tuning unit is used in the oscillator circuit of a receiver.

We now define ρ to be the product of the mean value of the volume of material in each domain which changes orientation from $-J_s$ to J_s at any particular value of J times the number of domains which will reverse when a change in the field of 1 oe. is applied. ρ = (Mean volume of material changing orientation for each Barkhausen jump.) $2J_s$ (Number of jumps when an additional field of one oersted is applied.) We now make the following assumptions:

$$\rho = \rho(J) \tag{1}$$

$$\rho\,(J_s) = 0 \tag{2}$$

$$\rho\,(0) = \rho_{max} \tag{3}$$

ρ is symmetric in J. (4)

J' is the total magnetization that arises from the jumps when J is varied from J_s to $-J_s$.

$$J' = \frac{1}{J_s} \int_{-J_s}^{J_s} \rho \, d\, J \tag{5}$$

A simple distribution function which satisfies the above conditions is:

$$\rho = \frac{1}{\lambda} \left[e^{-\alpha \left(\frac{J}{J_s} \right)^2} - e^{-\alpha} \right] \tag{6}$$

To evaluate λ:

$$1 = \frac{1}{J'\lambda}\left[\int_{-1}^{1} e^{-\alpha x^2}\,dx - \int_{-1}^{1} e^{-\alpha}\,dx\right]$$

$$\lambda = \frac{1}{J'}\left[\frac{1.494}{\sqrt{\alpha}} - 2e^{-\alpha}\right] \tag{7}$$

To obtain an idea of the order of magnitude of α, the data given by Sawada[1] were analyzed giving $\alpha \simeq 13$ for a rod specimen of 3% Si steel. Thus:

$$\lambda \simeq \frac{1.494}{J'\sqrt{\alpha}} \tag{7'}$$

$$\rho = \frac{J'\sqrt{\alpha}}{1.494}\left[e^{-\alpha\left(\frac{J}{J_s}\right)^2} - e^{-\alpha}\right] \tag{8}$$

With above definitions,

$$\Delta J = \int^{\Delta J} d\left[H(J)\ \chi_r(J) + H(J)\ \rho\right] \tag{9}$$

for all values of ΔJ. However, we shall again restrict ourselves to values of $\Delta J << J_s$. Eq (9) then becomes:

$$\Delta J = \Delta H\left[\chi_r\ (J) + \int^{\Delta J} d\ \rho\right] \tag{10}$$

$$\chi_\Delta = \chi_r + \int^{\Delta J} d\ \rho$$

$$\chi_\Delta = \chi_r + \frac{J'\sqrt{\alpha}}{1.494}\left(e^{-\alpha\left(\frac{J}{J_s}\right)^2}\right)\Bigg]^{\Delta J} \tag{11'}$$

The two constants J' and α must be evaluated for each material. One must determine how much these constants will vary from specimen to specimen.

It should be noted that using the above expression μ_Δ starts out linearly with increasing H, goes through a maximum, then decreases.

To obtain an idea of the validity of the assumptions we again use Sawada's data. Fig. 1 shows a plot of ρ against J using his data. From this it is observed that assumptions (1), (2), and (3) are fulfilled, but (4) only approximately so. The Gaussian assumption would thus be expected to hold for gross properties but not for differences in detail. When considering ρ we are considering a rather gross property of the shape of the distribution.

It should also be mentioned that if the wall barriers are considered, on the average, to be uniformly spaced, ρ is then proportional to the height of the internal barriers. The maximum value of ρ is therefore simply related to the coercive force.

4.2 Check of the Reversible Susceptibility Theory (D. M. Grimes)

Data have been taken on three cores purchased from the General Ceramics Company. B-H loops and μ_{rp}-H butterfly loops at temperatures of 100°C, 75°C, 50°C, 25°C, -30°C, and -70°C. The data are all similar to those shown in Quarterly Progress Report No. 2 and will therefore not be reproduced here. We have found that the value of J approached for very high fields differs depending upon whether it is measured around the toroid or parallel to its axis of rotation. The curves shown previously have had to be normalized to a different J_s. An example is that of core GC-G-5. At 25°C, around the toroid, when a biasing field of 225 oersteds was applied, the extrapolated value for J_s was found to be 270. For the measurement parallel with the toroidal axis of rotation, J_s was found to be in the neighborhood of 350. The other two cores showed a similar discrepancy.

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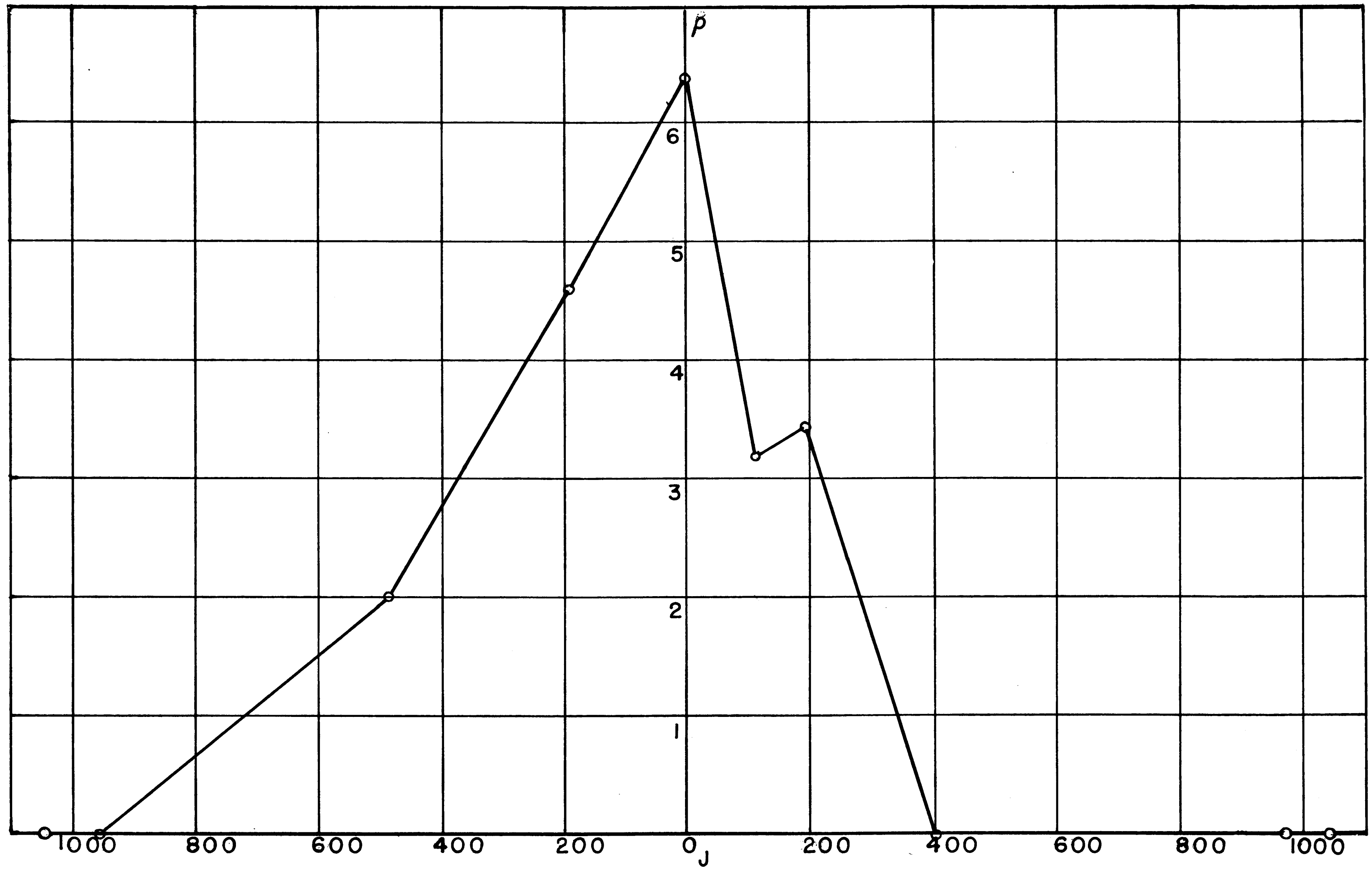


