ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

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

QUARTERLY PROGRESS REPORT NO. 8, TASK ORDER NO. EDG-6
Period Covering July 1, 1954 to September 30, 1954

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Project 2262

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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.

Personnel:

Electronic Defense Group:

Project Physicist: Mr. D. M. Grimes

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Comments:

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
Contracting Officer's Technical
Representative

## ABSTRACT

Permeability data are given for a core with a permeability of nearly two at 500 mc/sec with quite low losses. The study of a nickel zinc ferrite mixed with a univalent ferrite is continuing. The quality factor or Q of a ferrite core is described in some detail. An equivalent circuit is shown.

A preliminary study of the effect of grain size on the magnetic properties is reported. There is evidence of some correlation. Fabrication of cores by stamping has been accomplished and is reported. Further work on the dielectric constant is reported. The effect of space dependence on the time independent parameters on domain wall motion is outlined. The progress of the study of specific heat is described, though no data are given here.

STUDY, DEVELOPMENT, AND PRODUCTION OF FERROSPINELS
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## 1. PURPOSE

The purpose of this report is to summarize the progress made by Task Group 6 of the Electronic Defense Group from July 1, 1954 to September 30, 1954 on Signal Corps Contract No. DA-36-039 sc-63203.

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

The Physical Review has accepted for publication "Reversible Susceptibility in Ferromagnetics" by D. M. Grimes and D. W. Martin. It is currently scheduled to appear in the November 15 issue.

Professor L. Thomassen and Mr. Grimes attended the Solid State Reactions section of the Gordon Research Conferences, AAAS, July 12-16.

## 3. FACTUAL DATA

### 3.1 The General Program (D. M. Grimes)

An illustration of the correlation between different types of measurements is given by the following incident. The specific heat and magnetic moment of four Ni-Zn ferrites were measured. (See Section 3.7). From the interpretation of these data high values of $\mu_1/\mu_2$ to very high frequencies were predicted. A coaxial inductor measurement yielded the results shown in Table I.

TABLE I

PERMEABILITY SPECTRUM FOR A-32-1

| Core | f mc/sec | $\mu_1$ |
|---|---|---|
| A-32-4 | 50 | 2.7 |
| | 100 | 2.0 |
| | 200 | 1.8 |
| | 500 | 1.9 |

The ratio $\mu_1/\mu_2$ was still too large to be measured at 500 mc/sec but was at least 15.

Although this material was originally manufactured over a year ago, it was not previously measured in the above manner since it was considered to be paramagnetic. The more fundamental measurements and their ensuing interpretation predicted no domain walls and very many small regions of ferrimagnetic material. Thus the wall loss mechanism should be eliminated. The high frequency measurements substantiate this view.

The study of univalent substitution for high-Q high-$\mu_1$ cores is continuing. Table II shows the results of measurements on three cores using a Boonton Q-meter at 2 mc/sec.

TABLE II

$\mu_1$, Q, TIME DEPENDENCE OF THREE CORE TYPES

| Core | Initial | | 15 min. later | | $\mu_1$ 2 mc Permeameter |
|---|---|---|---|---|---|
| | C | Q | C | Q | |
| D-107-1 | 158 | 167 | 163 | 178 | 101 |
| D-107-2 | 156 | 162 | - | - | 104 |
| D-108-2 | 139 | 166 | 173 | 149 | 98 |

## 3.2 Properties of Ferrite Core Inductors (P. E. Nace)

To measure the magnetic properties of a ferrite one often measures first the properties of a ferrite-cored inductor and from the measurements obtains the properties of the ferrite. We shall discuss here the Q of the ferrite and how it is related to the measurements made on the ferrite inductor.

3.2.1 Quality Factor, Q, as Applied to Ferrites. The term Q of a ferrite has been used considerably and loosely in many places. The following is an effort to clarify what is meant by a ferrite Q.

The fundamental definition of Q is:

$$Q \triangleq \frac{\text{Peak stored energy}}{\text{Average energy dissipated per radian}} = \frac{W_S\big]_{peak}}{W_D} \qquad (1)$$

For the purpose of establishing the procedure for the calculation of Q we shall initially consider a more familiar situation. We calculate the Q of the circuit of Fig. 1.

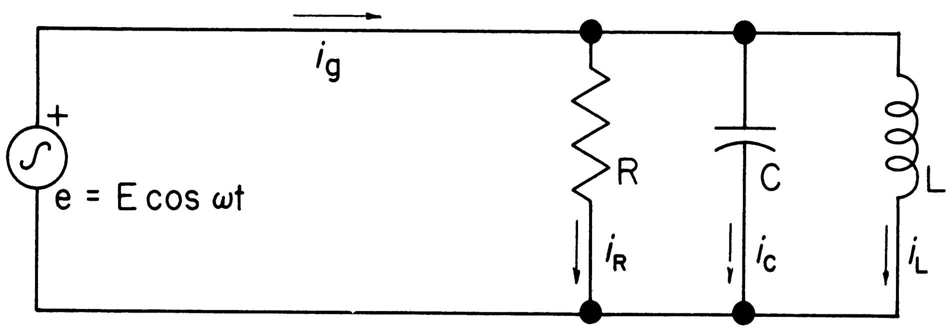


FIG I. CIRCUIT EQUIVALENT OF A DOMAIN WALL

The symbols used here are standard: R, L, and C for resistance, inductance and capacitance; e, i, and P for voltage, current and power; W and $\omega$ for energy and the radian frequency. The equation describing the circuit is

$$C \frac{de}{dt} + \frac{1}{R} e + \frac{1}{L} \int edt = i_g \tag{2}$$

This is a current equation with the first and third terms producing the stored energy, $W_s$.

