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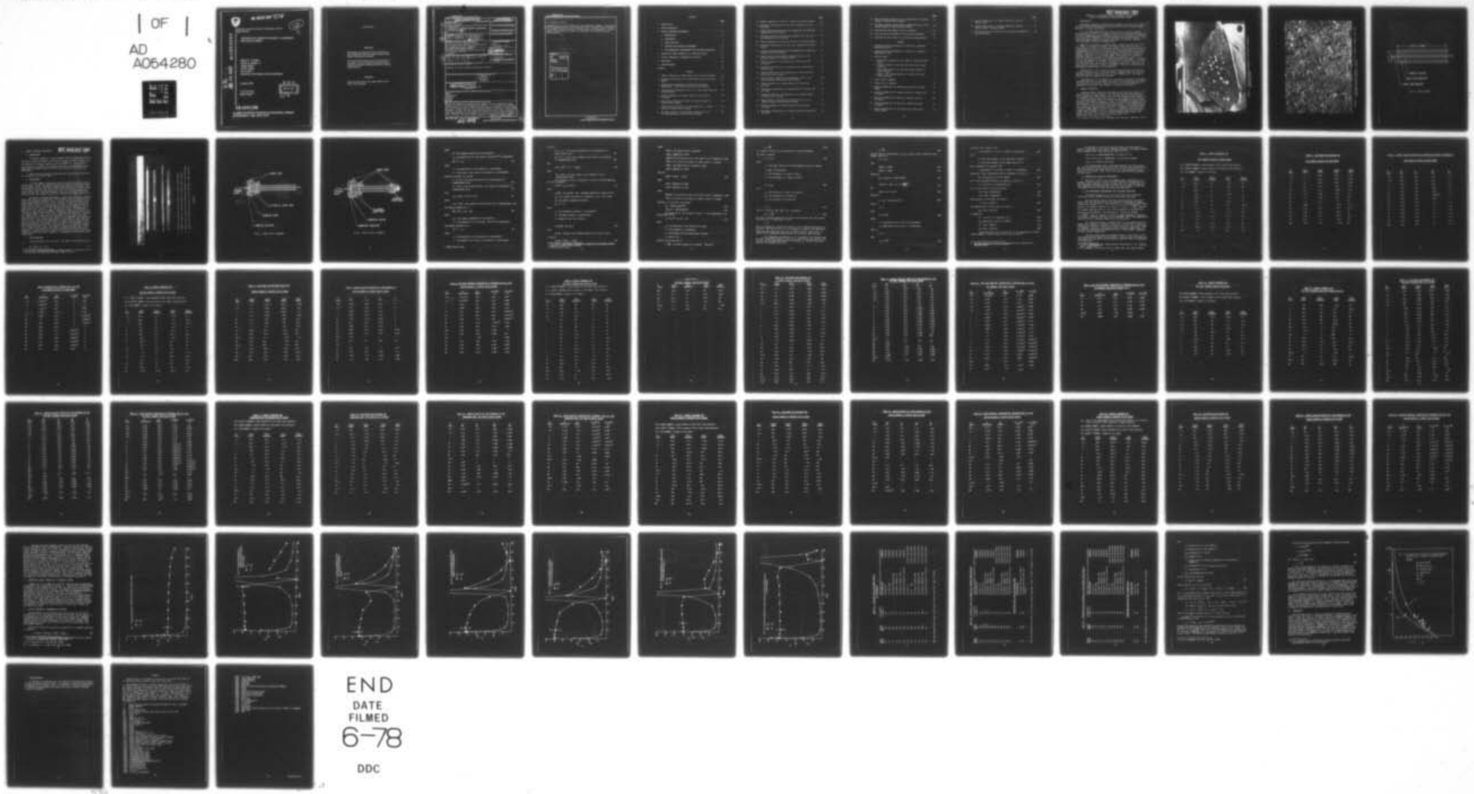

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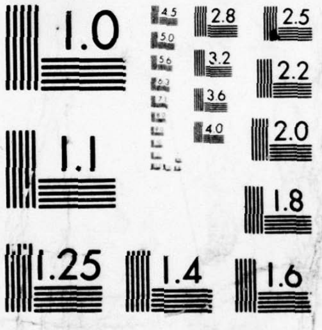

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PROPERTIES OF COMPOSITE MAGNETIC COMPONENTS FOR USE WITH HEMAC

Robert D. Finnegan
Robert O. Savage, Jr.
Joseph Megill
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January 1978

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Hybrid electromagnetic antenna couplers (HEMAC) offer the advantage of using convenient parts of the environment as antennas. In this report the synthesis and evaluation of flexible, shock-resistant, magnetic composites for use at high frequency in HEMAC coils and their characterization are described. Ferrites and carbonyl iron were cast into desired form using silicone as a matrix material. The complex impedance of the samples in the form of a coaxial line was measured from 1-100 MHz. The characteristic impedance, resistance, reactance, complex

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20. Abstract (cont'd)

permeability and complex permittivity, and losses were computed. The real part of the permeability for all materials was found to be equal to the reciprocal of the cube of the porosity up to 100 MHz, where p is the porosity. An experimental toroid mounted in a HEMAC on a simulated rifle exhibited improved characteristics.

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TABLES

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PROPERTIES OF COMPOSITE MAGNETIC COMPONENTS FOR USE WITH HYBRID ELECTROMAGNETIC ANTENNA COUPLERS (HEMAC)

1. INTRODUCTION

Hybrid Electromagnetic Antenna Couplers (HEMAC) have been under investigation at ECOM for the purpose of using convenient parts of the environment, natural or man-made, as antennas.

Dr. Ikrath has demonstrated the effectiveness of a properly matched HEMAC toroidal circuit.[1] For example, circuits like these have been deployed on trees in woods and jungles exploiting coupling to the canopy to control the directivity of RF radiation, which had previously been uncontrollable. In the urban environment, coupling to people, buildings, helicopters, lampposts, water and power lines has been demonstrated.

HEMAC is an insulated, wire-wound, empty toroidal coil which acts like the primary of a leaky transformer. The object around which the coil is placed serves as a single turn secondary winding. The RF wavelength employed is determined by the size of the object and related surrounding structures. Sometimes the coil size may be quite large as is required for trees or helicopters. Reduction in coil size may be achieved by inserting an inductive component coaxially inside the empty HEMAC. The presence of the magnetic material serves the purpose of increasing the permeability above air, enhancing the coupling to the object, and resulting in a decrease in the number of turns and diameter of the HEMAC. Another way of viewing this is to note that the velocity of the RF wave in the magnetic material is reduced as compared with air, producing a reduced wavelength. Thus, the structure may be made smaller proportional to this reduction.

The objective of this investigation was the preparation and characterization of flexible, shock-resistant, composite magnetic materials, and the characterization of their properties for use in HEMAC coils. The magnetic materials used are commercially available.

The preparation of the composites is described in Section 2; measurement procedures and data are described in Section 3; results obtained with composite toroids on a toy gun are reported in Section 4; and the dependence of permeability on porosity and frequency is discussed in Section 5.

2. SAMPLE PREPARATION

Flexible, elastic composites were made using ferrites and carbonyl iron with GE 615 RTV silicone rubbers. The ferrites used were Ferroxcube Corp. RD-3 < 60 mesh and Indiana General Q-1 < 60 mesh, as well as GAF carbonyl iron powders with particle size from 2-5 µm. The composites were formulated on a volume percentage basis with samples varying between 25 and 50 volume percent of the magnetic component. Pores in the composites introduce a third unwanted phase. To avoid introducing voids, removal of the adsorbed gas on the fillers, ferrites especially, and absorbed gases from the mixing process was accomplished through vacuum techniques. An example of the deleterious effect of trapped gases is shown in Fig. 1. A composite relatively free of trapped gases is shown in Fig. 2. The samples were poured into standard coaxial configurations (Fig.3) and further outgassed under vacuum. The samples were then cured at 150°C for one-half hour in air.

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[1] K. Ikrath, K.J. Murphy and W. Kennebeck, R&D Tech Rept, ECOM-4133, June 73.

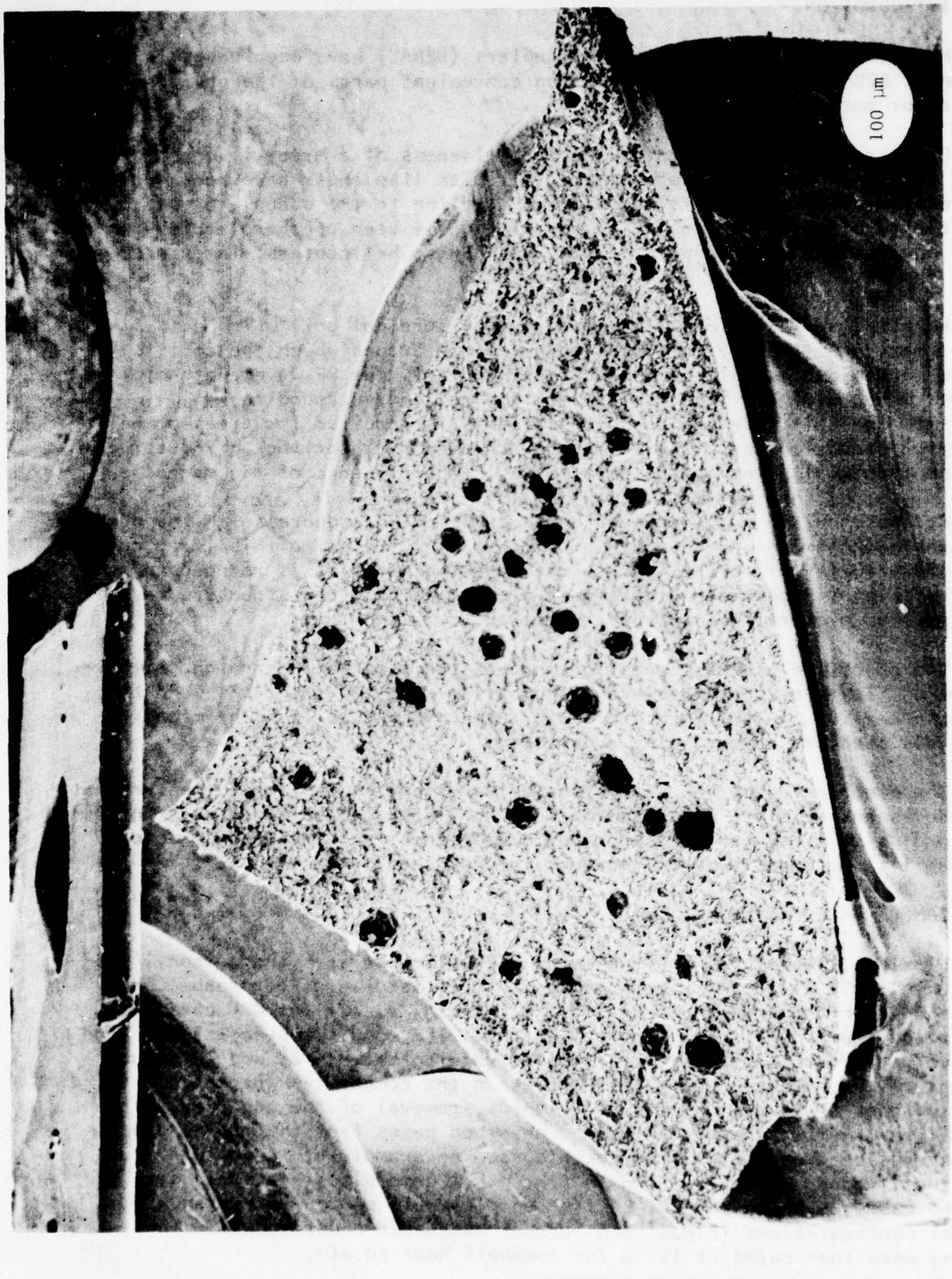

Figure 1. Scanning electron micrograph of a ferrite Q-1 composite. Magnification 20X

Figure 2. Scanning electron micrograph of a ferrite Q-1 composite. Magnification 135X. Black holes are due to pullout of grains.

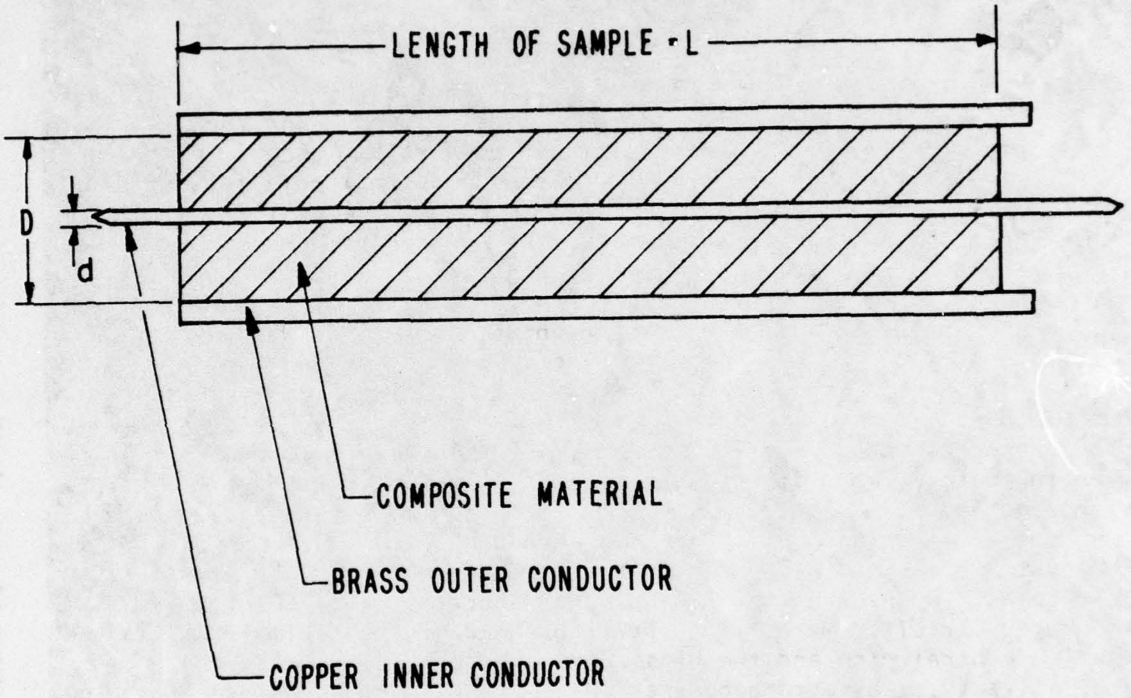

Fig. 3. Typical sample.

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3. COMPLEX IMPEDANCE MEASUREMENTS

a. INTRODUCTION

The complex impedance of these composite materials was measured with the aim of finding the complex quantities $\underline{K}^*$ and $\underline{K}_m^*$, where $\underline{K}^*$ = complex relative permittivity and $\underline{K}_m^*$ = complex relative permeability. The purpose of this section is to present the parameters measured, the experimental procedures, and the equation used to arrive at the results for this series of experiments.