IRREVERSIBLE MAGNETIZATION CHANGES AS A FUNCTION OF MAGNETIZATION

FIG 1

To ascertain if this apparent difference is a real difference a new magnet is being made. With it we will be able to measure both the B and H inside the specimen.

We will use two methods of measuring H. As a check we will wind the coil as illustrated in Fig. 2a. From this we will get B. Assuming the reluctance of the magnetic circuit to be entirely in the toroid, and knowing the ampere turns applied to the magnet we can obtain the applied field. Fig. 2b shows the second method. From leads A and B we measure the flux through the coil. From leads B and C we measure H. The permeability will be measured in the latter case as previously described from leads wound in the standard fashion.

<u>4.3 Manufacture of the Ferrites</u> (C. F. Jefferson, L. Thomassen)

<u>4.3.1 Manufacturing Equipment</u>. The oven described in Quarterly Progress Report No. 1 is still in use. It has been equipped with an auto transformer to reduce temperature variation due to time delay in the thermocouple control. A new oven has been received which will be more suitable for the work. It is planned to have the new oven installed and ready for use during the next quarter.

The Eppenbach mixer has not yet arrived so the mixing is still being done in the ball mill.

<u>4.3.2 Manufacturing Procedure</u>. The cores prepared can be divided into two classes consisting of those fired once and those fired once, crushed, pressed, and fired a second time. A considerable amount of difficulty has been encountered in preparing suitable cores with one firing, while satisfactory cores have been obtained using the second procedure.