$$W_s = \int P_s dt = \int e i_s dt = \int \left(L \frac{di_L}{dt}\right) i_L dt + \int e \left(C \frac{de}{dt}\right) dt$$

$$= \frac{1}{2} L i_L^2 + \frac{1}{2} Ce^2$$

$$i_L = \frac{e}{j\omega L} = \frac{E}{\omega L} \sin \omega t$$

$$W_s = \frac{1}{2} CE^2 \left[\cos^2 \omega t + \frac{\omega_o^2}{\omega^2} \sin^2 \omega t\right] \quad \text{where } \omega_o = \frac{1}{\sqrt{LC}}$$

$$W_s\Big]_{peak} = \begin{cases} \frac{1}{2} CE^2 & \text{for } \omega \geq \omega_o \\ \frac{1}{2} CE^2 \frac{\omega_o^2}{\omega^2} & \text{for } \omega \leq \omega_o \end{cases} \tag{3}$$

The second term of Eq. 2 leads to the dissipated energy.

$$W_D = \frac{1}{2\pi} \int_0^{\frac{2\pi}{\omega}} Pdt = \frac{1}{2\pi} \int_0^{\frac{2\pi}{\omega}} \frac{e^2}{R} dt = \frac{E}{2\omega R} \tag{4}$$

Then:

$$Q = \frac{W_s\Big]_{peak}}{W_D} = \begin{cases} \omega CR & \text{for } \omega \geq \omega_o \\ \omega CR\left(\frac{\omega_o}{\omega}\right)^2 = \frac{R}{\omega L} & \text{for } \omega \leq \omega_o \end{cases}$$

$$= R\sqrt{\frac{C}{L}} \left(\frac{\omega}{\omega_o}\right)^{\pm 1} \begin{cases} \text{use + sign for } \omega \geq \omega_o \\ \text{use - sign for } \omega \leq \omega_o \end{cases} \tag{5}$$

Normally one speaks of a Q that applies only for $\omega = \omega_o$. We have here derived a more general Q that applies to all frequencies.

Next we wish to apply the above procedure to the calculation of the Q of a ferrite. The energy within the ferrite which we are considering is that energy which arises when an rf field, $H = H_o \cos \omega t$, is applied. This energy is associated with the motion of domain walls. The equation describing the forces on a domain wall is:

$$m \frac{d^2x}{dt^2} + \beta \frac{dx}{dt} + \alpha x = gM_s H \qquad (6)$$

where m, β, α, and x are the mass per unit area, the viscous damping factor, the stiffness constant, and the displacement of wall respectively. g is a constant between 1 and 2 whose value depends upon the type of wall under consideration. $M_s$ is the saturation magnetization of the material. Let

$$W_s = \int F_s \, dx = \int F_s \frac{dx}{dt} dt = \int m \frac{d^2x}{dt^2} \frac{dx}{dt} dt + \int \alpha x \frac{dx}{dt} dt$$

since the first and third terms of Eq. 6 are the forces which produce stored energy respectively in the inertial energy and in the positional energy of the wall. Solving,

$$W_s = \frac{1}{2} m \left( \frac{dx}{dt} \right)^2 + \frac{1}{2} \alpha x^2 \qquad (7)$$

if x = 0 when F = 0. Solving Eq. 6 gives:

$$x = \frac{gM_s H_o \cos(\omega t + \phi)}{\left[(\alpha - \omega^2 m)^2 + m^2 \beta^2\right]^{1/2}} \qquad (8)$$

where $\tan \phi = \dfrac{\omega\beta}{\alpha - \omega^2 m}$

$$W_s = \frac{1}{2} \left[ \frac{m(gM_s H_o)^2 \, \omega^2 \sin^2(\omega t + \phi) + \alpha (gM_s H_o)^2 \cos^2(\omega t + \phi)}{(\alpha - \omega^2 m)^2 + \omega^2 \beta^2} \right]$$

$$W_s = \frac{(gM_sH_o)^2}{2\alpha} \bullet \frac{\frac{\omega^2}{\omega_o^2}\sin^2(\omega t + \phi) + \cos^2(\omega t + \phi)}{\left[1 - \frac{\omega^2}{\omega_o^2}\right]^2 + \frac{\omega^2}{\omega_1^2}}$$

where $\omega_o^2 = \frac{\alpha}{m}$ and $\omega_1 = \frac{\alpha}{\beta}$

$$W_s\Big]_{peak} = \begin{cases} \dfrac{\frac{1}{2\alpha}(gM_sH_o)^2}{\left(1 - \frac{\omega^2}{\omega_o^2}\right)^2 + \frac{\omega^2}{\omega_1^2}} & \text{for } \omega \leq \omega_o \\ \dfrac{\frac{1}{2}\frac{\omega^2}{\omega_o^2\alpha}(gM_sH_o)^2}{\left(1 - \frac{\omega^2}{\omega_o^2}\right)^2 + \frac{\omega^2}{\omega_1^2}} & \text{for } \omega \geq \omega_o \end{cases} \qquad (9)$$

The second term of Eq. 6 is the force $F_D$ which produces an energy dissipation.

$$W_D = \frac{1}{2\pi}\int_{t=o}^{t=\frac{2\pi}{\omega}} F_D\,dx = \frac{1}{2\pi}\int_o^{\frac{2\pi}{\omega}} F_D\frac{dx}{dt}\,dt$$

$$= \frac{1}{2\pi}\int_o^{\frac{2\pi}{\omega}} \beta\left(\frac{dx}{dt}\right)^2 dt = \frac{\omega\beta(gM_sH_o)^2}{2\left[(\alpha - \omega^2m)^2 + \omega^2\beta^2\right]} = \frac{\frac{1}{2\alpha}\cdot\frac{\omega}{\omega_1}\cdot(gM_sH_o)^2}{\left[1 - \frac{\omega^2}{\omega_o^2}\right]^2 + \frac{\omega^2}{\omega_1^2}}$$

$$Q = \frac{W_s\Big]_{peak}}{W_D} = \begin{cases} \dfrac{\omega_1}{\omega} & \text{for } \omega \leq \omega_o \\ \dfrac{\omega_1\omega}{\omega_o^2} & \text{for } \omega \geq \omega_o \end{cases}$$

$$= \frac{\omega_1}{\omega_o}\left(\frac{\omega}{\omega_o}\right)^{\pm 1} \quad \begin{cases} \text{use + sign for } \omega \geq \omega_o \\ \text{use - sign for } \omega \leq \omega_o \end{cases} \qquad (10)$$

For the special case of a domain wall whose inertial term m is negligible, $\omega_o \to \infty$ as $m \to o$. Thus $\omega < \omega_o$ for all frequencies, and $Q = \omega_1/\omega$ at all times.