Charts giving the measured quantities and the calculated quantities are included in this section (see e).

b. EXPERIMENTAL

A typical sample to be measured was in the form of a coaxial transmission line. The central conductor was made of copper and the outer conductor was made of brass. The material, whose properties were of interest, was formed between the inner and outer conductor and completely filled this region for the entire length of the coaxial line (Fig. 3). A typical sample was about 8 inches long. The outer diameter of the central conductor was 0.101 inches, and the inner diameter of the brass conductor was 0.292 inches (Fig. 4).

To make the impedance measurements a Hewlett Packard Vector Impedance Meter, Model 4815A, was connected to the left-hand side of the coaxial line using a CIU UG-626A/U connector (Figs. 5 and 6). Two pieces of cylindrically shaped copper braid were placed at the left-hand side and held firmly with rubber bands as shown in Figs. 5 and 6, in order to insure good contact between the outer part of the CIU UG-626A/U and the brass conductor. The impedance meter gave readings of $|\underline{Z}|$ the absolute value of the impedance in ohms, and θ, the angle of the complex impedance in degrees, as a function of frequency between 0.5 MHz and 100 MHz. Each sample was measured for two separate cases, "Open Circuit" (Fig. 5) and "Short Circuit" (Fig. 6). The first case "Open Circuit," means that the right-hand side was simply left alone with the central wire and the brass conductor not connected. The second case "Short Circuit," was arranged experimentally by shorting out the right-hand side with two cylindrically shaped pieces of copper braid as shown in Fig. 6. Usually the material of interest filling the coaxial line was made so that a small empty space existed on the right-hand side. This presented a problem for the "Short Circuit" case. The space was plugged up with a small cylindrical copper braid placed over the central conductor and under the brass conductor. A second cylindrical copper braid was placed over the outer brass conductor and over the central conductor. The assembly was held firmly with rubber bands.

c. BASIC EQUATIONS

Rationalized MKS units were used. The complex relative permittivity is[2]

$$\underline{K}^* = \underline{E}^*/E_v = K' - jK'' \tag{1}$$

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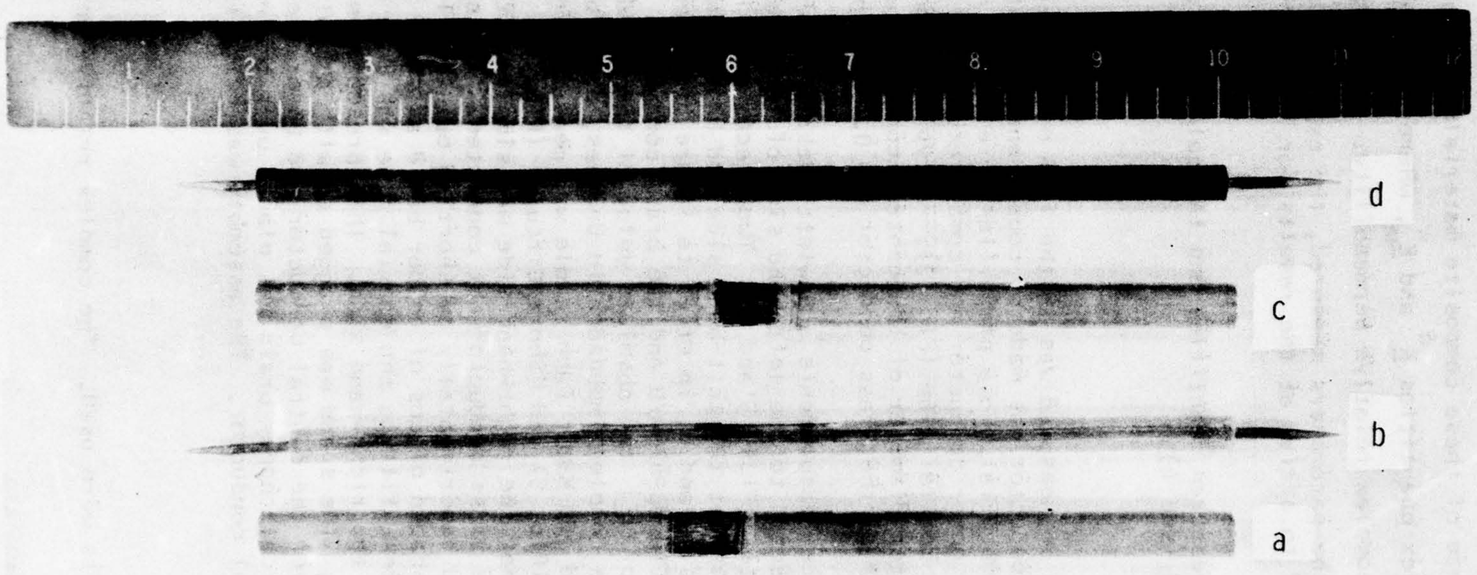
[2] A. Von Hipple, Dielectric Materials and Applications, (Technology Press of MIT and John Wiley and Sons, New York, 1954), 4-5, 125.



a. Brass outer conductor for the 100% G.E. silicone rubber sample.

b. Sample of 100% G.E. silicone rubber with inner copper conductor.

c. Brass outer conductor for the 30% Indiana General Q-1 ferrite sample.

d. Sample of 30% Indiana General Q-1 ferrite with inner copper conductor.

Figure 4.

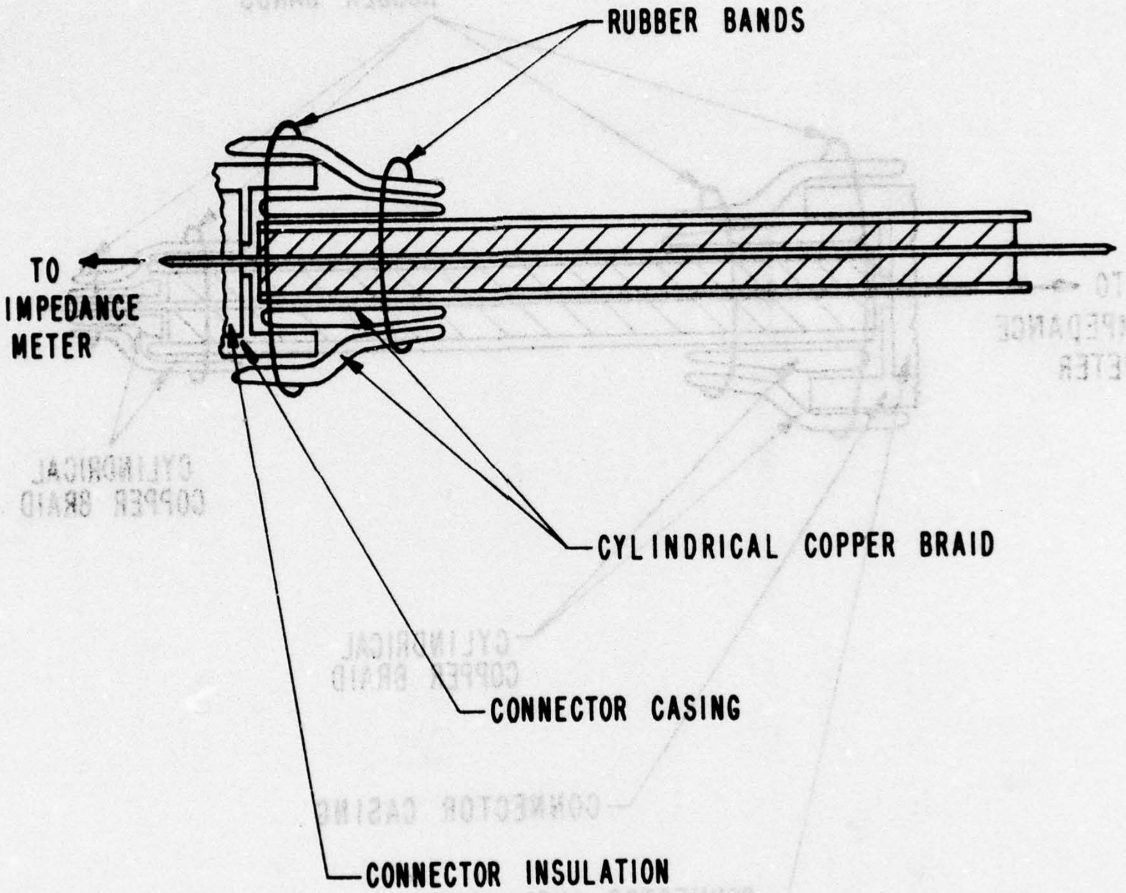


Fig. 5. "Open Circuit" assembly.

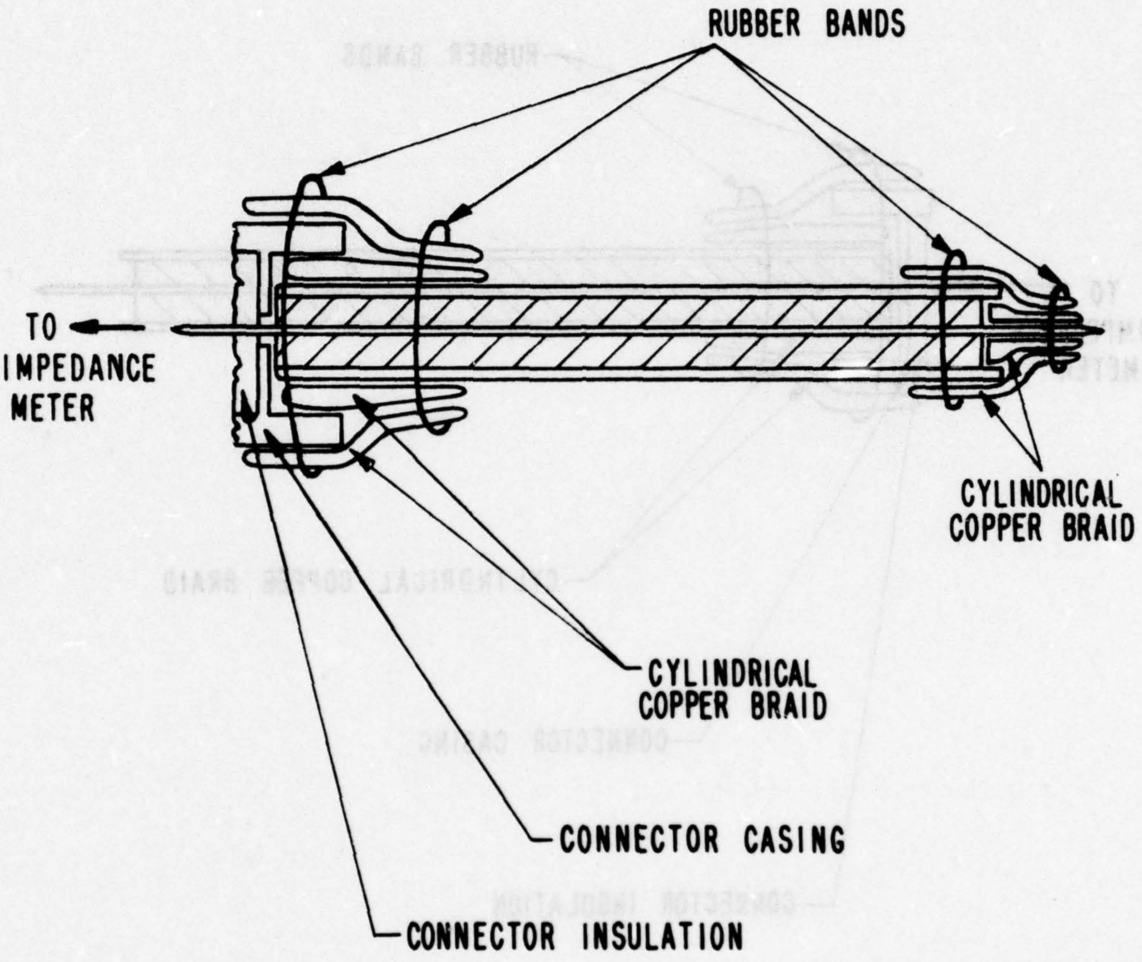


Fig. 6. "Short Circuit" assembly.

where

$\underline{E}^*$ = the complex permittivity of the material

E_v = the permittivity of the vacuum = $(8.854)\cdot(10^{-12})$ farads/meter

$$\underline{E}^* = E' - jE'' \qquad (2)$$

where

E' = the permittivity of the material in farads/meter

E'' = the electric loss factor of the material in farads/meter

Therefore from Eqs. (1) and (2)

$K' = E'/E_v$ = the relative permittivity of the material in dimensionless units (3)

$K'' = E''/E_v$ = the relative electric loss factor of the material in dimensionless units (4)

Also

$$\tan\delta\ (OC)^{\dagger} = E''/E' = K''/K' \qquad (5)$$

where

$\tan\delta$ (OC) = loss tangent for the electric loss in dimensionless units

The complex permeability is

$$\underline{K}_m^* = \underline{\mu}^*/\mu_v = K_m' - jK_m'' \qquad (6)$$

where

$\underline{\mu}^*$ = the complex permeability of the material

μ_v = the permeability of the vacuum = $(4\pi)\cdot(10^{-7})$ henrys/meter

The complex permeability is

$$\underline{\mu}^* = \mu' - j\mu'' \qquad (7)$$

where

μ' = the permeability of the material in henrys/meter

μ'' = the magnetic loss factor of the material in henrys/meter

---

† "Open Circuit" case

Therefore

$K'_m = \mu'/\mu_v$ = the relative permeability of the material in dimensionless units. (8)

$K''_m = \mu''/\mu_v$ = the relative magnetic loss factor of the material in dimensionless units (9)

Also

$\tan \delta$ (SC)[*] $= \mu''/\mu' = K''_m/K'_m$ (10)

where

$\tan \delta$ (SC) = the loss tangent for the magnetic loss in dimensionless units

With respect to coaxial transmission lines the following equations are true in general.[3]

$\underline{Z}\,(OC) = \underline{Z}_o \coth (\underline{P}\,L)$ (11)

where

$\underline{Z}$ (OC) = the complex input impedance measured for "Open Circuit"

$\underline{Z}_o$ = the complex characteristic impedance of the line in ohms

$\underline{P}$ = the complex propagation constant

$\underline{P} = A + jB$

where

A = the attenuation constant in radians/meter

B = the phase constant in radians/meter

L = length of the line in meters

$\underline{Z}\,(SC) = \underline{Z}_o \tanh (\underline{P}\,L)$ (12)

where

$\underline{Z}$ (SC) = complex input impedance measured for "Short Circuit"

In general

$\underline{Z}\,(OC) = R(OC) + j\,X(OC)$ (13)

---

[3] F.E. Rogers, The Theory of Networks in Communication and Other Fields, (Macdonald, London, 1957), 274-364.