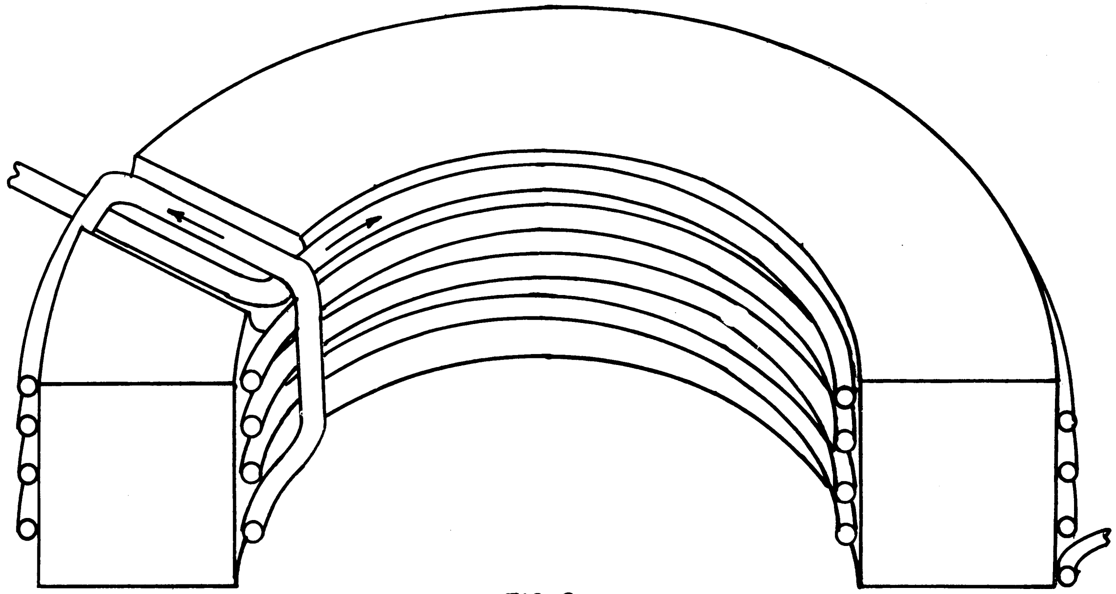


FIG 2A

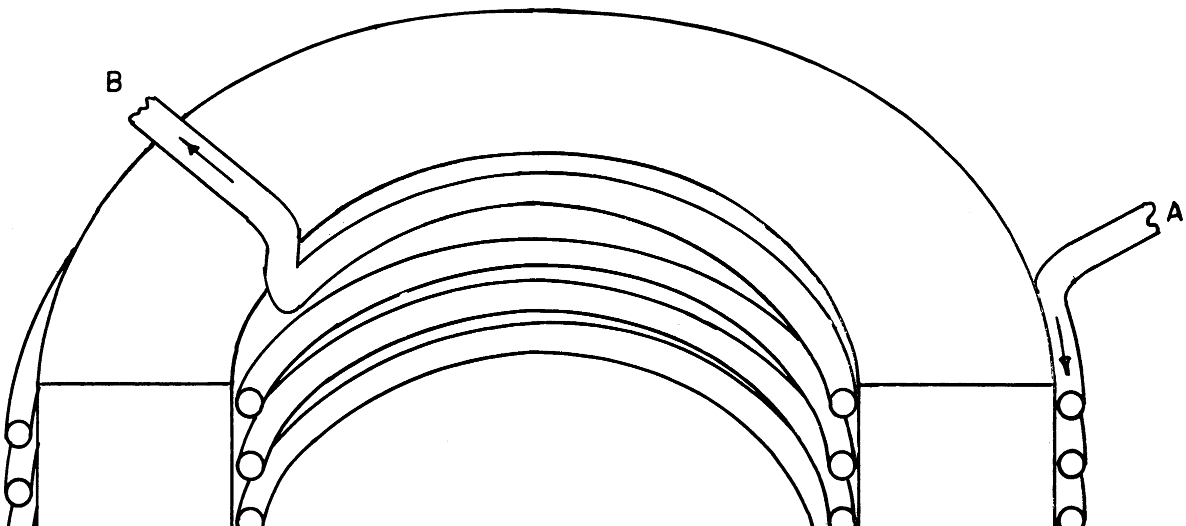


FIG 2B

WINDINGS TO OBTAIN BOTH B AND H

In preparing cores with one firing the following procedure was used:

(1) The oxides are placed in a ball mill and slurried with distilled water. The oxides are then milled for four hours.

(2) The oxides are removed from the mill and the slurry filtered. The oxides are placed in an oven and dried for eighteen hours at 120°C.

(3) The dried oxides are crushed in a mortar and passed through a 50-mesh screen.

(4) The cores are prepared by pressing the above material in a die, using eight tons total force on the die.

(5) The cores are removed from the die and placed on an alundum plate and fired by bringing the oven to 1305°C and holding for four hours.

(6) The oven is turned off and the cores are allowed to cool in the oven. The cooling rate is about 1500°C/hour at 1300°C, and falls to 240°/hour at 600°C.

It is found that the cores stick to the die during the pressing operation. In order to overcome this difficulty several methods were tried. The die was waxed, but no better results were obtained. The use of distilled water as a binder proved no more satisfactory. The best results were obtained by placing a thin film of oil on the face of the die.

During the firing process, the cores have a tendency to split. It is known that the cores undergo a considerable amount of shrinkage during the first firing. It would be expected that the cores would be under a considerable amount of strain during the time they were shrinking. It is not known at what temperature this shrinkage is most pronounced.

It has been found, however, that by raising the temperature rapidly to 1050°C and slowly raising the temperature the rest of the way the amount of splitting is greatly reduced. It is hoped to completely overcome splitting by determining the temperature range in which shrinkage occurs and decreasing the heating rate still further while passing through this range.

In preparing cores with two firings the following procedure was used.

(1) The oxides are placed in a ball mill and slurried with distilled water. The oxides are then milled for four hours.

(2) The oxides are removed from the mill and the slurry filtered. The oxides are placed in an oven and dried for eighteen hours at 120°C.

(3) The dried oxides are crushed in a mortar and passed through a 50-mesh screen.

(4) The oxides are placed in an alundum crucible and fired at 1305°C for four hours.

(5) The sintered material is crushed in a diamond mortar and screened through a 325-mesh screen.

(6) The powdered material is wet with just enough distilled water to make it cling together.

(7) The cores are prepared by pressing the above material in a die, using eight tons total force on the die, as in the case of the once-fired oxides.

(8) The cores are removed from the die and placed on an alundum plate. They are then dried for eighteen hours at 120°C.

(9) The cores are placed in the oven and fired by bringing the oven to 1305°C and holding it for four hours.

(10) The oven is turned off and the cores are allowed to cool in the oven as in the above procedure.

Satisfactory cores have been prepared using this procedure. There is a very small amount of shrinkage during the second firing. Most of the shrinkage takes place during the first firing. The initial difficulty of removing the cores from the die was overcome by using distilled water as a binder. Cores have been prepared in which the particle size in step 5 above was varied.

Cores prepared with one firing have higher densities than those fired twice. The once-fired cores have densities of 4.8, while twice-fired cores have densities of 4.1. The amount of linear shrinkage in once-fired cores is 14%, while the amount of linear shrinkage for twice-fired cores during the second firing is 4%.

4.3.3 Composition of Cores. Cores consisting of two different compositions have been prepared. The majority of the work has been done on cores with the following composition:

Fe_2O_3	50 mol %
ZnO	30 mol %
NiO	20 mol %

It is thought that the ferrites of the above composition are deficient in oxygen. Cores have been sent to an outside laboratory for analysis.

In order to introduce oxygen into the structure, cores containing V_2O_5 have been prepared with the following composition:

Fe_2O_3	49.25 mol %
ZnO	30.00 mol %
Ni O	20.00 mol %
V_2O_5	0.75 mol %

In preparing cores with the above composition the water is removed from the milled oxides by evaporation, instead of filtration, due to the solubility of V_2O_5.

It is planned to fire the cores in an oxygen atmosphere as soon as the new oven is ready for use.

4.4 Mid-Frequency Permeability Spectrum (B. Hershenov)

4.4.1 Permeameter Measurements. The radio frequency permeameter for measuring the complex initial permeability ($\mu = \mu_1 - j\mu_2$) arrived this quarter from the National Electronics Laboratories, Inc. It will be used in conjunction with a twin-T impedance bridge type 821-A and a bridge oscillator type 1330 manufactured by the General Radio Company, and a receiver detector, model N.C. 125, of the National Company.

For the permeameter we have two adapters which have the frequency ranges of 0.8 to 2.5 mcs and 2 to 5 mcs. A third adapter for the range 4 to 9 mcs is on order.

Most of the time was spent measuring μ_1 and μ_2 of the cores manufactured here during the past months and a few cores sent by Mr. G. Dewitz of the C.G.S. Laboratories.

The equations used for determining the complex permeability μ were derived by Mr. P. H. Haas.[2] These equations will give good results with the permeameter up to 5 mcs and with proper design of transformer an upper limit of at least 10 mcs may be reached.

A sample result at 1.2 mcs and at 4 mcs is shown in Table I.

TABLE I

Specimen	Freq. in cps.	μ_1	μ_2
A-5-2	1.2×10^6	316	62.4
A-5-2	4×10^6	324	250

4.4.2 Possible Frequency Extension of the Permeameter. In order to use the permeameter for frequencies up to 40 mcs, the equations were extended to consider the capacitance of the primary.