For a ferrite cored coil,

$$\mu^* - 1 = \mu_1 - 1 - j\mu_2 = K_1 \frac{dx}{dH} = \frac{gM_sK_1 \cdot \frac{1}{2}}{\left[1 - \frac{\omega^2}{\omega_o^2} + j\frac{\omega}{\omega_1}\right]}$$

where $K_1$ is a real constant and $\mu^*$ is the complex permeability.

$$\text{Then } \mu_1 - 1 = \frac{\left[1 - \frac{\omega^2}{\omega_o^2}\right] \frac{gM_sK_1}{\alpha}}{\left[1 - \frac{\omega^2}{\omega_o^2}\right]^2 + \frac{\omega^2}{\omega_1^2}} \tag{11}$$

$$\mu_2 = \frac{\frac{\omega}{\omega_1} \frac{K_1 gM_s}{\alpha}}{\left[1 - \frac{\omega^2}{\omega_o^2}\right]^2 + \frac{\omega^2}{\omega_1^2}} \tag{12}$$

Then: the coil impedance = $R + j\omega L = j\omega L^*$, where $L^*$ is a complex inductance.

$$j\omega L^* = \frac{\left[\frac{\omega^2}{\omega_1} + j\omega\left(1 - \frac{\omega^2}{\omega_o^2}\right)\right] \cdot \frac{gM_sK_1L_o}{\alpha}}{\left[1 - \frac{\omega^2}{\omega_o^2}\right]^2 + \frac{\omega^2}{\omega_1^2}} + j\omega L_o \tag{13}$$

We have neglected leakage inductance, winding resistance, and the self-capacitance of the windings.

$$\text{Coil } Q = \frac{\omega L}{R} = \frac{\text{Im}(j\omega L^*)}{\text{Re}(j\omega L^*)} = \frac{\mu_1}{\mu_2} = \frac{\omega_1}{\omega}\left(1 - \frac{\omega^2}{\omega_o^2}\right)\left(1 + \frac{\alpha}{gM_sK_1}\right) + \frac{\alpha\omega\omega_1}{gM_sK_1}\left(\frac{1}{\omega_1^2} - \frac{1}{\omega_o^2}\right) \tag{14}$$

$$\text{Core } Q = \frac{\mu_1 - 1}{\mu_2} = \frac{\omega_1}{\omega}\left[1 - \frac{\omega^2}{\omega_o^2}\right] \tag{15}$$

For $\omega << \omega_o$, Eq. 15 agrees with Eq. 10. For $\omega >> \omega_o$, the absolute value of Eq. 15 agrees with Eq. 10. But for $\omega \approx \omega_o$, Eq. 15 does not give the same answer. The difficulty lies with Eq. 14 which does not agree with Eq. 10 for $\omega \approx \omega_o$ and which carries a different sign for $\omega >> \omega_o$. The difficulty arises because $\frac{\omega L}{R}$ was used to calculate coil Q. That formula is correct for a case of only inductively stored energy. With a ferrite core which has a wall resonance, the stored energy is complicated in a manner similar to the shunting of a coil by a condenser. One must consider a ferrite cored coil in a manner similar to the circuit of Fig. 1. This was done for Eq. 10 and not for Eq. 14.

In general a ferrite has many domain walls with a range of values in m, $\beta$, and $\alpha$. This means a range of values of $\omega_0$ and $\omega_1$. In the region of wall resonance it is impossible to measure the Q of Eq. 10. One must instead measure a loss tangent defined by $\tan \delta = \frac{\mu_2}{\mu_1}$ which is the reciprocal of the coil Q of Eq. 14. If each of the domain walls of a ferrite has a relaxation instead of a resonance, Eqs. 10, 14, and 15 are correct since $\omega_0 \to \infty$.

We have shown that using the definition of Eq. 1 for Q and extending its application to all frequencies instead of the frequency of circuit resonance leads to a Q different from the Q in which circuits engineers are interested. In the case of a ferrite cored coil one might call the two Q's respectively a generalized Q and an apparent Q. The apparent Q is all that can be measured and therefore the one in which circuits engineers are interested. In the study of the ferrite material separate from circuits applications, the generalized Q is of interest.

In place of a generalized Q, one could equally well have discussed a dissipation factor D throughout the above where $D = \frac{1}{Q}$. The dissipation factor possesses the virtue that its discussion is not generally restricted to the resonant frequency.

3.2.2 Equivalent Circuit of a Ferrite Cored Coil. Differentiating Eq. 2 with respect to t gives:

$$C \frac{\partial^2 e}{\partial t^2} + \frac{1}{R}\frac{\partial e}{\partial t} + \frac{1}{L} e = \frac{\partial i_g}{\partial t}$$

This equation has the same form as Eq. 6. Therefore:

$$\frac{e}{\frac{\partial i_g}{\partial t}} = K_2 \frac{x}{H} = \frac{e}{j\omega i_g}$$

Solving the two differential equations gives:

$$\frac{e}{i_g} = \frac{1}{j\omega C + \frac{1}{R} + \frac{1}{j\omega L}} = \frac{j\omega K_2 x}{H} = \frac{j\omega K_2 g M_s}{\alpha - \omega^2 m + j\omega\beta} = \frac{K_2 g M_s}{j\omega m + \beta + \frac{\alpha}{j\omega}}$$

Thus an equivalent circuit is obtained by putting:

$$C = \frac{m}{K_2 g M_s} = m' \qquad R = \frac{K_2 g M_s}{\beta} = \frac{1}{\beta'}, \qquad \text{and } L = \frac{K_2 g M_s}{\alpha} = \frac{1}{\alpha'}$$

This circuit accounts for the contribution of the ferrite to the impedance of the coil. There is in addition the air inductance $L_o$, the leakage inductance $L_\ell$, the copper losses $R_{cu}$ and whatever shunting capacitance $C_s$ and shunting resistance $R_s$ there are present. Fig. 2 shows the equivalent circuit. Note that all elements are frequency independent. This circuit was established assuming only one domain wall. With many domain walls the equivalent circuit should have many tank circuits in series with $L_o$.