[*] "Short Circuit" case.

where

$R(OC)$ = the "Open Circuit" resistance

$R(OC) = |\underline{Z}(OC)| \cos\theta(OC)$

$|\underline{Z}(OC)|$ = the absolute value of the "Open Circuit" impedance in ohms

$\theta(OC)$ = the value of the angle for "Open Circuit" in radians

$X(OC)$ = the "Open Circuit" reactance in ohms

$X(OC) = |\underline{Z}(OC)| \sin\theta(OC)$

Similarly

$$\underline{Z}(SC) = R(SC) + j\,X(SC) \qquad (14)$$

where

$R(SC) = |\underline{Z}(SC)| \cos\theta(SC)$

$X(SC) = |\underline{Z}(SC)| \sin\theta(SC)$

where

$|\underline{Z}(SC)|$ = the absolute value of the "Short Circuit" impedance in ohms

$\theta(SC)$ = the value of the angle for "Short Circuit" in radians

From Eqs. (11) and (12), one obtains

$$\underline{Z}_o = ((\underline{Z}(OC))(\underline{Z}(SC)))^{\frac{1}{2}} \qquad (15)$$

$$\tanh \underline{P}\,L = (\underline{Z}(SC)/\underline{Z}(OC))^{\frac{1}{2}} \qquad (16)$$

An expression for the voltage at a point x in the transmission line can be shown to be

$$v_x = V_s e^{Ax} \sin(wt - Bx) \qquad (17)$$

where

V_s = the magnitude of the sending end voltage

w = the frequency in radians/sec

x = the distance from the sending end in meters

t = time in sec

From Eq. (17) we see that if

$x = \frac{2\pi}{B}$, the phase changes by 2π radians. Therefore,

$$\lambda_m = \frac{2\pi}{B} \tag{18}$$

is a general relation for the wavelength in a material medium.

For waves in general

$$c_v = f_v \lambda_v \tag{19}$$

where

c_v = the phase velocity of an electromagnetic wave in a vacuum

= 2.998×10^8 meters/sec

f_v = the frequency in a vacuum in #/sec

λ_v = the wavelength in a vacuum in meters

$$c_m = f_m \lambda_m \tag{20}$$

where

c_m = the velocity of a wave in the material

λ_m = the wavelength in the material

f_m = the frequency in the material

$$f_m = f_v \tag{21}$$

Therefore from Eqs. (18), (20), (21), one obtains

$$c_m = f_v \frac{2\pi}{B} \tag{22}$$

The general equations above may be simplified by assuming that the attenuation constant A is about equal to zero.

$$A \approx 0$$

When this assumption is made there results a set of simplified equations for $\underline{Z}_o$ and B. The justification for this assumption is based on the observation that when these simplified equations are used to obtain a value for B, it agrees with an independent determination of B using Eqs. (20) and (22).

The independent determination of B is obtained in the following way: Eq. (20) allows one to obtain a value for c_m from the physical length of the sample L, and the measured frequency at resonance f_m. To obtain λ_m from L one uses the resonance condition.

$$L = \frac{\lambda_m}{4} \tag{23}$$

The last step is to substitute f_v and c_m into Eq. (22) to obtain an independent value of B.

If $A \simeq 0$

then

$$\underline{Z}(OC) \approx j\ X(OC) \tag{24}$$

$$\underline{Z}(SC) \sim j\ X(SC) \tag{25}$$

Therefore

$$\underline{Z}_o = Z_o(\text{real}) = (X(OC) \cdot X(SC))^{\frac{1}{2}} \tag{26}$$

$$\tanh \underline{P}\ L = \tanh j\ B\ L = \left(\frac{X(SC)}{X(OC)} \right)^{\frac{1}{2}} \tag{27}$$

But

$$\tanh j\ B\ L = \tan B\ L \tag{28}$$

Therefore

$$B = \tan^{-1}\ (X(SC)/X(OC))^{\frac{1}{2}}/L \tag{29}$$

Also if

$A \simeq 0$

then

$$B = w(LC)^{\frac{1}{2}} \tag{30}$$

where

L = inductance of the circuit in henrys/meter

C = capacitance of the circuit in farads/meter

Also if

$A \sim 0$

then

$$Z_o \simeq (L/C)^{\frac{1}{2}} \tag{31}$$

In general for a coaxial line[4]

$$L \text{ henrys/meter} = \mu'(1/2\,\pi)\ \ln\ (D/d) \text{ in henrys/meter} \qquad (32)$$

where

D = the inner diameter of the brass outer conductor

d = the outer diameter of the copper central wire

Also in general for a coaxial line[4]

$$C \text{ farads/meter} = E'/((1/2\pi)\ \ln\ (D/d)) \text{ in farads/meter} \qquad (33)$$

Therefore, if Eqs. (8),(30),(31),(32) are combined, the result is

$$K_m' = (B\cdot Z_o)/(w\cdot\mu_v\cdot(1/2\,\pi)\ \ln\ (D/d)) \qquad (34)$$

and if Eqs. (3),(30),(31),(33) are combined, the result is

$$K' = (B\cdot(1/2\,\pi)\ \ln\ (D/d))/(w\cdot Z_o\cdot E_v) \qquad (35)$$

For the calculation of the loss tangents

$$\tan\delta\ (OC) = R(OC)/X(OC) \qquad (36)$$

$$\tan\delta\ (SC) = R(SC)/X(SC) \qquad (37)$$

Combining Eqs. (5) and (36), one obtains

$$K'' = (\tan\delta\ (OC))\ K' \qquad (38)$$

and combining Eqs. (10) and (37), the result is

$$K_m'' = (\tan\delta\ (SC))\ K_m' \qquad (39)$$

To summarize

$$K' = B\cdot(1/2\,\pi)\ \ln\ (D/d)/(w\cdot Z_o\cdot E_v) \qquad (40)$$

$$K_m' = (B\cdot Z_o)/(w\cdot\mu_v\cdot(1/2\,\pi)\ \ln\ (D/d)) \qquad (41)$$

$$K'' = (\tan\delta\ (OC))\ K' \qquad (42)$$

$$K_m'' = (\tan\delta\ (SC))\ K_m' \qquad (43)$$

A problem arises in the calculations for the nonmagnetic (silicone rubber) sample. A value of K_m' is one for such a material.

---

[4] American Institute of Physics Handbook, 2nd Edition, (McGraw Hill, New York) 5-48.

An estimate of the error of K_m' can be made using the theory of errors[5] if the errors in the initial readings are known. The Hewlett Packard Vector Impedance Meter Model #4815A has reading errors of

$$\text{error in } Z = \pm\ 4\% \pm (F\ \text{MHz}/30\ \text{MHz} + Z\ \Omega/25\ \text{k}\ \Omega)\ \text{in}\ \%$$

$$\text{error in } \theta = \pm\ (3 + F\ \text{MHz}/30\ \text{MHz} + Z\ \Omega/25\ \text{k}\ \Omega)\ \text{in degrees}$$

$$\text{error in } F = \pm\ 2\%\ \text{of full scale}$$

For the particular case of 30% Indiana General Q-1 Ferrite at 30 MHz, one finds that K_m' has an error of ± 11%. One can safely assume that all the values given in the charts have an error of ± 11%, due solely to the errors in the raw data. Other errors exist and ± 20% has been estimated as the total error.

d. PROBLEMS AND SUGGESTED IMPROVEMENTS

The origin of $K_m' = 2$ for the unloaded sample is obscure, but is probably related to the skin effect and the relatively low conductivity of the brass outer conductor. One way to check this is to coat the outer and inner conductors with ≅0.003 inches of silver, which is about 3 times the skin depth of silver at 10 MHz, and repeat the experiments.

e. RAW EXPERIMENTAL MEASUREMENTS AND CALCULATED QUANTITIES

The quantities ZO, K_m', K', K_m'', K'', tan δ (OC), tan δ (SC) were calculated from Eqs. (40-43) without any corrections being made.

The experimental results have been collected and may be found in Tables 1-28. All the data reflect the presence of dimensional resonance, explained by Brockman et al.[6] The velocity of an electromagnetic wave propagating in the magnetic composite is reduced by a factor of $1/\sqrt{K_m' K'}$ compared with vacuum, where $\underline{K_m'}$ and $\underline{K'}$ are the relative permeability and dielectric constants in the material. The wavelength in the material becomes $\lambda = c/f\sqrt{K_m' K'}$. When the length of the coaxial sample becomes $\lambda/4$ resonance will occur. Typically, the short circuit reactance X(SC) rises exponentially toward infinity at resonance (Tables 2,6,10,14,18,22,26).

For a practical device a constant value for the characteristic impedance as a function of frequency is required. From the data of Tables 8, 16,24,28, this condition is seen to hold sufficiently well over useful ranges of frequency. Actually, the frequency range is probably greater than indicated since dimensional resonance would occur at much higher frequencies for small toroidal geometries.

The tan δ (SC) values are characteristically of the order of 10^{-1} well below resonance (Tables 8,12,16,20,24). However, none of the materials investigated are considered low-loss materials and this result is consistent with expectation.

---

5. Y. Beers, Theory of Error, (Addison-Wesley Publishing Co., Inc., Reading, Mass., 1953), 33-35.
6. F.G. Brockman, P.H. Dowling and W.G. Stenek, Phys. Rev. 77, 85 (1950).

TABLE 1. COMPLEX IMPEDANCE FOR

100% GENERAL ELECTRIC SILICONE RUBBER

D1= 7.31X10^{-3} (METER) = Inner diameter of the brass outer conductor

D2= 2.57X10^{-3} (METER) = Outer diameter of the copper inner conductor

L1= 0.197 (METER) = Length of the sample

F1 (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
0.5	7100	-90	0.8	34
0.7	5050	-90	0.83	41
1	3500	-90	0.9	50
5	700	-90	3.03	79
10	342.5	-90	6.0	84.5
20	168	-90	11.75	88
30	106	-90	18.2	89.25
40	77.0	-90	25.0	90
50	56.0	-89.5	31.75	90
60	41.75	-88.5	40.75	90
70	30.9	-88.0	51.0	90
80	21.7	-86.5	64.5	90
90	13.6	-85.5	82.0	90
100	6.8	-79.5	103	90

TABLE 2. RESISTANCE AND REACTANCE FOR

100% GENERAL ELECTRIC SILICONE RUBBER

F1 (MHz)	R(OC) (OHMS)	R(SC) (OHMS)	X(OC) (OHMS)	X(SC) (OHMS)
0.5	0.00	0.663	-7100	0.447
0.7	0.00	0.623	-5050	0.541
1	0.00	0.578	-3500	0.689
5	0.00	0.577	-700	2.97
10	0.00	0.575	-342.5	5.97
20	0.00	0.410	-168	11.7
30	0.00	0.238	-106	18.2
40	0.00	0.00	-77	25
50	0.489	0.00	-56.0	31.75
60	1.09	0.00	-41.7	40.75
70	1.08	0.00	-30.8	51
80	1.32	0.00	-21.7	64.5
90	1.07	0.00	-13.5	82
100	1.24	0.00	-6.69	103

TABLE 3. COMPLEX RELATIVE PERMITTIVITY CONSTANT AND MAGNETIC PERMEABILITY

100% GENERAL ELECTRIC SILICONE RUBBER

Fl (MHz)	κ_m' (#)	κ' (#)	κ_m'' (#)	κ'' (#)
0.5	3.46	4.28	5.12	0.00
0.7	2.99	4.30	3.44	0.00
1	2.66	4.35	2.23	0.00
5	2.29	4.34	0.445	0.00
10	2.29	4.42	0.220	0.00
20	2.22	4.43	$7.74\text{X}10^{-2}$	0.00
30	2.22	4.53	0.029	0.00
40	2.19	4.49	0.00	0.00
50	2.10	4.66	0.00	0.040
60	2.07	4.79	0.00	0.125
70	1.99	4.98	0.00	0.174
80	1.88	5.32	0.00	0.325
90	1.70	6.00	0.00	0.472
100	1.34	7.66	0.00	1.42

TABLE 4, CHARACTERISTIC IMPEDANCE AND tan δ FOR 100% GENERAL ELECTRIC SILICONE RUBBER

FI (MHz)	BI (RADIANS/M)	ZO (OHMS)	tan δ(OC) (#)	tan δ(SC) (#)
0.5	4.03×10^{-2}	56.4	0	1.48
0.7	5.26×10^{-2}	52.2	0	1.15
1	7.13×10^{-2}	49.1	0	0.839
5	0.330	45.6	0	0.194
10	0.667	45.2	0	9.63×10^{-2}
20	1.31	44.4	0	3.49×10^{-2}
30	2.00	43.9	0	1.31×10^{-2}
40	2.63	43.9	0	0
50	3.28	42.1	8.73×10^{-3}	0
60	3.96	41.2	2.62×10^{-2}	0
70	4.62	39.6	3.49×10^{-2}	0
80	5.31	37.3	6.12×10^{-2}	0
90	6.02	33.3	7.87×10^{-2}	0
100	6.71	26.2	0.185	0

TABLE 5, COMPLEX IMPEDANCE FOR

INDIANA GENERAL Q1 FERRITE 30% BY VOLUME

D1= 7.41×10^{-3} (METER) = Inner diameter of the brass outer conductor

D2= 2.56×10^{-3} (METER) = Outer diameter of the copper inner conductor

L1= 0.204 (METER) = Length of the sample

F1 (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
0.5	4600	-90	0.95	56
0.7	3250	-90	1.2	63.5
1	2330	-90	1.65	69.75
5	458	-90	8.05	84
10	228	-90	16.1	86
20	104	-90	34.75	86.5
30	62.0	-90	61.25	86
40	36.75	-89	105	83
50	19.4	-84	227	73
59.3	6.5	-56.5	672.5	0
60	5.75	-50	650	-12.25
63.1	4.13	0	432.5	-46.5
70	11.3	63	195	-69.5
80	27.1	74	100	-76
90	46.75	74	61.0	-76.5
100	75.25	70.75	38.25	-72

TABLE 6. RESISTANCE AND REACTANCE VALUES FOR INDIANA GENERAL Q1 FERRITE 30% BY VOLUME

F1 (MHz)	R(OC) (OHMS)	R(SC) (OHMS)	X(OC) (OHMS)	X(SC) (OHMS)
0.5	0.00	0.531	-4600	0.787
0.7	0.00	0.535	-3250	1.07
1	0.00	0.571	-2330	1.55
5	0.00	0.841	-458	8.00
10	0.00	1.12	-228	16.1
20	0.00	2.12	-104	34.7
30	0.00	4.27	-62	61.1
40	0.641	12.8	-36.7	104
50	2.03	66.4	-19.3	217
59.3	3.59	672.5	-5.42	0.00
60	3.70	635	-4.40	-138
63.1	4.13	298	0.00	-314
70	5.13	68.3	10.1	-183
80	7.47	24.2	26.1	-97.0
90	12.9	14.2	44.9	-59.3
100	24.8	11.8	71.0	-36.4