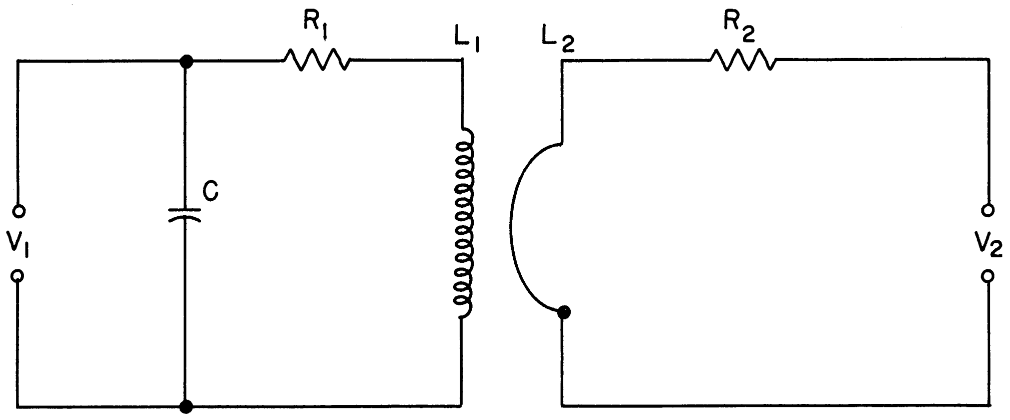


FIG. 3. EQUIVALENT PERMEAMETER CIRCUIT.

For the secondary open circuited

$$Z_1 = \frac{(R_1 + j\omega L_1)\frac{1}{j\omega c}}{R_1 + j\omega L_1 + \frac{1}{j\omega c}} = R_{1\ eff} + jX_{1\ eff} \qquad (1)$$

where the effective values indicates what the bridge measures.

For the secondary short circuited without sample inserted

$$Z_o = Z_1 + \frac{\omega^2 M^2}{R_2 + j\omega L_2} = R_{o\ eff} + j\,X_{o\ eff} \quad . \qquad (2)$$

For the secondary short circuited with the unknown ferrite specimen inserted, the secondary impedance is increased by $R_u + j\omega L_u$

$$Z_f = Z_1 + \frac{\omega^2 M^2}{(R_2 + R_u) + j\omega(L_2 + L_u)} = Z_{f\ eff} - jX_{f\ eff} \qquad (3)$$

$$\frac{V_1}{V_2} = \frac{Z_1}{j\omega M} = \frac{Z_1}{jN} \quad , \quad \text{where } \omega M = N.$$

From Z_o - Z_1 and Z_f - Z_1 we can solve for R_u and L_u. We get:

$$\text{a)}\quad R_u = \frac{N^2 R_{f1}}{R_{f1}^2 + X_{f1}^2} - \frac{N^2 R_{01}}{R_{01}^2 + X_{01}^2}$$

$$\text{b)}\quad L_u = \frac{N^2}{\omega}\left[\frac{X_{1f}}{R_{f1}^2 + X_{f1}^2} + \frac{X_{01}}{R_{01}^2 + X_{01}^2}\right] \tag{5}$$

where:

$$R_{01} = R_{o\ eff} - R_{1\ eff}$$

$$R_{f1} = R_{f\ eff} - R_{1\ eff}$$

$$X_{01} = X_{0\ eff} - X_{1\ eff}$$

$$X_{f1} = X_{f\ eff} - X_{1\ eff}$$

L_{a_1} = inductance due to the space having the dimensions of the test core

$$L_{a_1} = .4606\ h \log_{10}\left[\frac{r_0}{r_1}\right] \times 10^{-8} \text{ henries} \tag{6}$$

where h = toroidal height in cms

r_o = outside radius of core

r_1 = inside radius of core

$$\mu_1 - 1 = \frac{L_u}{L_{a1}} \tag{7}$$

This result is derived in the same manner as Sec. 4.5 for the coaxial inductor where:

$$L_u = L_f - L_a$$

$$r_o = r_1 = r_o$$

$$r_i = r_2 = r_1$$

$$h = t = d$$

The terms on the left of the first equality sign correspond to symbols used in this section whereas terms to the right correspond to expressions of Sec. 4.5.

Substituting L_u in Eq (7)

$$(\mu_1 - 1) = \frac{N^2}{\omega L_{a1}} \left[\frac{X_{1f}}{R_{f1}^2 + X_{f1}^2} + \frac{X_{01}}{R_{01}^2 + X_{01}^2} \right] \quad (8)$$

We define as before

$$\tan \delta m = \frac{\mu_2}{\mu_1} = \frac{R_\mu}{\omega L_u} \quad (9)$$

where tan δm is the initial dissipation factor, substituting from Eq (5):

$$\tan \delta m = \frac{R_{f1} (R_{01}^2 + X_{01}^2) - R_{01} (R_{f1}^2 + X_{f1}^2)}{X_{1f} (R_{01}^2 + X_{01}^2) + X_{01} (R_{f1}^2 + X_{f1}^2)} \quad (10)$$

For an admittance bridge, reading $G + j\omega C$, we have

$$\mu_1 - 1 = \frac{N^2}{L_{a1}} \left[\frac{(C_f A_1 - C_1 A_f)(A_f A_1)}{(G_f A_1 - G_1 A_f)^2 + (B_1 A_f - B_f A_1)^2} + k_1 \right] \quad (11)$$

where $A_i = B_i^2 + G_i^2$ $\qquad i = 1, 0, \text{ or } f$

$$k_1 = \frac{(C_1 A_o - C_o A_1)(A_o A_1)}{(G_o A_1 - G_1 A_o)^2 + (B_1 A_o - B_o A_1)^2}$$

and

$$B_i = \omega C_i$$

$$\tan \delta m = \frac{\dfrac{(G_f A_1 - G_1 A_f)(A_f A_1)}{(G_f A_1 - G_1 A_f)^2 + (B_1 A_f - B_f A_1)^2} - k_2}{\dfrac{(B_f A_1 - B_1 A_f)(A_f A_1)}{(G_f A_1 - G_1 A_f)^2 + (B_1 A_f - B_f A_1)^2} + \omega k_1} \quad (12)$$

where

$$k_2 = \frac{(G_o A_1 - G_1 A_o)(A_o A_1)}{(G_o A_1 - G_1 A_o)^2 + (B_1 A_o - B_o A_1)^2} .$$

4.4.3 Possible Frequency Extension of the Coaxial Inductor. Another possible method for measuring the permeability of the cores between 10 and 40 mc/sec is the extension of the frequency range of the coaxial inductor. An adapter would be made so it would fit the G.R. 821 bridge.