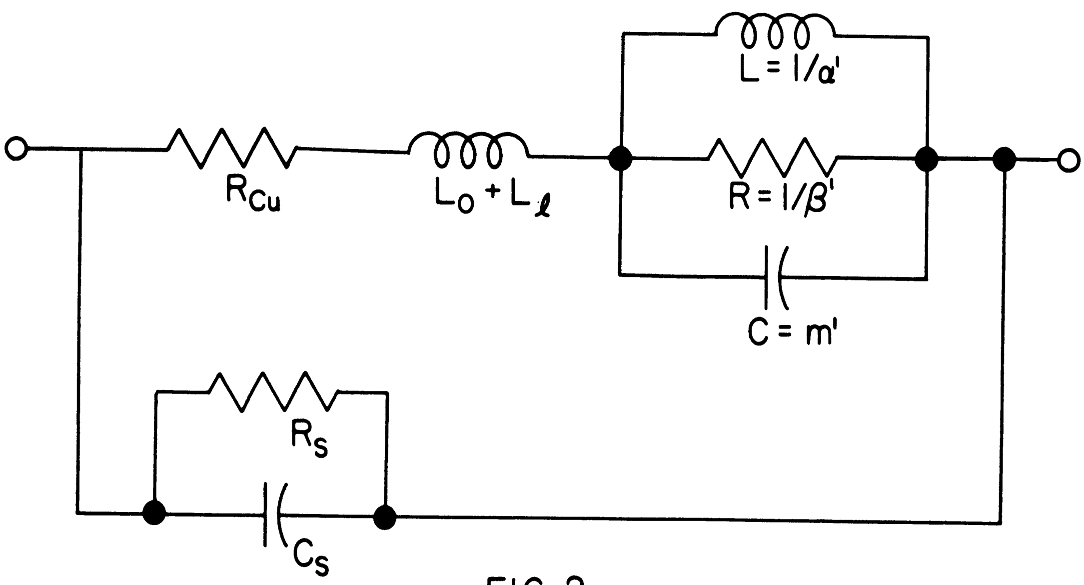


FIG 2
EQUIVALENT CIRCUIT OF A FERRITE CORED COIL

3.3 The Effect of Grain Size (D. M. Grimes, C. F. Jefferson, L. Thomassen)

An initial investigation of the effect of grain size on the permeability was carried out during the quarter to determine if further work on this line would be desirable. If it could be shown that some definite relationship existed then the metallurgical problem of reproducing ferrite material could be recast in metallurgical terms.

This investigation was made on seven cores that were prepared in as nearly as possible identical fashion, but which were found to have considerable variation in magnetic properties.

The cores were mounted in bakelite and polished with progressively finer metallographic papers and finally polishing using a diamond dust and a Linde "N" abrasive. The specimens were then etched in a .05N solution of $SnCl_2$ in HCl.

The grain count was obtained by using a microscope equipped with a filar eyepiece. A linear count of the grain size was obtained by moving the specimen in a straight line toward the center of the core. The count was begun at a specified distance from the edge of the core to attempt to eliminate edge effects and to obtain the best possible sampling. The locations where exceptionally large grains were found was avoided.

Graph I shows the grain size distribution obtained on the seven cores counted. The linear measurement was converted to a volume measurement by cubing the product of the linear dimensions times the number with that dimension. Thus, the mean volume is obtained by computing:

$$\bar{V} = \frac{\sum_i (n_i)^3 (\ell_i)^3}{\sum_i (n_i)^3}$$

Table III shows a comparison between $\bar{v}$ and the measured magnetic properties.*

* The unit of volume used here is 9.26 microns$^3$.

TABLE III

CORRELATION OF GRAIN SIZE AND MAGNETIC PROPERTIES

| A-231- | $\bar{v}$ | $\mu_1$ 2mc | $\mu_1$ 16mc | $\frac{\mu_1 \text{ 2mc}}{\mu_1 \text{ 16mc}}$ | $\mu_1/\mu_2$ 2mc | $\mu_1/\mu_2$ 16mc | $\mu_2$ 2mc | $\mu_2$ 16mc | $\frac{\mu_2 \text{ 2mc}}{\mu_2 \text{ 16mc}}$ |
|---|---|---|---|---|---|---|---|---|---|
| 25 | 1.936 | 912 | 487 | 1.87 | 3.03 | .731 | 301 | 665 | .498 |
| 3 | 1.081 | 723 | 410 | 1.77 | 4.73 | .851 | 153 | 484 | .316 |
| 13 | 1.054 | 749 | 450 | 1.70 | 4.68 | .798 | 160 | 564 | .284 |
| 14 | .994 | 803 | 480 | 1.67 | 4.51 | .764 | 178 | 628 | .283 |
| 19 | .992 | 711 | 445 | 1.60 | 6.52 | .801 | 109 | 554 | .197 |
| 18 | .781 | 693 | 465 | 1.49 | 6.93 | .775 | 100 | 600 | .167 |
| 5 | .700 | 674 | 421 | 1.60 | 5.71 | .835 | 118 | 508 | .232 |

The inherent error is quite large. Our knowledge of $\mu_2$ is quite uncertain. Further, many grains were pulled out during polishing. An estimate of the % voids was obtained by dividing the total linear distance occupied by voids by the total distance covered. The density of the material is about 96% of the X-ray density so that the % voids which one might expect to find if no material was pulled out during polishing would be about 4/3%. The % voids in the polished material is 30 times this amount.