TABLE 7. COMPLEX RELATIVE PERMITTIVITY AND PERMEABILITY

INDIANA GENERAL 01 FERRITE 30% BY VOLUME

FI (MHz)	K'_m (#)	K' (#)	K''_m (#)	K'' (#)
0.5	5.78	6.48	3.90	0
0.7	5.63	6.55	2.81	0
1	5.68	6.39	2.10	0
5	5.84	6.47	0.614	0
10	5.76	6.39	0.403	0
20	5.77	6.50	0.353	0
30	5.89	6.31	0.412	0
40	5.88	6.23	0.722	0.109
50	6.09	5.90	1.86	0.620
59.3	0.00	--	--	--
60	2.10	14.0	9.68	11.8
63.1	--	∞	--	∞
70	3.01	6.65	1.13	3.39
80	2.52	4.05	0.629	1.16
90	1.80	2.74	0.432	0.786
100	1.16	1.82	0.377	0.636

TABLE 8, THE PHASE CONSTANT, CHARACTERISTIC IMPEDANCE AND tan δ FOR INDIANA GENERAL Q1 FERRITE 30% BY VOLUME

F1 (MHz)	B1 (RADIANS/M)	Z0 (OHMS)	tan δ(OC) (#)	tan δ(SC) (#)
0.5	6.41×10^{-2}	60.2	0.00	0.675
0.7	8.91×10^{-2}	59.1	0.00	0.499
1	0.126	60.1	0.00	0.369
5	0.644	60.6	0.00	0.105
10	1.27	60.5	0.00	6.99×10^{-2}
20	2.57	60.1	0.00	6.12×10^{-2}
30	3.83	61.5	0.00	6.99×10^{-2}
40	5.07	61.9	1.75×10^{-2}	0.123
50	6.28	64.7	0.105	0.306
59.3	0.00	0.00	0.662	∞
60	6.83	24.6	0.839	4.61
63.1	∞	0.00	∞	0.949
70	6.57	42.9	0.510	0.374
80	5.36	50.3	0.287	0.249
90	4.19	51.6	0.287	0.240
100	3.04	50.8	0.349	0.325

TABLE 9. COMPLEX IMPEDANCE FOR GAF CORP. CARBONYL IRON 25% BY VOLUME

D1 = 7.36×10^{-3} (METER) = Inner diameter of the brass outer conductor

D2 = 2.59×10^{-3} (METER)= Outer diameter of the copper inner conductor

L1 = 0.202 (METER) = Length of the sample

F1 (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
0.5	1690	-84	0.8	46
0.6	1440	-84	0.9	50
0.7	1250	-84	1.0	54
0.8	1100	-84.5	1.1	57
0.9	1010	-85	1.2	60
1	910	-85	1.3	62
2	480	-86	2.4	74
3	320	-86	3.6	78
4	250	-86.5	4.8	81
5	202	-86.5	6.0	82.5
6	168	-87	7.2	83.5
7	145	-86.5	8.4	84
8	127	-86.5	9.6	84.5
9	112	-86.5	10.5	85
10	100	-86.5	11.8	85.5
20	46.0	-85.5	25.0	87
30	22.8	-81	45.0	87
40	8.3	-61	83.0	84.5
45.6	4.25	0.00	129	78.5
50	6.9	50	210	69.5
56	13.2	70	455	0.00

Table 9 Contd

GAF CORP. CARBONYL IRON 25% BY VOLUME

FI (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
60	18.0	74.5	247	-50.5
70	31.7	79	76.0	-69.5
80	44.7	79	34.8	-66
90	77.5	74	15.6	-48
97.75	111	64.5	9.5	0.00
100	127	59.5	9.8	18.5

TABLE 10. RESISTANCE AND REACTANCE FOR GAF CORP. CARBONYL IRON 25% BY VOLUME

FI (MHz)	R(OC) (OHMS)	R(SC) (OHMS)	X(OC) (OHMS)	X(SC) (OHMS)
0.5	176	0.556	-1680	0.575
0.6	150	0.578	-1432	0.689
0.7	130	0.588	-1243	0.809
0.8	105	0.599	-1094	0.922
0.9	88.0	0.600	-1006	1.04
1	79.3	0.610	-906	1.15
2	33.5	0.662	-479	2.31
3	22.3	0.748	-319	3.52
4	15.3	0.751	-250	4.74
5	12.3	0.783	-202	5.95
6	8.79	0.815	-168	7.15
7	8.85	0.878	-145	8.35
8	7.75	0.920	-127	9.56
9	6.84	0.915	-112	10.5
10	6.10	0.926	-99.8	11.8
20	3.61	1.31	-45.8	25.0
30	3.57	2.36	-22.5	44.9
40	4.02	7.96	-7.26	82.6
45.6	4.25	25.7	0.00	126
50	4.44	73.5	5.28	197
56	4.51	455	12.4	0.00
60	4.81	157	17.3	-190
70	6.05	26.6	31.1	-71.2
80	8.53	14.2	43.9	-31.8
90	21.4	10.4	74.5	-11.6
97.75	47.8	9.50	100	0.00
100	64.4	9.30	109	3.11

TABLE 11. COMPLEX RELATIVE PERMITTIVITY AND PERMEABILITY FOR GAF CORP. CARBONYL IRON 25% BY VOLUME

Fl (MHz)	K_m' (#)	K' (#)	K_m'' (#)	K'' (#)
0.5	4.35	17.6	4.20	1.85
0.6	4.34	17.2	3.64	1.81
0.7	4.36	17.0	3.17	1.79
0.8	4.35	16.9	2.83	1.63
0.9	4.36	16.4	2.52	1.43
1	4.33	16.2	2.30	1.43
2	4.35	15.5	1.25	1.08
3	4.42	15.4	0.939	1.08
4	4.45	14.8	0.704	0.903
5	4.45	14.6	0.586	0.891
6	4.44	14.5	0.506	0.761
7	4.42	14.4	0.465	0.879
8	4.40	14.3	0.424	0.873
9	4.26	14.3	0.373	0.875
10	4.28	14.3	0.337	0.875
20	4.06	13.9	0.213	1.10
30	3.82	14.8	0.200	2.35
40	2.97	19.4	0.286	10.8
45.6	--	∞	--	∞
50	3.43	13.0	1.28	10.9
56	0.00	--	--	--
60	4.62	5.49	3.81	1.52
70	2.51	4.44	0.937	0.863
80	1.24	3.50	0.554	0.680
90	0.463	2.11	0.417	0.604
97.75	0.00	--	--	--
100	0.116	1.34	0.348	0.791

TABLE 12. THE PHASE CONSTANT, CHARACTERISTIC IMPEDANCE AND tan δ FOR GAF CARBONYL IRON 25% BY VOLUME

FI (MHz)	BI (RADIANS/M)	ZO (OHMS)	tan δ(OC) (#)	tan δ(SC) (#)
0.5	9.18×10^{-2}	31.1	0.105	0.966
0.6	0.109	31.4	0.105	0.839
0.7	0.127	31.7	0.105	0.727
0.8	0.144	31.8	9.63×10^{-2}	0.649
0.9	0.159	32.3	8.75×10^{-2}	0.577
1	0.175	32.4	8.75×10^{-2}	0.532
2	0.344	33.2	6.99×10^{-2}	0.287
3	0.519	33.5	6.99×10^{-2}	0.213
4	0.679	34.4	6.12×10^{-2}	0.158
5	0.844	34.6	6.12×10^{-2}	0.132
6	1.01	34.6	5.24×10^{-2}	0.114
7	1.17	34.8	6.12×10^{-2}	0.105
8	1.33	34.8	6.12×10^{-2}	9.63×10^{-2}
9	1.47	34.2	6.12×10^{-2}	8.75×10^{-2}
10	1.64	34.3	6.12×10^{-2}	7.87×10^{-2}
20	3.15	33.8	7.87×10^{-2}	5.24×10^{-2}
30	4.74	31.8	0.158	5.24×10^{-2}
40	6.36	24.5	0.554	9.63×10^{-2}
45.6	∞	0.0	∞	0.203
50	6.99	32.2	0.839	0.374
56	0.00	0.0	0.364	∞

TABLE 12, THE PHASE CONSTANT, CHARACTERISTIC IMPEDANCE AND tan δ FOR GAF CARBONYL IRON 25% BY VOLUME (Contd)

F1 (MHz)	B1 (RADIANS/M)	Z0 (OHMS)	tan δ(OC) (#)	tan δ(SC) (#)
60	6.34	57.5	0.277	0.824
70	4.89	47.1	0.194	0.374
80	3.50	37.3	0.194	0.445
90	1.86	29.4	0.287	0.900
97.75	0.00	0.0	0.477	∞
100	0.828	18.4	0.589	2.99

TABLE 13. COMPLEX IMPEDANCE FOR
GAF CORP. CARBONYL IRON 30% BY VOLUME

D1= 0.00739 (METER) = Inner diameter of the brass outer conductor

D2= 2.60×10^{-3} (METER) = Outer diameter of the copper inner conductor

L1= 0.200 (METER) = Length of the sample

F1 (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
0.5	1290	-80.5	0.975	45
0.6	1100	-81	1.05	50.5
0.7	990	-82	1.15	54.5
0.8	880	-82	1.275	58
0.9	800	-82.5	1.4	60
1	730	-83	1.5	62.5
2	387.5	-84	2.825	74
3	270	-85	4.2	78.5
4	206	-86	5.6	81
5	166	-86	7.025	82
6	138	-86	8.425	83

TABLE 13. COMPLEX IMPEDANCE FOR GAF CORP. CARBONYL IRON 30% BY VOLUME (Cont'd)

F1 (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
7	118	-86	9.825	84
8	103	-86	11.0	84.25
9	94.0	-86	12.5	85
10	84.0	-86	14.0	85
20	34.5	-84	31.25	86
30	13.8	-74	62.25	85
38.7	4.3	0	137	77.5
40	4.75	24	163	74
46.4	--	--	1400	0
50	16.3	72	230	-52.5
60	31.5	77.5	62.0	-70.5
70	54.0	76	25.1	-63
80	97.0	66	9.9	-15
81.75	--	--	9.45	0
90	171	23	15.7	53.75
93.2	165	0	19.25	60
100	101	-32.5	28.8	69

TABLE 14. RESISTANCE AND REACTANCE FOR GAF CORP. CARBONYL IRON 30% BY VOLUME

Fl (MHz)	R(OC) (OHMS)	R(SC) (OHMS)	X(OC) (OHMS)	X(SC) (OHMS)
0.5	212	0.690	-1270	0.689
0.6	172	0.668	-1090	0.810
0.7	137	0.668	-980	0.936
0.8	122	0.676	-871	1.08
0.9	104	0.700	-793	1.21
1	89.0	0.692	-724	1.33
2	40.5	0.779	-385	2.72
3	23.5	0.837	-268	4.12
4	14.4	0.876	-205	5.53
5	11.6	0.978	-165	6.96
6	9.63	1.03	-137	8.36
7	8.23	1.03	-117	9.77
8	7.18	1.10	-102	10.9
9	6.56	1.09	-93.8	12.4
10	5.86	1.22	-83.8	13.9
20	3.61	2.18	-34.3	31.2
30	3.80	5.42	-13.3	62.0
38.7	4.30	29.6	0.00	133
40	4.34	44.9	1.93	157
46.4	--	1400	--	0.00
50	5.04	140	15.5	-182
60	6.82	20.7	30.8	-58.4
70	13.1	11.4	52.4	-22.4
80	39.5	9.56	88.6	-2.56
81.75	--	9.45	--	0.00
90	157	9.28	66.8	12.7
93.2	165	9.62	0.00	16.7
100	85.2	10.3	-54.3	26.9

TABLE 15. COMPLEX RELATIVE PERMITTIVITY AND PERMEABILITY FOR GAF CORP. CARBONYL IRON 30% BY VOLUME

Fl (MHz)	K'_m (#)	K' (#)	K''_m (#)	K'' (#)
0.5	5.24	23.5	5.24	3.94
0.6	5.13	23.0	4.23	3.64
0.7	5.08	21.8	3.63	3.06
0.8	5.14	21.5	3.21	3.02
0.9	5.12	21.0	2.96	2.76
1	5.06	20.6	2.63	2.53
2	5.15	19.4	1.48	2.04
3	5.19	18.5	1.06	1.61
4	5.21	18.0	0.825	1.26
5	5.22	17.8	0.733	1.25
6	5.20	17.8	0.638	1.24
7	5.17	17.7	0.543	1.24
8	5.03	17.6	0.506	1.23
9	5.04	17.0	0.441	1.19
10	5.03	17.0	0.440	1.19
20	4.73	17.4	0.331	1.83
30	4.14	19.8	0.362	5.67
38.7	--	∞	--	∞
40	2.41	31.4	0.692	70.5
46.4	0.00	--	--	--
50	5.21	7.24	3.99	2.35
60	2.53	5.55	0.897	1.23
70	1.08	3.61	0.548	0.901
80	0.121	2.09	0.450	0.931
81.75	0.00	--	--	--
90	0.504	2.35	0.370	5.53
93.2	--	∞	--	∞
100	0.891	2.40	0.342	3.77

TABLE 16. PHASE CONSTANT, CHARACTERISTIC IMPEDANCE AND tan δ FOR GAF CORP. CARBONYL IRON 30% BY VOLUME

FI (MHz)	BI (RADIANS/M)	ZO (OHMS)	tan δ(OC) (#)	tan δ(SC) (#)
0.5	0.116	29.6	0.167	1.00
0.6	0.136	29.7	0.158	0.824
0.7	0.154	30.3	0.141	0.713
0.8	0.176	30.7	0.141	0.625
0.9	0.195	31.0	0.132	0.577
1	0.214	31.0	0.123	0.521
2	0.419	32.3	0.105	0.287
3	0.615	33.3	8.75×10^{-2}	0.203
4	0.813	33.7	6.99×10^{-2}	0.158
5	1.01	33.9	6.99×10^{-2}	0.141
6	1.21	33.9	6.99×10^{-2}	0.123
7	1.40	33.9	6.99×10^{-2}	0.105
8	1.58	33.5	6.99×10^{-2}	0.101
9	1.75	34.2	6.99×10^{-2}	8.75×10^{-2}
10	1.94	34.2	6.99×10^{-2}	8.75×10^{-2}
20	3.81	32.7	0.105	6.99×10^{-2}
30	5.69	28.7	0.287	8.75×10^{-2}
38.7	∞	0.00	∞	0.222
40	7.30	17.4	2.25	0.287
46.4	--	--	∞	--
50	6.44	53.2	0.325	0.767
60	4.72	42.4	0.222	0.354
70	2.89	34.2	0.249	0.510
80	0.842	15.1	0.445	3.73
81.75	--	--	--	∞
90	2.05	29.1	2.36	0.733
93.2	∞	0.00	∞	0.577
100	3.07	38.2	1.57	0.384