4.5 VHF Permeability Spectrum (P. E. Nace)

A relatively fast method of measuring permeability as a function of frequency in the range 30 mc/s to 500 mc/s was desired. For this purpose three pieces of equipment were obtained from the Hewlitt-Packard Company: 1) a signal generator covering the desired frequency range; 2) an impedance measuring bridge designed for VHF frequencies; 3) a VHF signal detector. Finally, a toroid holder for the ferrite sample, hereafter called the coaxial inductor, was designed and built within the research laboratories. Fig. 4 is an assembly diagram of the coaxial inductor. Basically it consists of the following: a short 50 ohm transmission line designed to connect to the VHF bridge through an adapter also constructed here; this short transmission line is then tapered abruptly to the line's termination, a one-turn coaxial inductance of proper size to hold the ferrite toroid loosely. It is a characteristic of the VHF bridge to

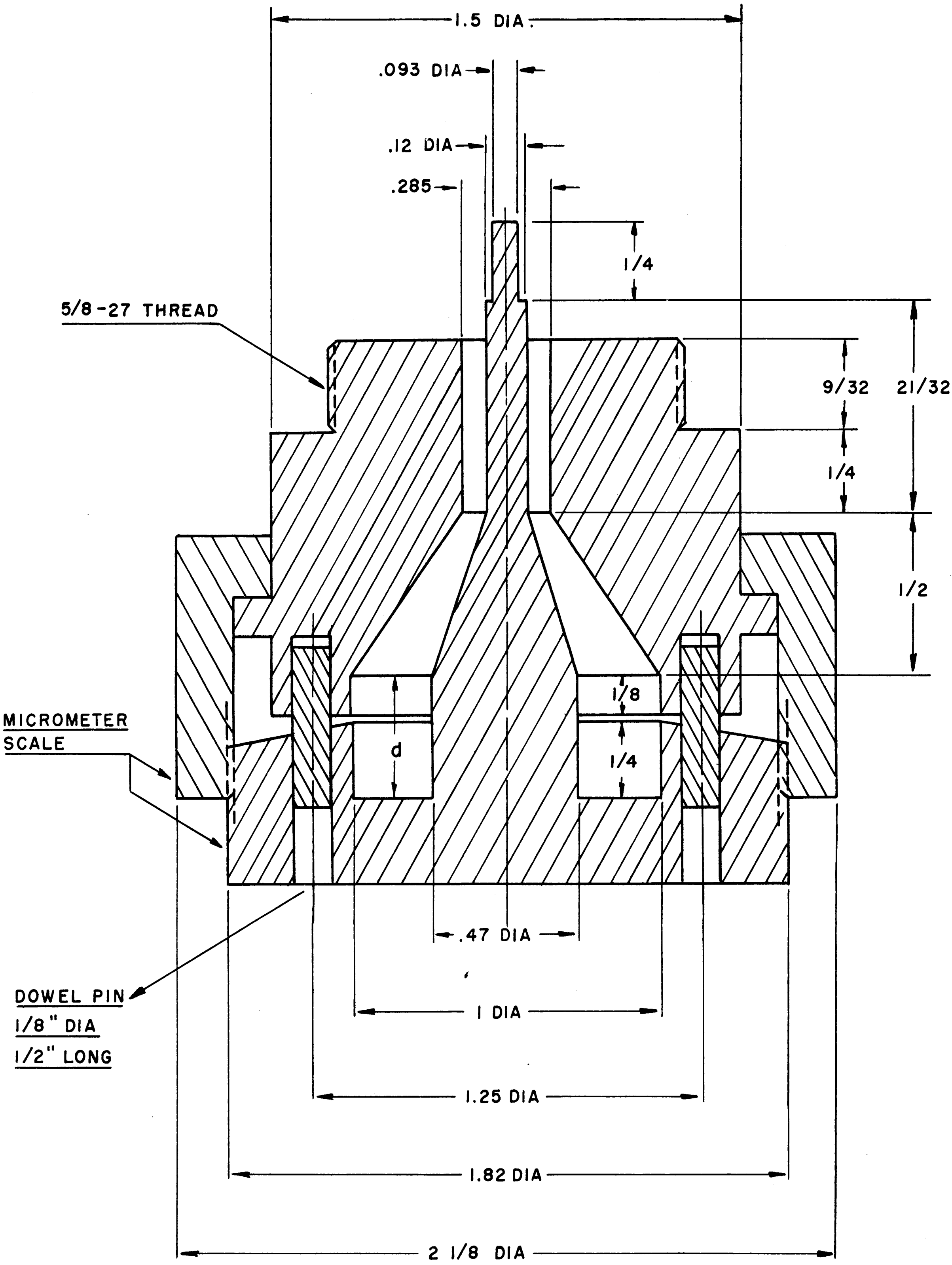


FIG. 4

V.H.F. COAXIAL INDUCTOR.

measure the impedance at a point a short distance (about 3 cm of 50 ohm coax) from the place to which the coaxial inductor is connected. In order to measure the impedance associated with the inductive termination in the coaxial inductor, one must correct the bridge impedance reading for the two short pieces of transmission line separating the termination and the point of measurement. This necessitated the measurement of the electrical length of a coax line separating the two points. This was done by shorting the coaxial inductor at a point d distant from the end of the coaxial inductor (see Fig. 4). Then impedance measurements were made and the data was treated according to the formula for a shorted transmission line of impedance $Z_o = 50$.

$$Z = Z_o \tan \beta \ell = Z_o \tan \frac{\omega \ell}{c}$$

This formula is an approximation in this case due to the taper at the end of the line. However, electrically this taper is very short at these frequencies and the approximation is good. The length ℓ was measured and found to be $\ell = 7.95$ cm. The following establishes the relationship between the permeability $\mu_f = \mu_1 - j\mu_2$ of the ferrite sample and the measurements made. The inductor's termination is a one turn toroid of thickness d and inner and outer radii of r_i and r_o. The core cross-section is partly air and partly ferrite, where the ferrite is a toroid with dimensions t, r_1, and r_2.