It is obvious that an improved method of polishing is needed. An attempt is being made to develop a procedure for polishing that will not pull out the material.

It is known that there is a variation in grain size from place to place in the ferrite. For example, the grains were found to be smaller at the edge of the core than in the center. For this reason a lot of confidence cannot be placed in measurements over a relatively small distance.

Nonetheless, it is felt that the results are of sufficient value to state that the agreement between $\bar{v}$ and $\mu_{1\ 2mc}$, $\mu_{2\ 2mc}$, $\mu_{1\ 2mc}/\mu_{1\ 16mc}$ and $\mu_{2\ 2mc}/\mu_{2\ 16mc}$ is probably not accidental. Further work in this field is indicated.

<u>3.4 Fabrication of Cores by Stamping</u> (D. M. Grimes)

This experiment was halted by Mr. Kimura's leaving the University July 16 to accept another position. Prior to his leaving he succeeded in fabricating two types of cores in the manner described in Section 3.6 of QPR No. 7. These core types are designated A-315 and A-316 (both 20-30 Ni-Zn ferrites). All were cut in the manner described, then heated slowly to 900°C where they were held for one hour. Following this they were fired at 1250°C for four hours. Types A-315 were made from a mix of 35 gms of oxides and 20 $cm^3$ of a 1.5% solution of gum tragacanth. Types A-316 were made from 40 gms of oxides mixed with 20 $cm^3$ of 2.5% solution of polyvinyl alcohol.

The cores were mechanically strong, but were not as regular as those pressed in a die.

The results at 2 mc/sec are: (See Table IV).

TABLE IV

MAGNETIC PROPERTIES OF STAMPED CORES

| Type | $\mu_1$ | $\mu_2$ |
|---|---|---|
| A-315-1 | 515 | 333 |
| -2 | 556 | 393 |
| -3 | 466 | 256 |
| -4 | 596 | 457 |
| -5 | 557 | 383 |
| A-316-1 | 602 | 418 |
| -2 | 681 | 575 |

## 3.5 Dielectric Constant and Resistivity (P. E. Nace)

The dielectric constant and resistivity have been measured over a frequency range of 150 cycles to 30 mc. The bare core was placed in the General Radio dielectric sample holder and measurements were made on the General Radio Twin-T Bridge above 460 kc and on the General Radio Capacitance Bridge at the lower frequencies. (See Figs. 3 and 4). Note that the results are significantly different from those cited in the last Quarterly Progress Report. Also note the scattering of data. The latter is believed due to poor electrical contact with the sample. Measurements are currently being made with aluminum foil electrodes applied with a thin film of Vaseline as an adhesive. The General Radio Twin-T has been modified in order to extend its conductance range and thereby facilitate these measurements.

Three baking silver paints were used for some d-c resistivity measurements. Table V below compares the results for the three paints. Each sample was first measured between point electrodes pressed upon the bare ferrite surface. A range of resistance values (independent of the distance between the electrodes) was obtained by moving the electrodes along the surface. Then Ag-paint was applied and measurements were made between two such electrodes and also between one such electrode and one point electrode pressed upon bare ferrite. For two of the cores the polarity of applied voltage was reversed. For one sample the surface was polished before the application of one of the two electrodes of each measurement.

The tests show Dumont's Type F, No. 4731 paint to be unacceptable for us. It actually increased the resistance. Perhaps at the high temperature of baking the Ag-ions possessed enough mobility to penetrate into a thin surface layer setting up a chemical barrier layer and a rectifying action. The other two paints

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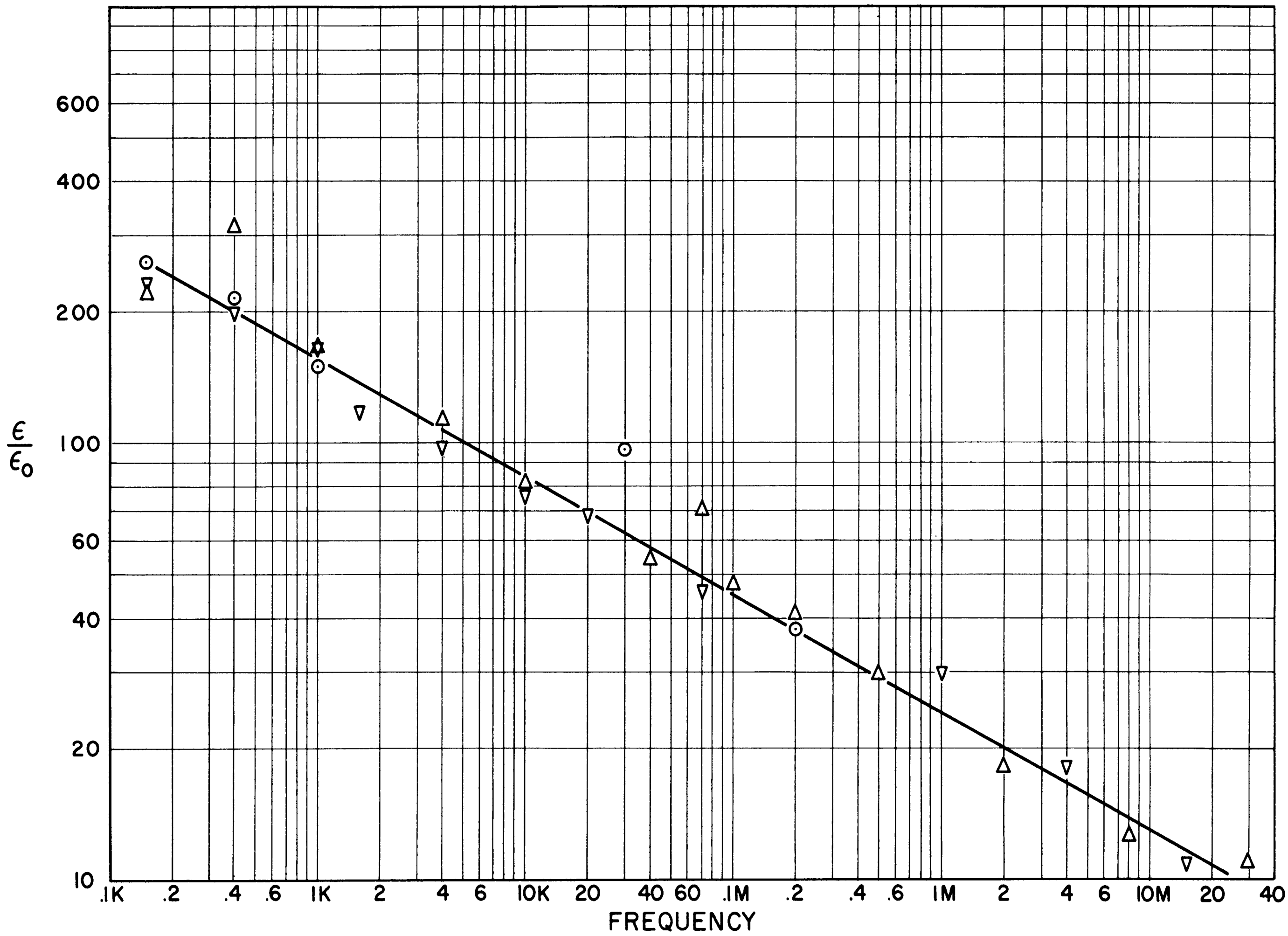