TABLE 17. COMPLEX IMPEDANCE FOR FERROXCUBE CORP. RD3 FERRITE 30% BY VOLUME

D1= 8.05×10^{-3} (METER) = Inner diameter of the brass outer conductor

D2= 0.00259 (METER) = Outer diameter of the copper inner conductor

L1= 0.198 (METER) = Length of the sample

F1 (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
0.5	2100	-86.5	1.0	57.5
0.7	1530	-87.0	1.275	64.0
1	1090	-87.5	1.775	70.5
5	238	-89.0	8.6	84.0
10	117	-88.5	17.4	85.5
20	51.5	-87.0	39.0	85.5
30	24.0	-82.0	77.5	82.0
40	7.15	-48.0	196	68.0
43.2	5.3	0.0	317	49.5
46.7	7.6	45.5	435	0.0
50	12.2	60.0	290	-44.0
60	29.4	72.5	89.5	-69.5
70	52.5	72.0	41.5	-68.0
80	92.5	63.0	19.5	-51.5
88.8	153	39.75	11.6	0.0
90	160	32.0	11.8	9.0
95.5	167.5	0.0	15.6	40.0
100	138	-21.5	21.4	53.0

TABLE 18. RESISTANCE AND REACTANCE FOR FERROXCUBE CORP. RD3 FERRITE 30% BY VOLUME

F1 (MHz)	R(OC) (OHMS)	R(SC) (OHMS)	X(OC) (OHMS)	X(SC) (OHMS)
0.5	128	0.537	-2100	0.843
0.7	80.1	0.559	-1530	1.14
1	47.5	0.592	-1090	1.67
5	4.15	0.899	-238	8.55
10	3.06	1.36	-117	17.3
20	2.70	3.06	-51.4	38.9
30	3.34	10.8	-23.8	76.7
40	4.78	73.4	-5.31	182
43.2	5.30	206	0.00	241
46.7	5.33	435	5.42	0.00
50	6.10	209	10.6	-201
60	8.84	31.3	28.0	-83.8
70	16.2	15.5	49.9	-38.5
80	42.0	12.1	82.4	-15.3
88.8	118	11.6	97.8	0.00
90	136	11.7	84.8	1.84
95.5	167.5	12.0	0.00	10.0
100	128	12.9	-50.6	17.1

TABLE 19. COMPLEX PERMITTIVITY AND PERMEABILITY FOR FERROXCUBE CORP. RD3 FERRITE 30% BY VOLUME

FI (MHz)	K_m' (#)	K' (#)	K_m'' (#)	K'' (#)
0.5	5.97	15.6	3.80	0.954
0.7	5.79	15.3	2.82	0.801
1	5.92	15.0	2.09	0.655
5	5.98	13.6	0.629	0.237
10	5.86	13.3	0.461	0.349
20	5.66	13.1	0.446	0.685
30	5.35	13.6	0.752	1.91
40	3.85	18.4	1.56	16.6
43.2	--	∞	--	∞
46.7	0.00	--	--	--
50	4.39	9.53	4.55	5.50
60	2.99	5.88	1.12	1.85
70	1.60	3.84	0.645	1.25
80	0.637	2.34	0.507	1.19
88.8	0.00	--	--	--
90	7.20×10^{-2}	2.13	0.455	3.40
95.5	--	∞	--	∞
100	0.548	2.93	0.413	7.43

TABLE 20. PHASE CONSTANT, CHARACTERISTIC IMPEDANCE, AND tan δ FOR FERROXCUBE CORP. RD3 FERRITE 30% BY VOLUME

F1 (MHz)	B1 (RADIANS/M)	ZO (OHMS)	tan δ(OC) (#)	tan δ(SC) (#)
0.5	0.101	42.0	6.12×10^{-2}	0.637
0.7	0.138	41.8	5.24×10^{-2}	0.488
1	0.197	42.7	4.37×10^{-2}	0.354
5	0.944	45.1	1.75×10^{-2}	0.105
10	1.85	45.0	2.62×10^{-2}	7.87×10^{-2}
20	3.61	44.7	5.24×10^{-2}	7.87×10^{-2}
30	5.36	42.7	0.141	0.141
40	7.06	31.1	0.900	0.404
43.2	∞	0.00	∞	0.854
46.7	0.00	0.00	0.983	∞
50	6.78	46.1	0.577	1.04
60	5.27	48.5	0.315	0.374
70	3.63	43.8	0.325	0.404
80	2.05	35.5	0.510	0.795
88.8	0.00	0.00	1.20	∞
90	0.738	12.5	1.60	6.31
95.5	∞	0.00	∞	1.19
100	2.65	29.5	2.54	0.754

TABLE 21. COMPLEX IMPEDANCE FOR
INDIANA GENERAL Q1 FERRITE 50% BY VOLUME

D1= 0.00812 (METER) = Inner diameter of the brass outer conductor

D2= 2.57×10^{-3} (METER) = Outer diameter of the copper inner conductor

L1= 0.198 (METER) = Length of the sample

F1 (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
0.5	2270	-77.5	1.375	55.75
0.7	1720	-78.0	1.775	63.75
1	1270	-79.5	2.425	70.0
5	313	-83.25	11.5	84.0
10	162	-84.0	24.3	86.0
20	76.25	-83.5	57.25	85.0
30	39.75	-78.25	121	80.0
40	18.2	-59.0	377.5	50.0
43.75	12.8	-37.75	535	0.0
47.7	11.1	0.0	342.5	-44.0
50	12.8	21.0	261	-55.5
60	31.6	55.75	108	-69.5
70	62.25	58.0	62.5	-69.0
80	112	45.25	37.25	-60.5
90	168	6.25	23.4	-38.5
91.25	168	0.0	22.4	-34.25
99.2	134	-30.0	20.7	0.0
100	128	-31.75	21.0	3.75

TABLE 22. RESISTANCE AND REACTANCE FOR INDIANA GENERAL Q1 FERRITE 50% BY VOLUME

Fl (MHz)	R(OC) (OHMS)	R(SC) (OHMS)	X(OC) (OHMS)	X(SC) (OHMS)
0.5	491	0.774	-2220	1.14
0.7	358	0.785	-1680	1.59
1	231	0.829	-1250	2.28
5	36.8	1.20	-311	11.4
10	16.9	1.70	-161	24.2
20	8.63	4.99	-75.8	57.0
30	8.09	21.0	-38.9	119
40	9.37	243	-15.6	289
43.75	10.1	535	-7.84	0.00
47.7	11.1	246	0.00	-238
50	11.9	148	4.59	-215
60	17.8	37.8	26.1	-101
70	33.0	22.4	52.8	-58.3
80	78.8	18.3	79.5	-32.4
90	167	18.3	18.3	-14.6
91.25	168	18.5	0.00	-12.6
99.2	116	20.7	-67.0	0.00
100	109	21.0	-67.4	1.37

TABLE 23. COMPLEX PERMITTIVITY AND PERMEABILITY FOR INDIANA GENERAL Q1 FERRITE 50% BY VOLUME

Fl (MHz)	K'_m (#)	K' (#)	K''_m (#)	K'' (#)
0.5	7.95	15.0	5.41	3.33
0.7	7.95	14.1	3.92	3.01
1	7.96	13.3	2.90	2.47
5	7.90	10.6	0.831	1.25
10	8.09	9.87	0.566	1.04
20	8.21	9.06	0.719	1.03
30	8.35	8.58	1.47	1.78
40	7.88	8.33	6.62	5.00
43.75	0.00	--	--	--
47.7	--	∞	--	∞
50	3.13	15.1	2.15	39.4
60	3.30	5.95	1.23	4.05
70	2.25	3.48	0.863	2.17
80	1.26	2.33	0.714	2.31
90	0.462	8.27	0.581	75.5
91.25	--	∞	--	∞
99.2	0.00	--	--	--
100	4.77×10^{-2}	2.46	0.728	3.97

TABLE 24. PHASE CONSTANT, CHARACTERISTIC IMPEDANCE AND tan δ FOR INDIANA GENERAL Q1 FERRITE 50% BY VOLUME

FI (MHz)	BI (RADIANS/M)	ZO (OHMS)	tan δ (OC) (#)	tan δ (SC) (#)
0.5	0.115	50.2	0.222	0.681
0.7	0.156	51.8	0.213	0.493
1	0.216	53.3	0.185	0.364
5	0.959	59.6	0.118	0.105
10	1.87	62.5	0.105	6.99×10^{-2}
20	3.62	65.7	0.114	8.75×10^{-2}
30	5.32	68.1	0.208	0.176
40	6.79	67.2	0.601	0.839
43.75	0.00	0.00	1.29	∞
47.7	∞	0.00	∞	1.04
50	7.21	31.4	2.61	0.687
60	5.57	51.4	0.681	0.374
70	4.10	55.5	0.625	0.384
80	2.87	50.8	0.991	0.566
90	3.69	16.3	9.13	1.26
91.25	∞	0.00	∞	1.47
99.2	0.00	0.00	1.73	∞
100	0.718	9.62	1.62	15.3

TABLE 25. COMPLEX IMPEDANCE FOR INDIANA GENERAL Q1 FERRITE 50% BY VOLUME

N.B. This is the same sample as the previous one except it is cut down to about 2 inches to allow resonance at higher frequency.

D1= 0.00813 (METER) = Inner diameter of the brass outer conductor

D2= 2.57X10^{-3} (METER) = Outer diameter of the copper inner conductor

L1= 8.02X10^{-2} (METER) = Length of the sample

F1 (MHz)	Z(OC) (OHMS)	θ(OC) (DEGREES)	Z(SC) (OHMS)	θ(SC) (DEGREES)
0.5	5425	-80.25	0.87	49.75
0.7	4000	-81.0	0.95	58.0
1	2940	-82.25	1.2	65.5
5	657.5	-85.25	5.5	85.0
10	332.5	-85.75	10.8	88.0
20	168	-86.0	22.9	88.5
30	107	-86.0	36.0	88.0
40	77.0	-84.5	53.25	87.0
50	55.75	-83.5	76.0	85.0
60	40.25	-81.0	109	82.0
70	28.9	-77.75	175	74.5
80	18.8	-69.5	320	53.0
88.5	11.9	-55.5	450	0.0
90	10.8	-50.0	425	-11.5
95	8.4	-28.25	315	-36.0
99.2	7.75	0.0	249	-47.5
100	7.8	4.0	237.5	-49.0

TABLE 26. RESISTANCE AND REACTANCE FOR INDIANA GENERAL Q1 FERRITE 50% BY VOLUME

F1 (MHz)	R(OC) (OHMS)	R(SC) (OHMS)	X(OC) (OHMS)	X(SC) (OHMS)
0.5	919	0.562	-5350	0.664
0.7	626	0.503	-3950	0.806
1	396	0.498	-2910	1.09
5	54.4	0.479	-655	5.48
10	24.6	0.377	-332	10.8
20	11.7	0.599	-168	22.9
30	7.46	1.26	-107	36.0
40	7.38	2.79	-76.6	53.1
50	6.31	6.62	-55.4	75.7
60	6.30	15.2	-39.8	108
70	6.13	46.8	-28.2	169
80	6.58	192	-17.6	256
88.5	6.74	450	-9.81	0.00
90	6.94	416	-8.27	-84.7
95	7.40	255	-3.98	-185
99.2	7.75	168	0.00	-184
100	7.78	156	0.544	-179

TABLE 27. COMPLEX RELATIVE PERMITTIVITY AND PERMEABILITY FOR INDIANA GENERAL Q1 FERRITE 50% BY VOLUME

Fl (MHz)	K_m' (#)	K' (#)	K_m'' (#)	K'' (#)
0.5	11.5	15.4	9.69	2.64
0.7	9.92	14.8	6.20	2.35
1	9.41	14.1	4.29	1.92
5	9.42	12.5	0.824	1.04
10	9.21	12.2	0.322	0.911
20	9.45	11.7	0.248	0.821
30	9.37	11.6	0.327	0.813
40	9.56	11.2	0.501	1.08
50	9.64	11.0	0.843	1.25
60	9.65	10.7	1.36	1.70
70	10.0	10.0	2.79	2.18
80	9.50	10.0	7.16	3.76
88.5	0.00	--	--	--
90	3.22	21.8	15.8	18.3
95	3.51	22.7	4.83	42.3
99.2	--	∞	--	∞
100	1.29	63.0	1.12	902

TABLE 28. THE PHASE CONSTANT, CHARACTERISTIC IMPEDANCE AND tan δ FOR INDIANA GENERAL Q1 FERRITE 50% BY VOLUME

FI (MHz)	BI (RADIANS/M)	ZO (OHMS)	tan δ (OC) (#)	tan δ (SC) (#)
0.5	0.139	59.6	0.172	0.847
0.7	0.178	56.4	0.158	0.625
1	0.241	56.4	0.136	0.456
5	1.14	59.9	8.31×10^{-2}	8.75×10^{-2}
10	2.23	59.8	7.43×10^{-2}	3.49×10^{-2}
20	4.42	61.9	6.99×10^{-2}	2.62×10^{-2}
30	6.56	62.0	6.99×10^{-2}	3.49×10^{-2}
40	8.66	63.8	9.63×10^{-2}	5.24×10^{-2}
50	10.8	64.8	0.114	8.75×10^{-2}
60	12.8	65.5	0.158	0.141
70	14.7	69.0	0.217	0.277
80	16.4	67.1	0.374	0.754
88.5	0.00	0.00	0.687	∞
90	15.8	26.5	0.839	4.92
95	17.8	27.1	1.86	1.38
99.2	∞	0.00	∞	0.91
100	18.9	9.88	14.3	0.869

The most important parameters sought are the real and imaginary parts of the complex relative permeability. These are plotted as a function of the frequency in Figs. 7-13. With the exception of the unloaded silicone rubber, all samples exhibit a magnetic resonance corresponding to the dimensional resonance. For most of the compositions, the real K_m' and imaginary K_m'' parts of the permeability are fairly constant for the frequency range below the resonance peak. This is essential for use in a practical device. The fact that the resonance phenomenon is not an intrinsic property of the materials, but is related to the dimensions of the coaxial line sample, is borne out by the data of Figs. 12 and 13. The data in Fig. 12 is for an 8-inch coaxial line while that in Fig. 13 is for a 2-inch line each with the same volume % of Q1. Note that the resonance peak for the shorter sample occurs at almost twice the frequency for that of the longer sample. This suggests that the actual useful frequency range for these materials extends out in frequency much beyond the resonance point, that is, to a point where intrinsic magnetic resonances would occur. The intrinsic magnetic resonance will occur at much higher frequencies for composite materials than for dense bulk materials. The origin of this effect is discussed in Section 5.