The mean value of the magnetic field (MKS units) of the whole toroid is:

$H_{air} = \dfrac{I}{r_o - r_i} \; \dfrac{\ell n \frac{r_o}{r_i}}{2\pi}$ where I is the current flowing in the one turn. In the ferrite, it is $H_f = \dfrac{I \; \ell n \frac{r_2}{r_1}}{2\pi(r_2 - r_1)}$. The total flux linking the one turn is:

$$\phi = e^{j\omega t}\,\phi_o = \phi_{air} + \phi_{ferrite} = \mu_o\, H_{air}(r_o - r_i)\, d + (\mu_1 - \mu_o)\, H\, (r_2 - r_1)t$$

the inductance with the ferrite is:

$$L_f = \frac{d\phi}{dI} = \frac{j\omega\, e^{j\omega t}\phi_o}{j\omega\, e^{j\omega t} I_o} = \frac{\mu_o d}{2\pi}\,\ell n\,\frac{r_o}{r_i} + \frac{(\mu_1 - \mu_o)t}{2\pi}\,\ell n\,\frac{r_2}{r_1} \qquad (1)$$

The inductance without the ferrite is:

$$L_A = \frac{\mu_o d}{2\pi}\,\ell n\,\frac{r_o}{r_i} \qquad (2)$$

Solving for $\frac{\mu_1 - \mu_o}{\mu_o} = (\mu'_1 - 1)$ if μ'_1 is the relative permeability:

$$\mu'_1 - 1 = \frac{d\,\ell n\,\frac{r_o}{r_i}}{t\,\ell n\,\frac{r_2}{r_1}} \left\{\frac{L_f}{L_A} - 1\right\} \qquad (3)$$

But d = 1.02 cm and r_o = .998 inch and r_i = .480 inch. Also $\frac{r_2}{r_1} \cong 1.69$ for all of the ferrite samples we will use at present. Thus we obtain $\mu'_1 - 1 = \frac{1.42}{t}\left(\frac{L_f}{L_A} - 1\right)$ where t is in centimeters. Let $Z_g = R_g + j\,X_g$ be the reading obtained from the bridge. Then the terminating impedance $Z_L = R_L + j\,X_L$ is given by the familiar transmission line formula for a lossless line:

$$Z_L = Z_o\,\frac{Z_g - j\,Z_o \tan\beta\ell}{Z_o - j\,Z_g \tan\beta\ell} = Z_o\,\frac{\frac{R_g}{Z_o} + j\left(\frac{Z_g}{Z_o} - \tan\beta\ell\right)}{\left(1 + \frac{X_g}{Z_o}\tan\beta\ell\right) + j\,\frac{R_g}{Z_o}\tan\beta\ell} \qquad (4)$$

By use of a Z-ϕ chart it is not necessary to resort to this formula for computations. A Z-ϕ chart of the size necessary to obtain results accurate to three significant figures rapidly has been calculated and this chart will soon be available. Since $X_L = \omega L_f$ we have:

$$\mu'_1 - 1 = \frac{1.42}{t}\left(\frac{X_L}{\omega L_A} - 1\right) \text{ which determines } \mu'_1 . \qquad (5)$$

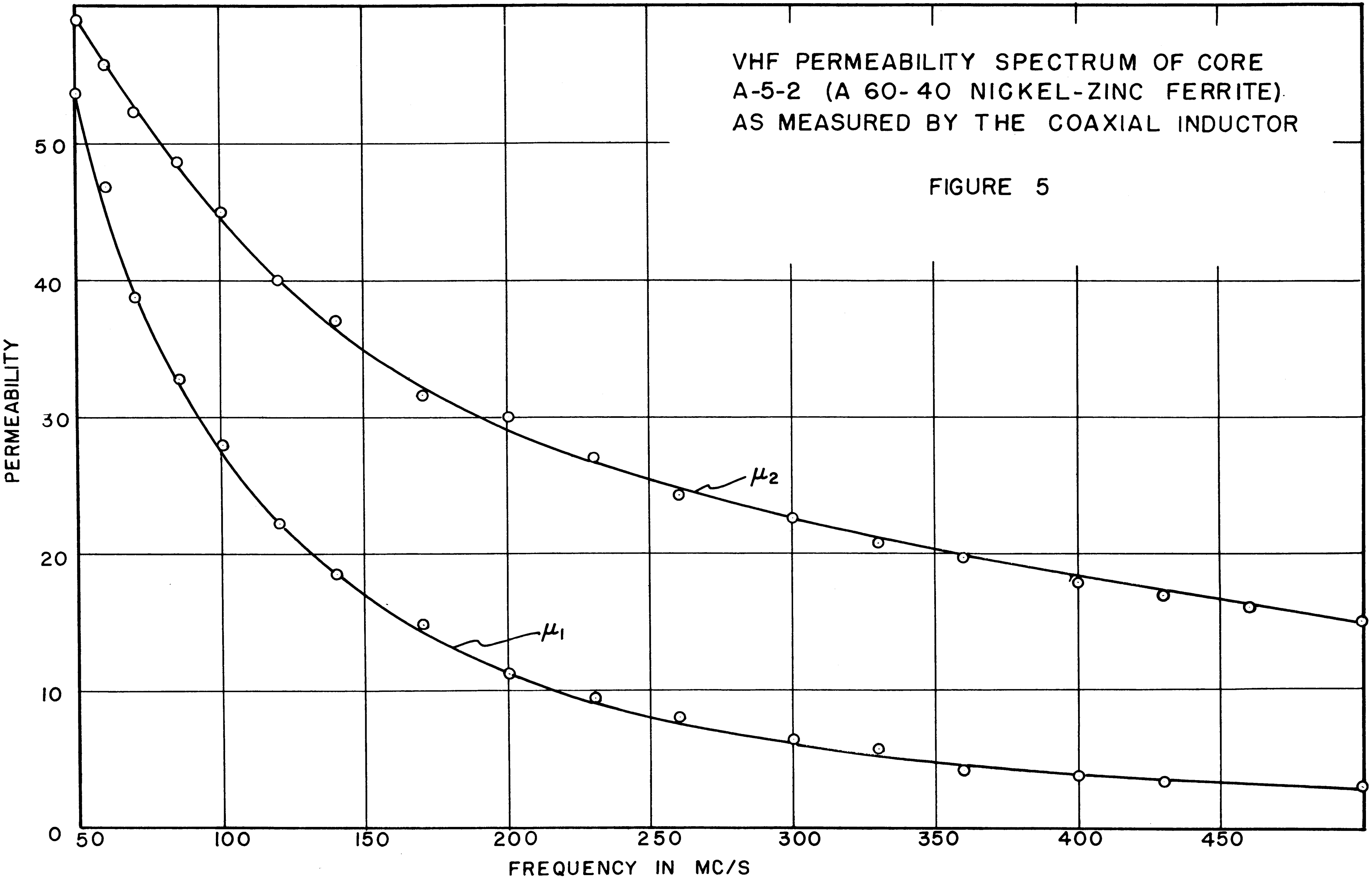
Let $R_1 + j\omega L_1$ be that portion of Z_L due only to the region occupied by the ferrite. $R_1 = R_L$ if the empty inductor is assumed lossless. $L_1 = (L_f - L_A)\frac{\mu_1}{\mu'_1 - 1}$ $\frac{\mu'_1}{\mu'_2}$ = the quality factor of the ferrite = $\frac{\omega L_1}{R_1}$. Using the expressions for L_1 and R_1 and using Eq (5), one obtains therefore

$$\mu'_2 = \frac{\omega(L_f - L_A)}{R_L\ (\mu'_1 - 1)} = \frac{1.42\ R_L}{\omega L_A\ t} \qquad (6)$$