## FIG 3
## DIELECTRIC CONSTANT VS FREQUENCY
## CORE A-88-3

PLANAR METALLIC ELECTRODES PRESSED UPON SURFACE
DIFFERENT SYMBOLS DISTINGUISH DIFFERENT RUNS

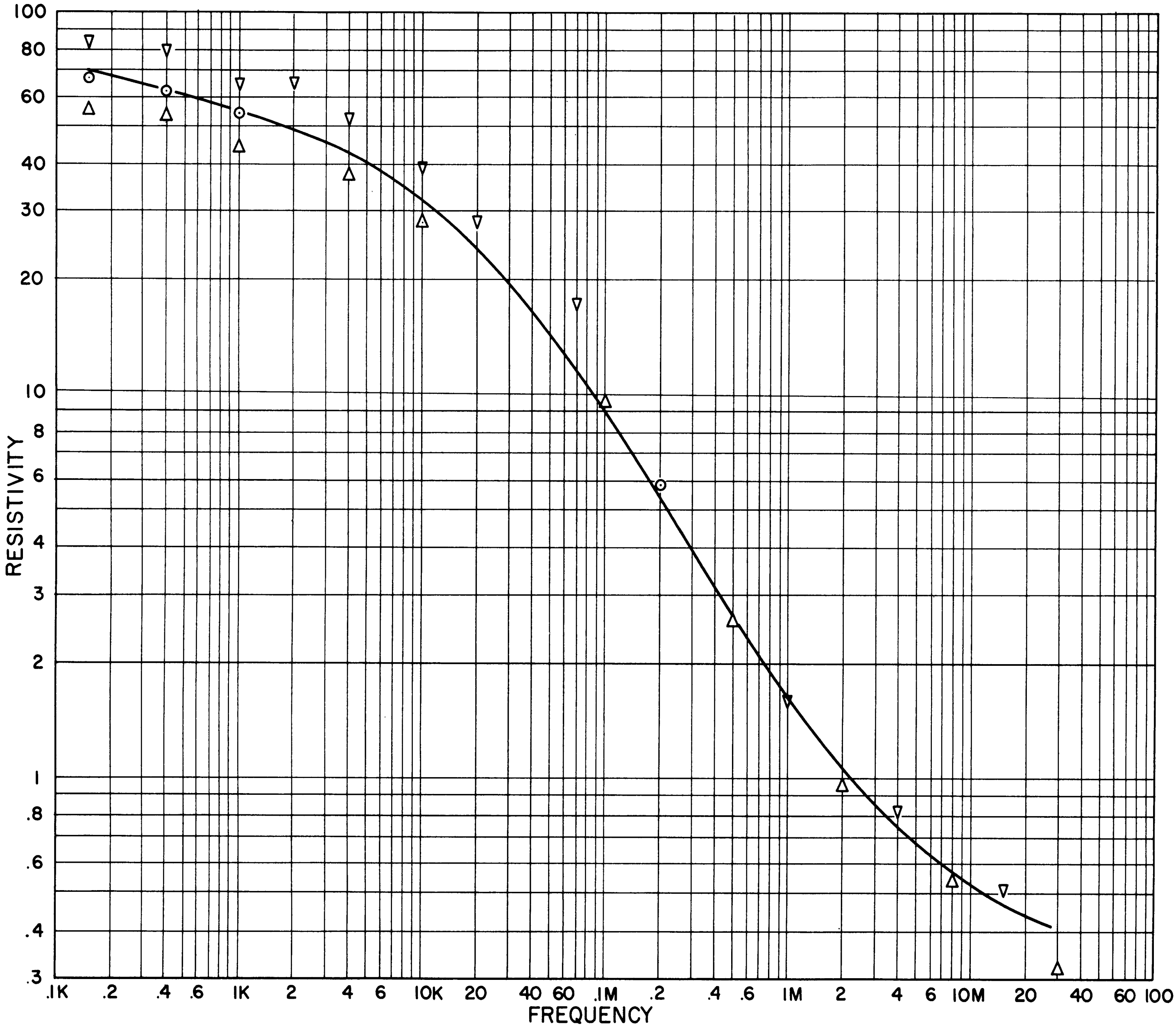


FIG 4

RESISTIVITY VS FREQUENCY
CORE A-88-3

PLANAR METALLIC ELECTRODES PRESSED UPON SURFACE
DIFFERENT SYMBOLS DISTINGUISH DIFFERENT RUNS

look promising. Dumont's Type F, No. 4887 was baked at 425°C. Micro-circuits' Type SCT-32 was baked at 250°C.