4. COMPARATIVE SIGNAL INTENSITY OF A COMPOSITE TOROID

A toroid 7/8" I.D., 2-5/8" O.D., and 7/8" cross section was fabricated from carbonyl iron as described in Section 2. Several turns of multistranded insulated wire were wrapped around the coil and optimized for operating at 27.125 MHz. The Q was found to be 45. The inductor (toroid with windings) was mounted on the barrel of a simulated rifle and the impedance matched to a walkie-talkie tuned to 27.125 MHz. The signal strength was then measured with an FI meter plus whip for the rifle in different positions as indicated in Table 29. Comparative data is given for an air HEMAC mounted on an M-16 rifle (Table 30), and a dense ferrite rod of Q2 mounted on the gun (Table 31). These results, when compared with signal strengths obtained with an XMTR whip (bottom of Tables 30,31), indicate that the ferrite toroid is comparable to a whip, but has directional or anisotropic response not available with a whip.

5. INITIAL PERMEABILITY DEPENDENCE ON DILUTION

The experimental results indicate that the real part of the initial permeability for all the composites studied fall within a narrow range, 1 to 10, compared with the range found for bulk magnetic materials. Maxwell[7] studied dilution of one conductor in a matrix of a second, and Rayleigh[8] studied the static dielectric constant of one material in another. Both assume spherical particles and at high dilution the resulting additivity laws become identical.

According to Baldwin,[9] the relative susceptibility of magnetic particles is given as

$$\chi = M/\mu_o H_a = fM_1/M_o H_a = f\chi_1/(1 + pM_o N_g \chi_1) \tag{44}$$

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[7] J.C. Maxwell, Treatise on Electricity and Magnetism, 3rd Edition, (Oxford University Press, Oxford, England, 1904), 440.

[8] J. W. Rayleigh, Phil. Mag. 34, 481 (1892).

[9] J. A. Baldwin, Jr., J. Appl. Phys. 39, 217 (1968).

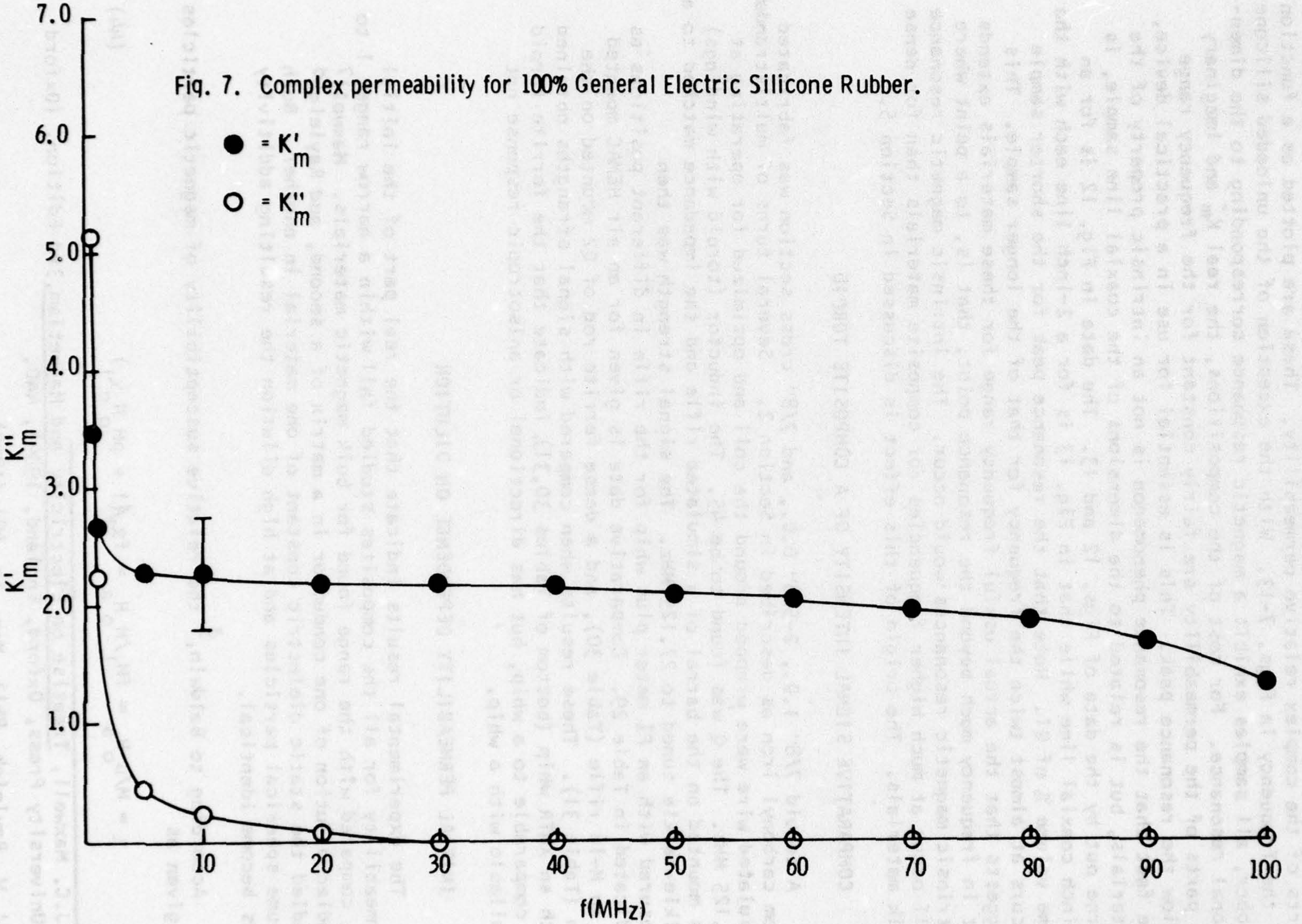

Fig. 7. Complex permeability for 100% General Electric Silicone Rubber.

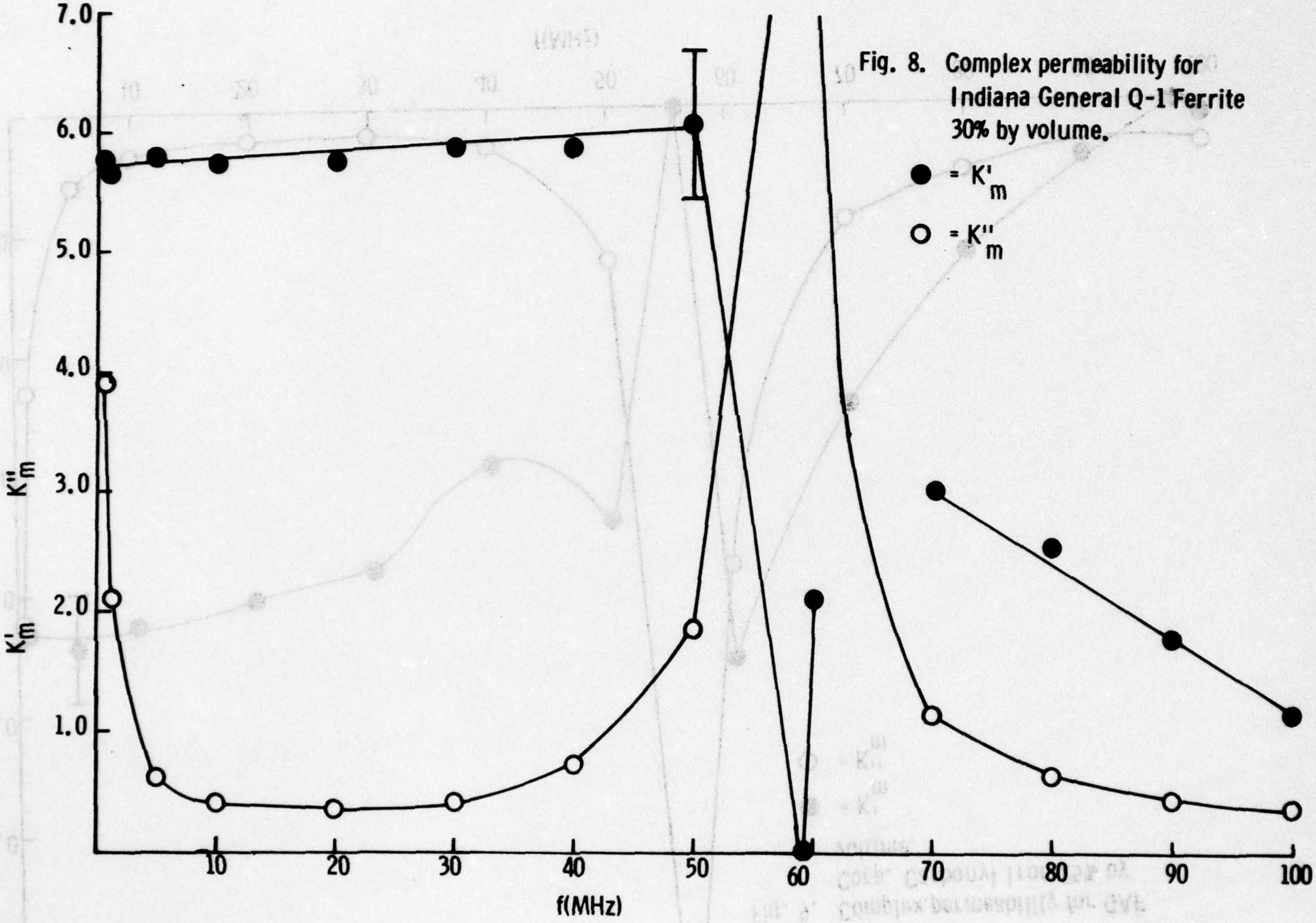

Fig. 8. Complex permeability for Indiana General Q-1 Ferrite 30% by volume.

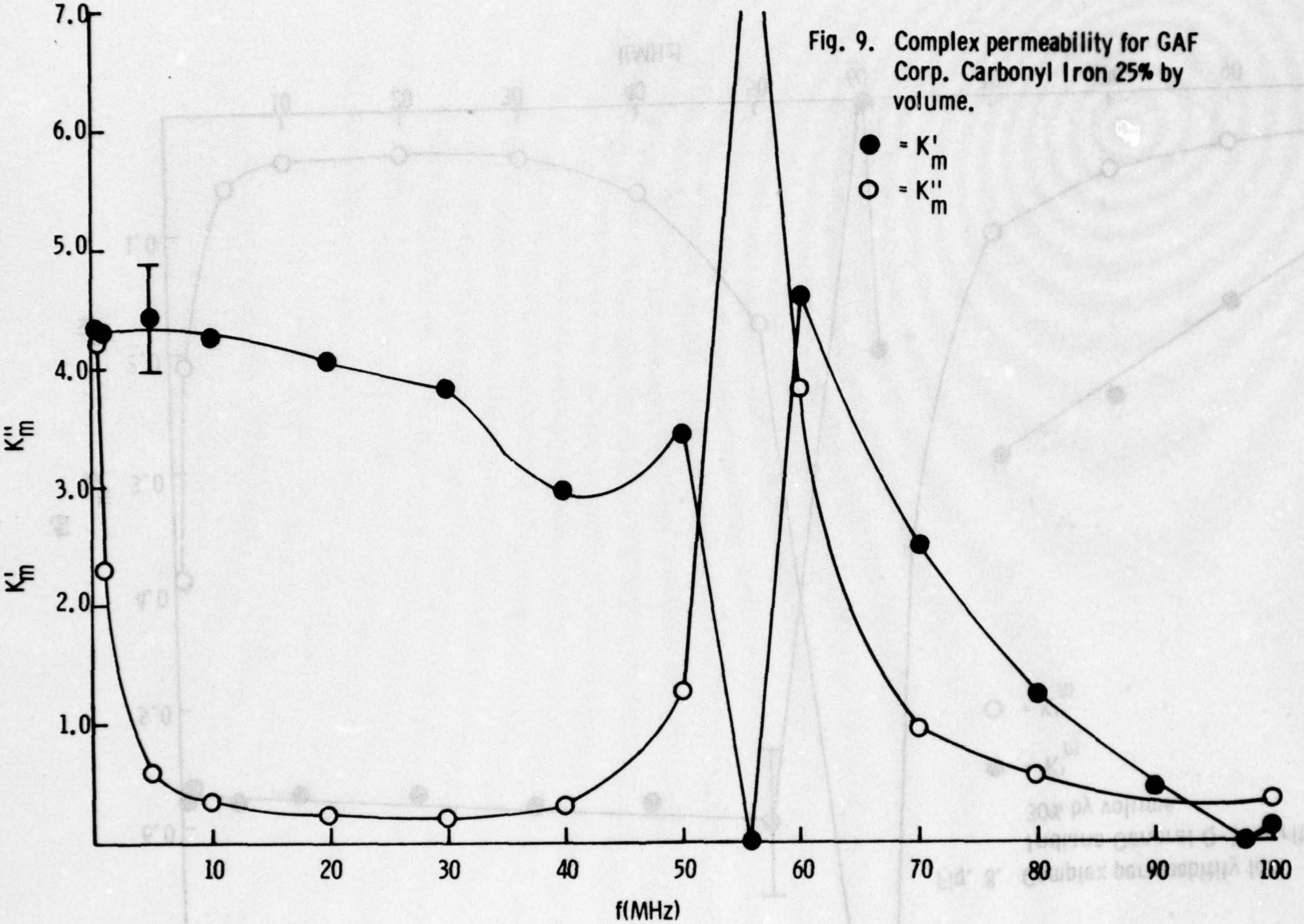

Fig. 9. Complex permeability for GAF Corp. Carbonyl Iron 25% by volume.