The impedance of the coaxial inductor without the ferrite inside was measured and found to be for all practical purposes purely inductive (as assumed in the derivation of μ'_2 above) with an inductance of 1.38×10^{-9} henries = L_A.

By use of the above formulae one determines μ'_1 and μ'_2 from the measurement Z_g. Fig. 5 is the result of measurements made on a Ni - Zn ferrite manufactured here recently.

An additional method of measuring permeability as a function of frequency (VHF band) is planned. This method will also yield the dielectric constant as a function of frequency. For this method the coaxial inductor will be replaced by a coaxial line which will soon be constructed. Measurements will be made for the ferrite first placed at a position adjacent to a short circuit and then repositioned one-quarter of a wavelength from the short. The analysis of this method and results obtained will be covered in future reports.


VHF PERMEABILITY SPECTRUM OF CORE
A-5-2 (A 60-40 NICKEL-ZINC FERRITE)
AS MEASURED BY THE COAXIAL INDUCTOR
FIGURE 5
μ_2
μ_1
PERMEABILITY
0
10
20
30
40
50
FREQUENCY IN MC/S
50
100
150
200
250
300
350
400
450

The reason for resorting to an additional method are as follows:

1. To obtain a check upon the coaxial inductor measurements
2. To avoid the approximations necessary with the coaxial inductor
3. To obtain the dielectric constant.
4. To be able to obtain μ'_1 and μ'_2 when the wavelength of the electromagnetic wave in the ferrite is no longer much greater than the thickness of the ferrite sample. This would happen for ferrites of high enough permeability-dielectric-constant-product or for samples of great thickness. The coaxial inductor gives the correct results only when the inductor termination can be considered as a lumped impedance rather than a distributed impedance.

The drawback of the second method is the higher cost of equipment and the more complicated process required to determine μ'_1 and μ'_2.

4.6 Magnetostriction (D. W. Martin)

It is well known[8] that the bulk magnetic properties of a ferromagnetic specimen are partly, or in special circumstances, largely determined by the magnetostriction and the state of stress of the material. It is easily shown[3] that the anisotropy energy, measured under the ordinary circumstance of constant stress, contains an extra term arising from the working of magnetostrictive distortions against elastic crystal forces. This term appears in addition to the a priori anisotropy energy at constant strain, and can be of the same order of magnitude. Its coefficient has the form, for cubic crystals:

$$K_m = 9/4 \left[(C_{11} - C_{12}) \lambda^2_{100} - 2C_{44} \lambda_{111} \right]$$

where the C's are elastic moduli and the λ's are magnetostriction constants. The highest permeabilities in the Permalloy series appear at compositions near 85% nickel, where the magnetostriction, and hence K_m, is zero.

In addition, the working of magnetostrictive distortions against stresses, either applied externally, or arising from internal strains due to crystal imperfections, introduces a dependence of magnetic properties on these quantities. Bozorth[4] presents an elementary argument deriving the expected effects of external tension on the initial permeability μ_0 and shows that it is experimentally confirmed for nickel. By a very similar argument, he finds that the dependence on internal strains is given by:

$$\mu_0 - 1 = \frac{8\pi}{9} \frac{I_s^2}{\lambda \sigma_i}$$

where the strain (actually a tensor) is crudely represented as a vector whose direction and magnitude vary from place to place. These directions are assumed to be randomly oriented throughout the sample, and σ_i is an average magnitude. I_s is the saturation magnetization and λ the (assumed isotropic) magnetostriction. Thus the quantity σ_i measures some crudely defined "degree of strain" of the crystal. Values of σ_i experimentally derived from the above relation agree surprisingly well with similarly ill-defined magnitudes from other magnetic properties and from X-ray line breadth studies.[4]

The point is that μ_0 is in general related inversely to some "degree" of strain of the crystal because of magnetostriction. Hence well annealed materials should display the highest permeabilities, as they do.

The properties of ferrites are found to be very sensitive to small details of the manufacturing process. Separate evaluation of factors which effect the magnetostriction directly, and of those which determine the degree of strain, would be of great aid in optimizing the many manufacturing variables.

Furthermore, measurement of the magnetostriction of a sample in various directions provides direct information on the degree of crystal orientation in the polycrystalline ferrites. The magnestostriction of single crystals is not isotropic, but depends upon the measurement direction relative to crystal axes. Similarly, the differences in magnestostriction in various directions provide an indication of any preferred domain orientations in the demagnetized state, and hence of the nature of the changes involved in magnetization.

It is planned that magnetostriction measurements be made an integral part of the present studies in ferrite manufacture. Wire resistance strain gauges will be used. They provide a true strain measurement instead of an absolute displacement. The bridge circuits are easily compensated for temperature through use of dummy gauges in other bridge arms. The gauges are small enough not to interfere with other apparatus used simultaneously and finally, it is possible to extend to A. C. measurements at not too high frequencies.

Preliminary checks indicate that a sensitivity of order 10^{-6} can be easily attained with the galvanometers at hand, in a simple D.C. wheatstone bridge. Goldman[5] has reported sensitivities of order 10^{-8} with more elaborate apparatus, which can be used if it seems desireable. An investigation of the possibilities of A.C. bridge measurements will also be made. Gauges are currently on order, and work will begin in the immediate future.

4.7 Hall Effect (B. Hershenov)

Very little time was spent on the Hall apparatus because of the permeameter's arrival. Time was devoted to measuring the backlog of manufacturing cores, etc. (sec. 4.4)

The specimen holder was completed as described in Quarterly Progress Report No. 2 and the apparatus was recalibrated. A minor modification in measurement was instituted. The apparatus was initially designed for work on non-magnetic materials and as such an ammeter was calibrated to read H, the field intensity. For ferrites we must measure the magnetic induction, and in view of this a calibrated test coil will be used to measure B, the flux density.