In physical appearance F-4731 was excellent, F-4887 good, and SCT-32 fair to poor. The SCT-32 formed the best mechanical bonding to the surface. All of the paints were poor in bonding to low-fired cores, but were fairly good for cores fired at 1100°C or above.

TABLE V

DEPENDENCE OF MEASURED RESISTANCE ON ELECTRODE PAINT

| Designation | | Resistance in Arbitrary Units | | |
|---|---|---|---|---|
| Core | Paint | Bare Core | One Electrode of Ag-paint | Both Electrodes with Ag-paint |
| A-108-2 | F-4731 | 1.2-2.8 | 2.0 | 10 drifts badly |
| A-109-2 | " | 2-4 | 1.7 | 10 |
| A-126-2 | " | 2-50 | 4 | 15 |
| A-105-4 | F-4887 | 2-2.35 | 0.30 | .0026 |
| A-35-2 | " | ∞ | 10-50 drifts badly | - |
| A-107-2 | " | 1-2.5 | 0.1-0.5 | 0.10 |
| A-33-2 | SCT-32 | 100 | 60-200 | 0.041 |
| A-105-2 | " | 1.2-4 | - | 0.065 |
| A-106-2 | " | 1-3 | 0.7-3<br>0.03-0.08 with opposite polarity | 0.003 |
| A-106-4 | " | 2-10<br>0.05-0.5 | 0.05-0.3<br>0.05 with opposite polarity | 0.0014 |

## 3.6 Theoretical Frequency Dependence of the Complex Permeability

It is customary to handle the magnetic susceptibility arising from domain wall motion by assuming the wall obeys the differential equation:

$$m\frac{d^2x}{dt^2} + \beta\frac{dx}{dt} + \alpha x = \gamma M_s H$$

where m, $\beta$, and $\alpha$ are constant. The solution of this equation yields:*

$$\frac{\chi_1}{\chi_0} = \frac{1 - \omega^2/\omega_0^2}{(1 - \omega^2/\omega_0^2)^2 + \omega^2/\omega_1^2}$$

$$\frac{\chi_2}{\chi_0} = \frac{\omega/\omega_1}{(1 - \omega^2/\omega_0^2)^2 + \omega^2/\omega_1^2}$$

where: $\omega_1 = \alpha/\beta$, $\omega_0 = \sqrt{\alpha/m}$.

Resonance occurs at the frequency $\omega_0$ if $m \neq 0$, a relaxation is defined as $m \to 0$. The resonance solution yields a $\chi_1$ relative maximum before it drops to zero, then is negative at frequencies higher than $\omega_0$. The relaxation produces neither a negative $\chi_1$ nor a relative maximum.

Experimentally it is found that $\chi_1$ shows the characteristic of a resonance by going through a relative maximum and a relaxation by going negative only at very high frequencies if at all. For a simple oscillator the two are irreconcilable.

We look for the solution to this dilemma by considering both $\omega_0$ and $\omega_1$ to be finite but to vary from grain to grain. This causes the measured $\chi$ vs $\omega$ curve to be an average of many curves with different parameters.

To calculate this it was first assumed that $\omega_1$ retained a fixed value but $\omega_0$ varied between grains. If $p(\omega_0)$ is the fraction of a unit volume with effective $\omega_0$ between $\omega_0$ and $\omega_0 + d\omega_0$, then:

* These equations must be the Hilbert Transforms of each other.

$$p(\omega_o) = K \qquad \omega_A \leq \omega_o \leq \omega_B$$

$$p(\omega_o) = 0 \qquad \omega_o < \omega_A ; \omega_o > \omega_B$$

Thus:

$$\frac{\overline{X}_1}{X_2} = \frac{1}{\omega_B - \omega_A} \int_{\omega_A}^{\omega_B} \frac{(1 - \omega^2/\omega_o^2) d\omega_o}{(1 - \omega^2/\omega_o^2)^2 + (\omega/\omega_1)^2}$$

$$\frac{\overline{X}_2}{X_0} = \frac{1}{\omega_B - \omega_A} \int_{\omega_A}^{\omega_B} \frac{(\omega/\omega_1) d\omega_o}{(1 - \omega^2/\omega_o^2)^2 + (\omega/\omega_1)^2}$$

The integrated expressions are quite involved and so will not be given here. The values of $\frac{\omega_A}{2\pi}$ = 8 mc/sec and $\frac{\omega_B}{2\pi}$ = 40 mc/sec were picked from the experimental curve for Core A-120-1. Both experimental and calculated average curves are shown in Fig. 5. Note that the $\mu_1$ curves agree reasonably, but the $\mu_2$ curves are considerably different. To improve the $\mu_2$ agreement consider: (A) The distribution chosen has a fixed value of $\omega_1$. The $X_1$ and $X_2$ terms should also be integrated over $\omega_1$. (B) Some sort of compromise between (A) and the distribution described above could be made. One example would be to consider $\omega_o/\omega_1$ as constant, then integrate over a range of $\omega_o$. (C) A different distribution function could be picked. An example would be:

$$p(\omega_o) = \frac{2(\omega_o - \omega_A)}{(\omega_B - \omega_A)(\omega_C - \omega_A)} \qquad \omega_A \leq \omega_o \leq \omega_B$$

$$p(\omega_o) = \frac{2(\omega_C - \omega_o)}{(\omega_C - \omega_B)(\omega_C - \omega_A)} \qquad \omega_B \leq \omega_o \leq \omega_C$$

$$p(\omega_o) = 0 \qquad \omega_o < \omega_A ; \omega_o > \omega_C .$$

We expect to try both (B) and (C). (A) seems impractical due to computational difficulties.