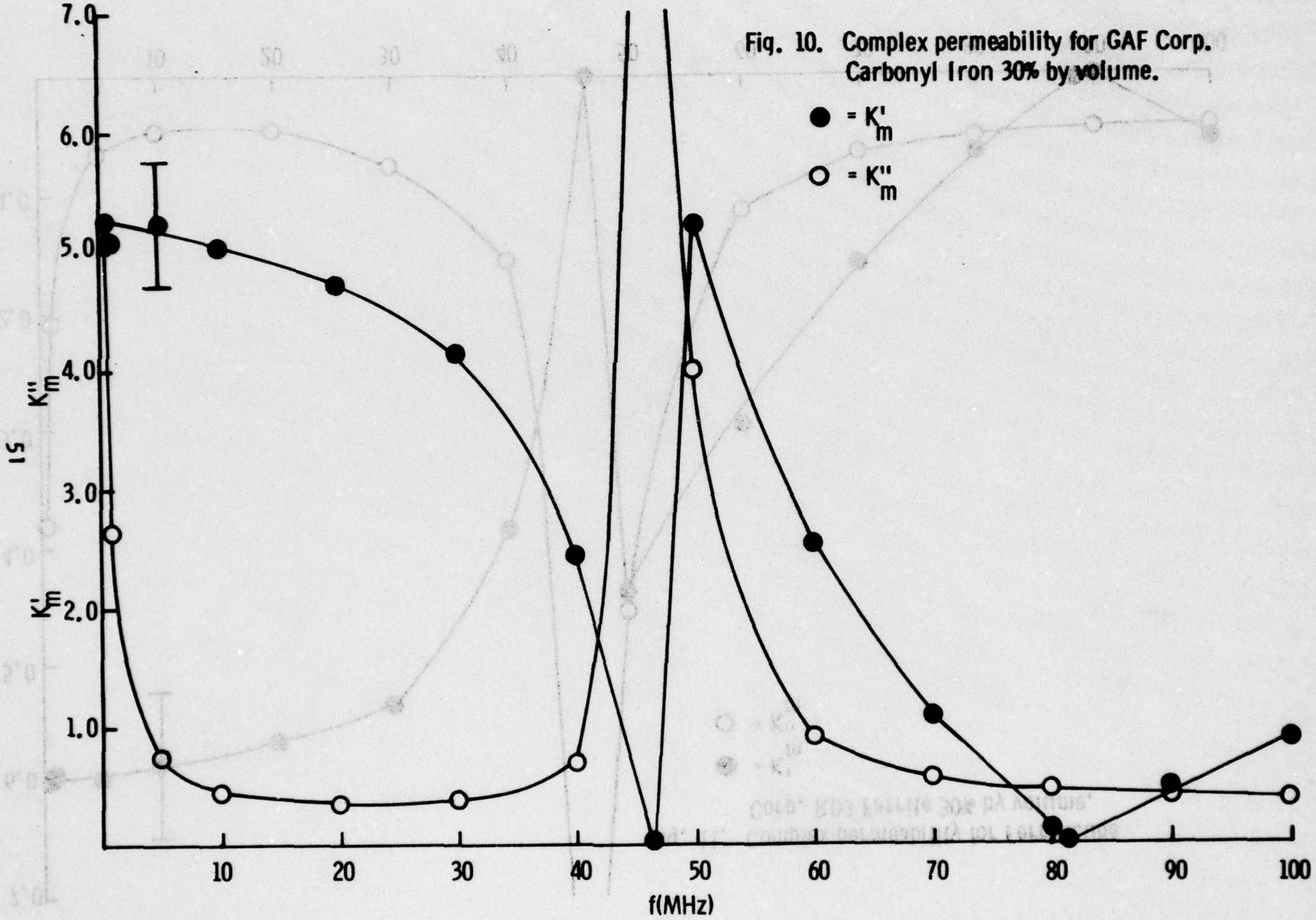

Fig. 10. Complex permeability for GAF Corp. Carbonyl Iron 30% by volume.

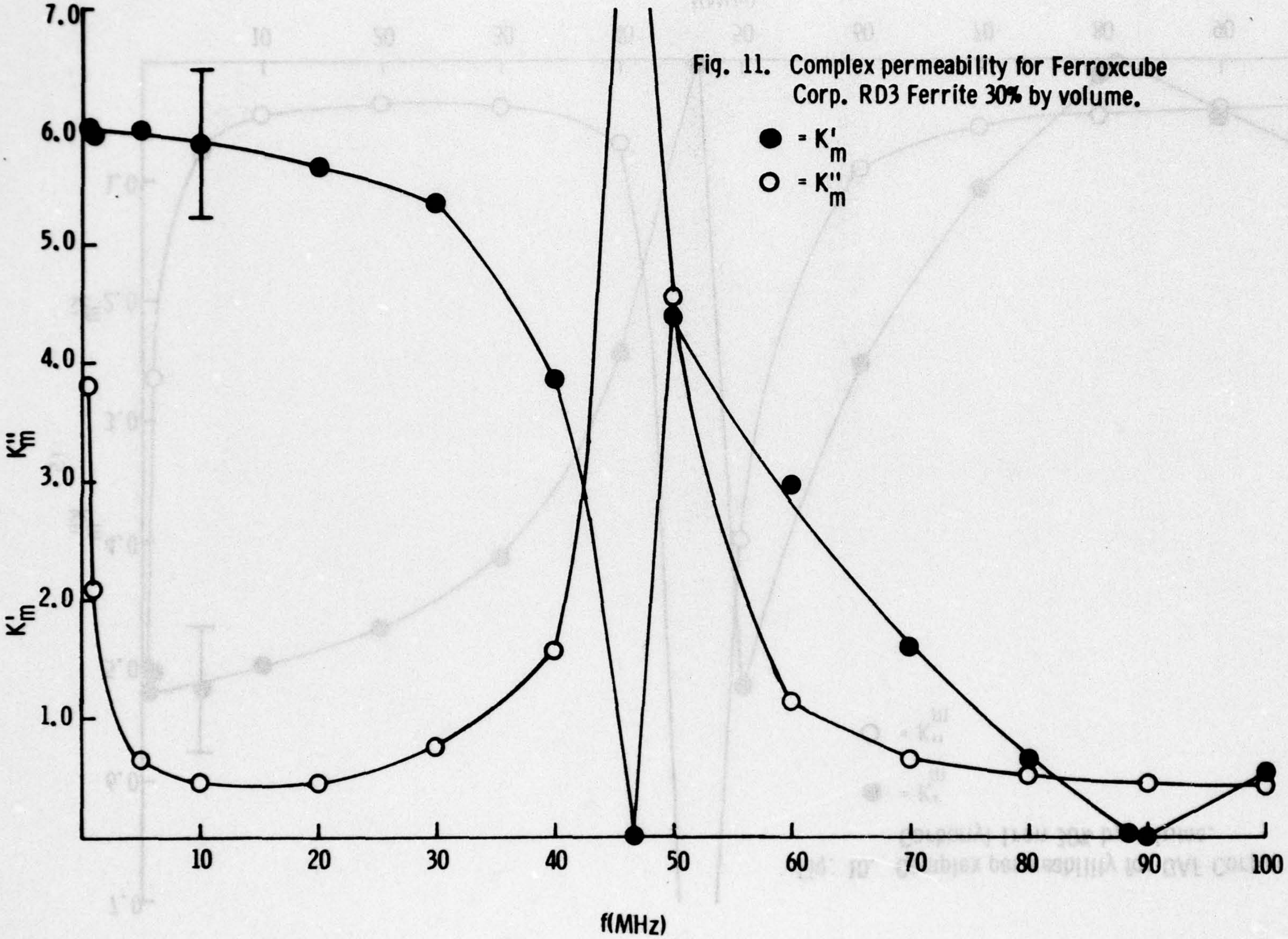

Fig. 11. Complex permeability for Ferroxcube Corp. RD3 Ferrite 30% by volume.

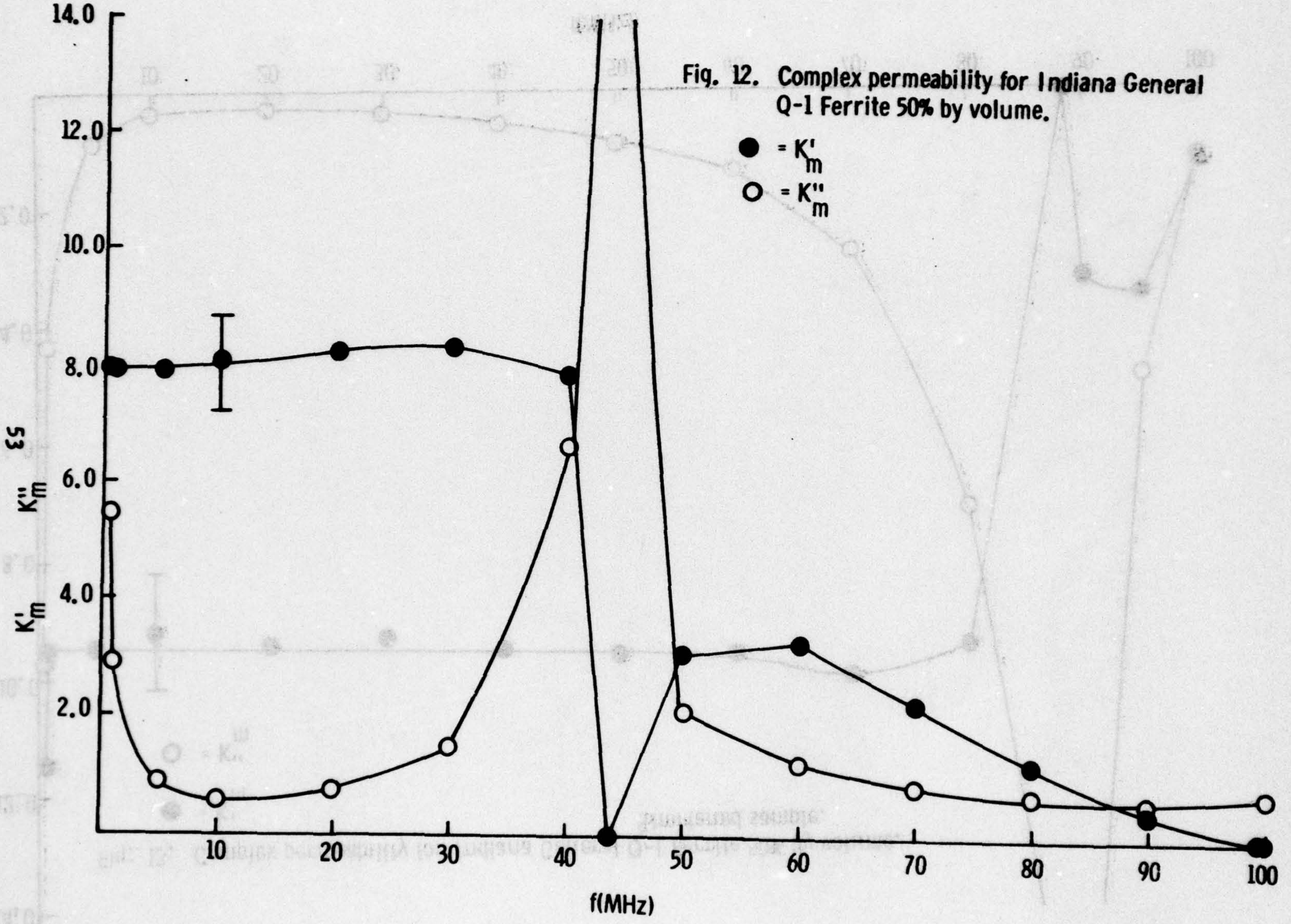

Fig. 12. Complex permeability for Indiana General Q-1 Ferrite 50% by volume.

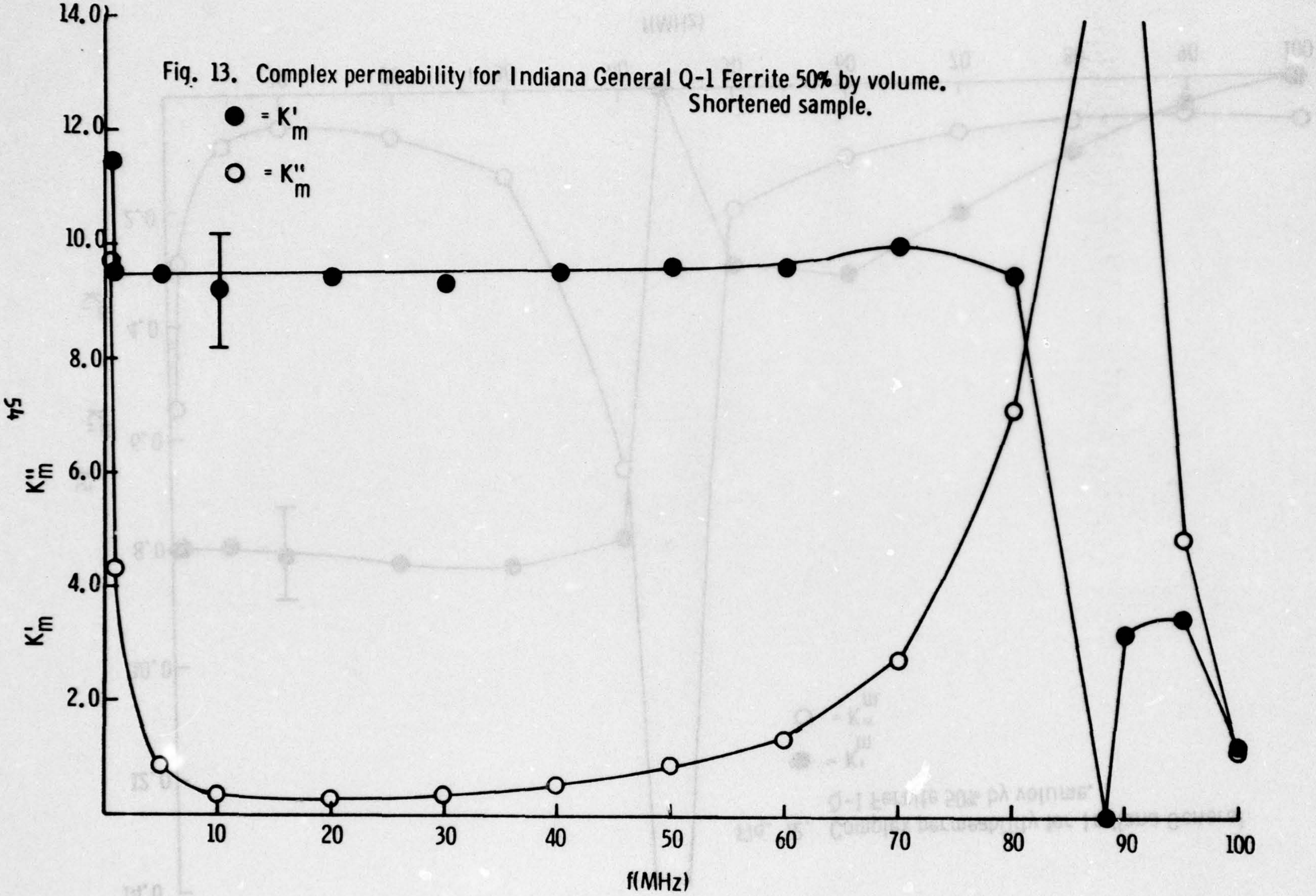

TABLE 29. SIMULATED GUN WITH RUBBER TOROID

Q-1 COMPOSITE

Noise dB/µV	Signal dB/µV	Signal/Noise dB	Position-Orientation Relative to Receiver Location Rifle Position	 Operator
-14	+46	60	vertical up	standing
-10	+42	52	vertical down	standing
- 5	+49	54	horizontal pointing away	standing
-13	+48	61	horizontal sideways left	standing
-14	+50	64	horizontal sideways right	standing
-13	+48	61	horizontal pointing to receiver	standing
-10	+36	46	vertical up	lying on the ground
-13	+40	53	vertical down	lying on the ground
- 9	+36	45	horizontal pointing away	lying on the ground
-17	+32	49	horizontal sideways left	lying on the ground
-14	+35.5	49.5	horizontal sideways right	lying on the ground
-10	+31	41	horizontal pointing to receiver	lying on the ground