4.8 Specific Heat of Ferrite Materials (D. M. Grimes, E. Katz, E. F. Westrum, Jr.)

4.8.1 Theoretical Considerations. We wish to consider the minimum energy conditions on the basis of the Yafet and Kittel[6] model. If E is the internal energy of the system, from Quarterly Progress Report No. 2,

$$-\frac{E}{n} = M_a^2 \, (\alpha_1-\alpha_2 \cos 2\phi) + 4\, M_a M_b \sin\phi \sin\psi + M_b^2 \, (\gamma_1-\gamma_2 \cos 2\psi) \quad (1)$$

Taking variations to obtain a minimum energy condition we have:

(let $M_a \equiv A; M_b \equiv B$)

$$0 = \delta A \left[A(\alpha_1-\alpha_2 \cos 2\phi)+2B \sin\phi \sin\psi \right] + \delta B \left[2A \sin\phi \sin\psi + B\,(\gamma_1-\gamma_2 \cos 2\psi)\right] + \delta\phi \left[\alpha_2 A^2 \sin 2\phi + 2AB \cos\phi \sin\psi \right] + \delta\psi \left[(2AB \sin\phi \cos\psi + \gamma_2 B^2 \sin 2\psi \right]$$

$$\delta A = \frac{\partial A}{\partial \phi}\delta\phi + \frac{\partial A}{\partial \psi}\delta\psi + \frac{\partial A}{\partial T}\delta T$$

$$\delta B = \frac{\partial B}{\partial \phi}\delta\phi + \frac{\partial B}{\partial \psi}\delta\psi + \frac{\partial B}{\partial T}\delta T$$

To determine the minimum energy conditions at a constant temperature, set $\delta T = 0$, and consider the coefficients of $\delta\psi$ and $\delta\phi$ both separately zero.

$$0 = \frac{\partial A}{\partial \phi}\left[A(\alpha_1 - \alpha_2 \cos 2\phi) + 2B \sin\phi \sin\psi\right] + \frac{\partial B}{\partial \phi}\left[2A \sin\phi \sin\psi + B(\gamma_1 - \gamma_2 \cos 2\psi)\right] + \left[\alpha_2 A^2 \sin 2\phi + 2AB \cos\phi \sin\psi\right] \quad (2)$$

$$0 = \frac{\partial A}{\partial \psi}\left[A(\alpha_1 - \alpha_2 \cos 2\phi) + 2B \sin\phi \sin\psi\right] + \frac{\partial B}{\partial \psi}\left[2A \sin\phi \sin\psi + B(\gamma_1 - \gamma_2 \cos 2\psi)\right] + \left[2AB \sin\phi \cos\psi + \gamma_2 B^2 \sin 2\psi\right] \quad (3)$$

Only the last bracket in each equation is considered in the literature. The question now becomes one of determining the effect of the first two brackets.

Let A and B be defined, as usual, in terms of a Brillouin function of the molecular field on each sublattice.

The first observation is that when $\phi = \psi = 0$ Eq (2) and (3) each term goes to zero. One now compares the magnitude of the first two brackets in the Eqs (2) and (3) as compared with the last.

Let 0 symbolize "the order of."

$$A \sim 0\left\{A_o B_j(a)\right\}$$

$$\frac{\partial A}{\partial \phi} \sim 0\left\{A_o A \frac{g\beta}{kT} n B_j'(a)\right\}$$

B_j' represents the derivative of the Brillouin function with respect to its argument. "a" represents the argument of the Brillouin function. Assume $n \sim 0\{1\}$.

$$n \sim 0\{1\}$$

$$A_o \sim 0\{250\}$$

$$g \simeq 2$$

$$\beta = 9.25 \times 10^{-21} \text{ c.g.s. units}$$

$$k = 1.381 \times 10^{-16} \frac{\text{ergs}}{°\text{C}}$$

Thus:

$$\frac{A}{\frac{\delta A}{\delta \phi}} \sim 0 \left\{ \frac{100\ T}{B_j{}'(a)} \right\}$$

$B_j(a)$ is a maximum at 0°K and is a monotonic decreasing function of T. Thus it would seem that the neglection of the first two brackets of Eqs (2) and (3) would be justified. These conclusions would be valid away from the transition points. The resulting perturbation around the transition points will be considered in subsequent reports.

4.8.2 Experimental Techniques. No further direct experimental progress on the test of the magnetic transitions has been possible because of the unavailability of a pure sample of ferrite of unambiguous composition and good magnetic properties.

Very pure preparations are in progress on the closely related materials alpha ferric oxide (α - Fe_2O_3, Haematite) gamma ferrice oxide (γ - Fe_2O_3, Goethite), and magnetite (Fe_3O_4). These materials are being prepared from ultra-high purity iron rods (Westinghouse, "Puron") with great care as to stochiometry and purity (especially freedom from ferromagnetic impurities). The preparative methods are those outlined by I. David and A. J. E. Welch.[7] It is planned to study the thermodynamic properties of these materials over the range 5 to 600°K and to search for magnetic transitions upon achievement of satisfactory samples and the establishment of their purity.

5. CONCLUSIONS (D. M. Grimes)

5.1 Core Manufacture

The manufacturing program is now well under way. More refined controls will be added as soon as possible. In the meantime check gross effects are being checked.

5.2 Theoretical Program

Utilizing an assumption of random or Gaussian distribution of internal barriers, we have arrived at an expression for χ_Δ . Work is continuing along this line.

5.3 Experimental Measurements

Much of the necessary data for a comprehensive check of the theory of reversible susceptibility have been taken. The results to date indicate qualitative agreement.

The measurement of the permeability frequency spectrum has been started. The apparatus has been or is currently being set up for the frequency range of 5 kc to 500 mc.

Magnetostriction measurements are awaiting the arrival of strain gauges.

6. PROGRAM FOR THE NEXT INTERVAL (D. M. Grimes)

6.1 Core Manufacture

The present program will continue as rapidly as possible. The effect of added V_2O_5 is currently being investigated.

6.2 Experimental Measurements

Additional reversible susceptibility data, especially for transverse fields, will be taken.

Permeability-frequency measurements will continue. The magnetostriction measurements will be instigated shortly.

Specific heat measurements will be made as soon as a sample with an oxygen content sufficiently close (1 mol % deficient in oxygen) can be produced. The date is estimated as August 1.

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