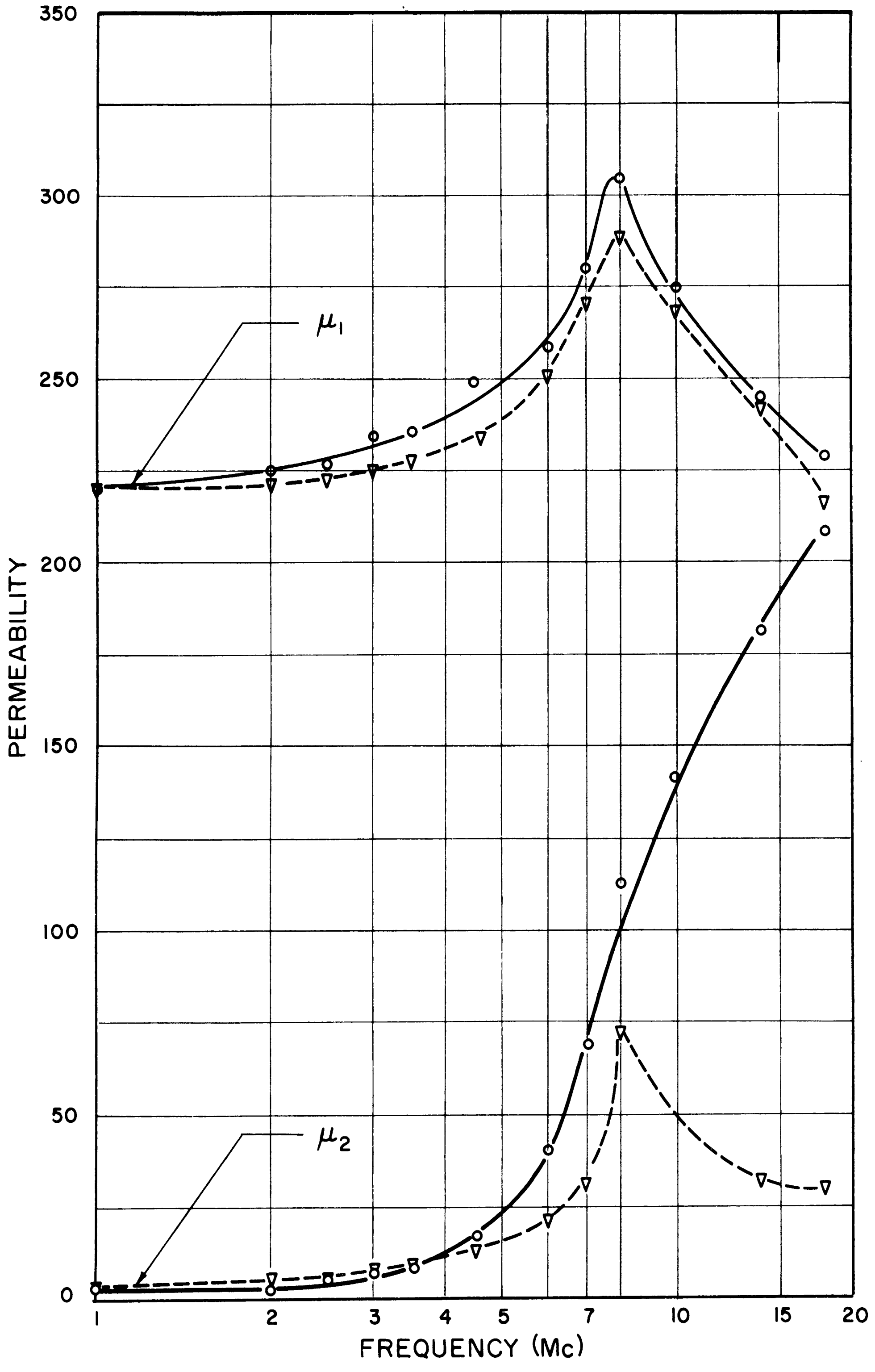


FIG 5
EXPERIMENTAL AND CALCULATED FREQUENCY SPECTRA

3.7 Specific Heat of Some Ni-Zn Ferrites (E. F. Westrum, Jr. and D. M. Grimes)

The specific heats have now been measured from about 4.5°K to about 300°K on four nickel zinc ferrites $Ni_{1-x}Zn_xFe_2O_4$, with compositions given by x = 0.9, 0.8, 0.7, and 0.6. It is expected that a technical report will be issued either late in this quarter or early in the next, so the details will not be given here. Suffice it to say that for large values of x, the molecular field treatment proposed by Neel, Yafet and Kittel, Smart, et al breaks down, for the local conditions vary considerably with spatial coordinate.

## 4. CONCLUSIONS

It has been seen possible to "stamp" cores with zero pressure. The work has not been progressed sufficiently to see if any significant gains can be made in this fashion. However, the five made show smaller values of percentage deviation from the mean for Type A-88, for example. It is possible the deviation could be further reduced by more intensive mixing.

Preliminary results show a definite, though not complete, correlation between mean grain volume, $\bar{v}$, and $\mu_1$ at 2 mc/sec, $\mu_2$ at 2 mc, and the ratio $\frac{\mu_1 \text{ 2 mc}}{\mu_1 \text{ 16 mc}}$ and $\frac{\mu_2 \text{ 2 mc/sec}}{\mu_2 \text{ 16 mc/sec}}$. If these could be definitely established, the problem of core manufacture for reproduction of permeability could be reformulated into the problem of reproduction of grain size and possibly grain size distribution. More work is indicated.

The meaning of "Q" as applied to a ferrite is considered in some detail.

## 5. PROGRAM FOR THE NEXT INTERVAL

The study of the effect of univalent substitution will be continued. More refined techniques will be brought into play for counting grain sizes.

The dielectric constant and resistivity measurements will continue. We will continue work on averaging the values of $\omega_0$ and $\omega_1$ over a range of values to get expressions closer to experimental results than before.

The specific heat and magnetization data will be analyzed. It is hoped that a technical report can be issued either during this quarter or the subsequent one.

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