(All data measured with Singer field intensity meter plus whip. Power = 100 mW)

TABLE 30. M-16(1-A) RIFLE WITH HEMAC COIL MOUNTED LONGITUDINALLY

Noise dB/μV	Signal dB/μV	Signal/Noise dB	Position-Orientation Relative to Receiver Location Rifle Position	 Operator
-16	+28	44	vertical up	standing
-15	+23.5	38.5	vertical down	standing
- 8	+44.5	52.5	horizontal pointing away	standing
- 8	+38.5	46.5	horizontal sideways left	standing
-16	+45	61	horizontal sideways right	standing
-15	+28	43	horizontal pointing to receiver	standing
-17	+29	46	vertical up	lying on the ground
-15	+25	40	vertical down	lying on the ground
-15	+32	47	horizontal pointing away	lying on the ground
-17	+20	37	horizontal sideways left	lying on the ground
-16	+36	52	horizontal sideways right	lying on the ground
-17	+26	43	horizontal pointing to receiver	lying on the ground
			COMPARISON CHECK WITH WHIP ANTENNA XMTR	
			Whip Position	Operator
-15	+29	44	horizontal pointing to receiver	standing
-17	+43	60	horizontal pointing away from receiver	standing

(All data measured with Singer field intensity meter plus whip. Power = 100 mW; Frequency = 27.125 MHz)

TABLE 31. SIMULATED GUN WITH FERRITE Q-2 ROD MOUNTED LONGITUDINALLY

Noise dB/μV	Signal dB/μV	Signal/Noise dB	Position-Orientation Relative to Receiver Location	
			Rifle Position	Operator
-13	+14	27	vertical up	standing
-12	+16	28	vertical down	standing
-12	+ 4	16	horizontal pointing away	standing
-11	+23	34	horizontal sideways left	standing
-11	+21	32	horizontal sideways right	standing
-14	+ 1	15	horizontal pointing to receiver	standing
-11	+13	24	vertical up	lying on the ground
-12	+16	28	vertical down	lying on the ground
-13	+16	29	horizontal pointing away	lying on the ground
-12	+22	34	horizontal sideways left	lying on the ground
-14	+25	39	horizontal sideways right	lying on the ground
-18	+12	30	horizontal pointing to receiver	lying on the ground

COMPARISON CHECK WITH WHIP ANTENNA XMTR

			Whip Position	Operator
-16	+51	67	vertical up	standing
-15	+42	57	vertical down	standing

(All data measured with Singer field intensity meter plus whip. Power = 100 mW)

where

χ = susceptibility of the composite

M = magnetization of the composite

M_o = permeability of vacuum

H_a = applied field

f = volume fraction (volume of magnetic particles/volume of composite)

χ_1 = susceptibility of the magnetic particles

p is the porosity = 1-f

N_g = the demagnetization factor

In the limit of high dilution

$$\chi = f\chi_1/(1 + \mu_o N_g \chi_1) \tag{45}$$

Substituting $M_1 = \chi_1 + 1$, one obtains

$$(\mu - 1)/(\mu - 1 + 1/\mu_o N_g) = f(\mu_1 - 1)/(\mu_1 - 1 + 1/M_o N_g) \tag{46}$$

If μ_1 is the permeability of magnetic particles in a matrix whose permeability is μ_2, and observing that $\mu_1 \rightarrow \mu_1/\mu_2$ and $\mu \rightarrow \mu/\mu_2$, the following result is obtained by substituting in Eq. (46)

$$(\mu - \mu_2)/(\mu + (1/\mu_o N_g - 1)\mu_2) = f(\mu_1 - \mu_2)/(\mu_1 + (1/\mu_o N_g - 1)\mu_2) \tag{47}$$

For spheres $1/M_o N_g = 3$. Making this substitution yields

$$(\mu - \mu_2)/(\mu + 2\mu_2) = f(\mu_1 - \mu_2)/(\mu_1 + 2\mu_2)$$

which is the Maxwell-Rayleigh formula for dilute mixtures.

Bruggeman[10] has derived the following expression for more concentrated mixtures using Eq. (47):

$$(\mu_1 - \mu)/(\mu_1 - \mu_2) = P(\mu/\mu_2)^{M_o N_g}$$

Baldwin[9] has simplified this equation for application to real systems. He assumed that the permeability of the nonmagnetic matrix material equals one, ($\mu_2 = 1$). If we consider porosities $\geq .3$, the permeability of the particles is relatively independent of μ_1 and depends to a great degree upon demagnetization effects. One obtains an approximate expression by setting $\mu_1 = \infty$.

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10. D.A.G. Bruggeman, Ann. Phys. 24, 636 (1935).

Using the indicated substitutions Bruggeman's expression becomes

$$1 = p(\mu/\mu_2)^{M_oN_g}$$

$$\mu = \mu_2(1/p)^{1/M_oN_g}$$

$$\mu = p^{-(1/M_oN_g)} \tag{48}$$

For a sphere, Eq. (48) yields

$$\mu = 1/p^3 \tag{49}$$

In Fig. 14 the permeability is plotted as a function of porosity for a number of experimental samples. The solid curve labeled $1/p^3$ refers to Eq. (49); the curve labeled M-R (Maxwell-Rayleigh) is obtained by plotting $\mu = (3(1-p)/p) + 1$. This equation was derived from Eq. (44) by substituting $(\mu - 1)$ for χ and $(\mu_1 - 1)$ for χ_1, and assuming μ_1 infinite and spherical particles. Both curves of Fig. 14 assume that the permeability of the bulk magnetic material is infinite.

As a zero order approximation the fit to the Bruggeman equation is good. Baldwin[9] has shown that curing of composites in a magnetic field enhances the permeability leading to a large deviation from the $1/p^3$ dependence. A most interesting result of this investigation is that the $1/p^3$ dependence holds to very high frequency. The data of Alekseev and Poltinnikov[11] indicates that the permeability of NiZn ferrite remains constant out to almost 1000 MHz.

In bulk magnetic materials the largest contribution to the initial permeability arises from displacement of domain walls. Since few domains are present in the small magnetic particles and the particles are well separated, the displacement mechanism contributes little. The major contribution is from rotational permeability. Because displacement of walls is generally absent, the low frequency loss associated with it is absent. This is the origin of the observed constant permeability which extends to much higher frequencies than observed for the same material in bulk form.

6. CONCLUSION

The principal result of this investigation is the confirmation of Baldwin's $K_m' = 1/p^3$ law to a frequency of 100 MHz in composite magnetic materials. A material scientist or engineer designing a composite magnetic inductive device need only consult a plot of K_m' vs p for any concentration desired and the permeability is known. Considerations of Q, electrical resistivity, dielectric constant or characteristic impedance at high frequency are then the major considerations. Thought must also be given to dimensional resonance effects in designing components since the size of components can limit the maximum frequency of use. This work could be extended to include materials cured in a dc magnetic field in order to increase permeability, an investigation of the temperature coefficient of K_m', and a study of the effect of a dc bias on K_m'.

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[11] A.G. Alekseev and S.A. Poltinnikov, Izvestiya Akademii Nauk SSSR, Neorganicheskie Materialy 9, 455 (1973).

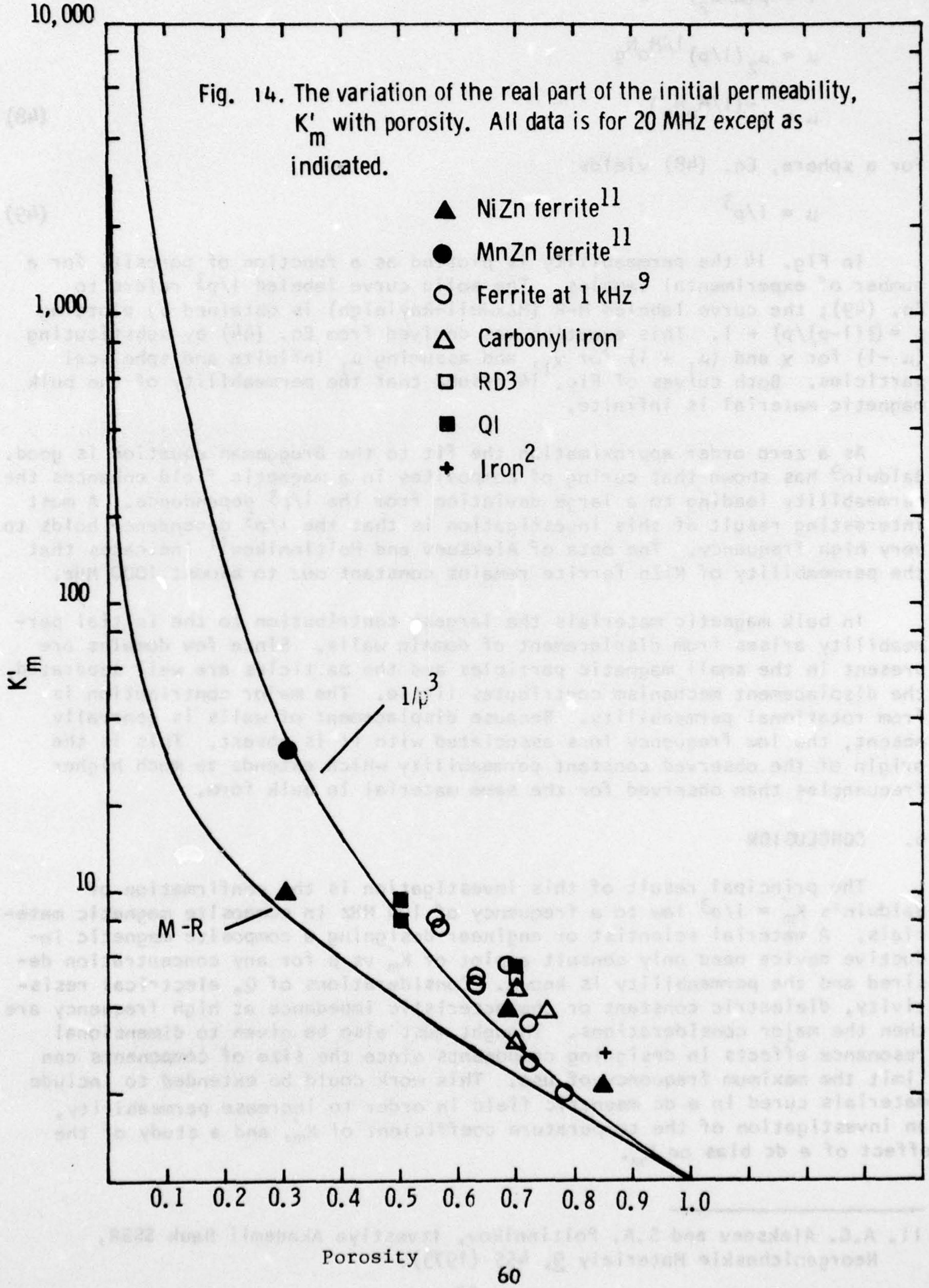

Fig. 14. The variation of the real part of the initial permeability, K'_m with porosity. All data is for 20 MHz except as indicated.

7. ACKNOWLEDGMENTS

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APPENDIX

The following is the computer program used to calculate the values for all samples using Eqs. (40-43) without any corrections.

The language is "Basic." The raw data is put into a file C8 FILE in the format: The first line contains an identifying string and a number which designates the number of frequency entries. The second line has three numbers, which are, respectively, the inner diameter of the outer brass conductor = D1 in inches, the outer diameter of the inner copper conductor = D2 in inches, and the length of the sample = L1 in inches. The remaining lines of the raw data have five numbers, which are, respectively, the frequency in MHz, $|Z(OC)|$ in ohms, $\theta(OC)$ in degrees, $|Z(SC)|$ in ohms, $\theta(SC)$ in degrees. The output from this program is saved in files R8 FILE, M8 FILE, E8 FILE. The program is:

```
100     PRINT "DID YOU SPECIFY FILE-NAME WITH EQUATE C8 FILE = FILE-NAME
        BEFORE RUNNING"
152     M=100
154     A$ = "UNSPECIFIED"
160     FILES C8 FILE, R8 FILE (50), M8 FILE (50), E8 FILE (50)
460     GO TO 2150
500     STOP
2150    INPUT #1, A$, M
2200    INPUT #1, D1, D2, L1
2300    P1=3.14159265
2400    K1=(1/(2*P1))*LOG(D1/D2)
2500    L8=L1*2.54E-2
2600    PRINT
2700    PRINT
2800    PRINT
2900    PRINT "NAME OF FILE": A$
3000    PRINT "L(METER)="L8; "K1="K1
3100    PRINT "F1","R(OC)","R(SC)","X(OC)","X(SC)"
3110    PRINT "(MHZ)","(OHMS)","(OHMS)","(OHMS)","(OHMS)"
3120    PRINT "Z0","BETA","C1","L3","MU(R)"
3140    PRINT "(OHMS)","(1/M)","(FARAD)","(HENRY)","(#)"
3160    PRINT "E(R)","TD(OC)","TD(SC)","MU(R)L","E(R)L"
3180    PRINT "(#)","(#)","(#)","(#)","(#)"
3300    FOR N=1 TO M
3400    INPUT #1:9000,F1,Z1,T1,Z3,T3
3500    O1=2*P1*F1*1E6
3600    R1=Z1*COS(T1*(P1/180))
3700    R3=Z3*COS(T3*(P1/180))
3800    X1=Z1*SIN(T1*(P1/180))
3900    X3=Z3*SIN(T3*(P1/180))
4000    Z0=SQR(ABS(X1)*ABS(X3))
4100    B1=(ATN(SQR(ABS(X3)/ABS(X1))))/L8
4200    M1=(B1*Z0/(K1*O1)
4300    E1=(B1*K1)/(O1*Z0)
4400    M9=M1/(4*P1*1E-7)
4500    E9 = E1/(8.854E-12)
4600    C1=L3=-1
4700    IF X1 /LT 0 THEN 6000
```

```
4800    IF X3 /GT 0 THEN 7000
4810    T5=R1/(ABS(X1))
4820    T7=R3/(ABS(X3))
4840    E8=T5*E9
4860    M8=T7*M9
4900    PRINT F1,R1,R3,X1,X3,Z0,B1,C1,L3,M9,E9,T5,T7,M8,E8
4910    PRINT
4920    PRINT
4940    PRINT #2,F1,R1,R3,X1,X3,Z0
4960    PRINT #3,F1,M9,E9,M8,E8
4980    PRINT #4,F1,C1,L3,T5,T7
5000    NEXT N
5100    GOTO 9999
6000    C1=1/(01*ABS(X1))
6100    GO TO 4800
7000    L3=X3/01
7100    GO TO 4810
9000    PRINT"FILE IS OUT OF DATA;LIST FILE TO SEE IF THERE IS A PROBLEM"
9100    GOTO 9999
9999    END
```

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