GENERAL ELECTRIC

RESEARCH AND DEVELOPMENT CENTER

SCHENECTADY, NEW YORK

CLASS 1

MEASUREMENT OF MAGNETIC PROPERTIES OF COBALT-RARE EARTH PERMANENT MAGNETS

by

M. G. Benz and D. L. Martin
Metallurgy & Ceramics Laboratory

Report No. 70-C-318 September 1970

GENERAL ELECTRIC

RESEARCH AND DEVELOPMENT CENTER

SCHENECTADY, NEW YORK

TECHNICAL INFORMATION SERIES

AUTHOR	SUBJECT	NO.
Benz, MG Martin, DL	permanent magnets	70-C-318 DATE Sept. 1970
TITLE Measurement of Magnetic Properties of Cobalt-Rare Earth Permanent Magnets		GE CLASS 1 NO. PAGES
ORIGINATING COMPONENT Metallurgy and Ceramics Laboratory		RESEARCH & DEVELOPMENT CENTER SCHENECTADY, N.Y.

SUMMARY

Cobalt-rare earth permanent magnets generally display a high intrinsic coercive force. In order to make magnetic measurements with such materials fully saturated, we have found it necessary to use magnetizing fields in excess of 50 kOe. The superconducting solenoid is ideally suited for generating such fields. In this study, we have used a 100 kOe niobium-tin superconducting solenoid for magnetizing samples and for measuring saturation magnetization. Demagnetization properties of long cyclindrical samples have been measured in the superconducting solenoid, and also with a conventional hysteresigraph after the samples have been saturated with the superconducting solenoid or in some cases with a pulsed field solenoid.

Short disk samples or ring magnets such as are used in traveling wave tube (TWT) designs are difficult to measure by these techniques. We have found torque magnetometry to be useful for such shapes. Open circuit magnetization is measured in this case. Results for ring magnets will be compared with peak axial field measurements for a periodic TWT structure.

Reversible and irreversible changes in magnetization with temperature are also of interest. Techniques for measuring these changes are discussed.

This report was presented at IEEE 1970 Conference on Electron Device Techniques, September 23, 24, 1970, New York City, N. Y.

KEY WORDS permanent magnets, rare earth permanent magnets cobalt-samarium permanent magnets, traveling wave tube magnets, microwave tube magnets, magnetic measurements

INFORMATION PREPARED FOR ______________________

Additional Hard Copies Available From — Distribution Unit, P.O. Box 43 Bldg. 5, Schenectady, N.Y., 12301

Microfiche Copies Available From — Technical Information Exchange, P.O. Box 43 Bldg. 5, Schenectady, N.Y., 12301

MEASUREMENT OF MAGNETIC PROPERTIES OF COBALT-RARE EARTH PERMANENT MAGNETS

M. G. Benz and D. L. Martin
General Electric Research and Development Center
Schenectady, New York

ABSTRACT

Cobalt-rare earth permanent magnets generally display a high intrinsic coercive force. In order to make magnetic measurements with such materials fully saturated, we have found it necessary to use magnetizing fields in excess of 50 kOe. The superconducting solenoid is ideally suited for generating such fields. In this study, we have used a 100 kOe niobium-tin superconducting solenoid for magnetizing samples and for measuring saturation magnetization. Demagnetization properties of long cylindrical samples have been measured in the superconducting solenoid, and also with a conventional hysteresigraph after the samples have been saturated with the superconducting solenoid or in some cases with a pulsed field solenoid.

Short disk samples or ring magnets such as are used in traveling wave tube (TWT) designs are difficult to measure by these techniques. We have found torque magnetometry to be useful for such shapes. Open circuit magnetization is measured in this case. Results for ring magnets will be compared with peak axial field measurements for a periodic TWT structure.

Reversible and irreversible changes in magnetization with temperature are also of interest. Techniques for measuring these changes are discussed.

INTRODUCTION

The significantly higher coercive force and maximum energy products achieved with cobalt-rare earth magnets make it necessary to use fields approaching 50 kOe and above for magnetic measurements. In this paper we discuss techniques and methods that we have found to be effective utilizing these high fields. It is our objective to present these procedures in sufficient detail that they may be considered for use by others. Furthermore, it is hoped that such a presentation will allow the engineer and designer of magnetic circuits to evaluate performance information being presented [as for example in Ref. (1)]; such that this information may be used as the basis for new designs.

The techniques to be discussed include: 1) measurement of magnetization in a superconducting solenoid, 2) measurement of a B:H curve with a hysteresigraph using an iron yoke electromagnet, 3) measurement of open circuit magnetization with a torque magnetometer, including temperature coefficient measurements, 4) measurement of the axial field in the periodic magnetic focusing structure for a traveling wave tube.

MEASUREMENT OF MAGNETIZATION IN A SUPERCONDUCTING SOLENOID

A coil of wire, such as is shown in Fig. 1, is basic to the measurement of magnetization and applied field in a superconducting solenoid, and for measurement of open circuit induction directly when the applied field is equal to zero. For the case shown, magnetic flux φ links a coil of n turns enclosing an area A. If the flux level is changed as a function of time t a voltage E is generated in the coil such that:

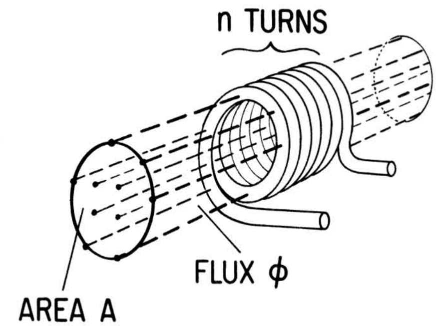


Fig. 1 Magnetic flux φ links a coil of n turns and cross sectional area A.

$$E = -10^{-8}\, n\, \frac{d\varphi}{dt} \qquad (1)$$

Magnetic induction B, by definition, is equal to the magnetic flux φ per unit area A. Hence, equation (1) may be written:

$$E = -10^{-8}\, n\, A\, \frac{dB}{dt} \qquad (2)$$

The units are gauss, cm^2, volts, and seconds.

The induction B is also the sum of the internal field H and the flux density resulting from the magnetization J:

$$B = H + 4\pi J \qquad (3)$$

Under open circuit conditions, the internal field H is determined by:

$$H = H_a - N(4\pi J) \qquad (4)$$

Where H_a is the applied field and N is the demagnetizing factor. The demagnetizing factor N is a shape dependent parameter and is discussed in detail in later sections of this paper.

By combining equations (3) and (4) and differentiating:

$$dB = (1-N)d(4\pi J) + dH_a \qquad (5)$$

Now, by combination of equation (5) with equation (2):

$$[(1-N)d(4\pi J) + dH_a]\, nA = -10^{8}\, Edt \qquad (6)$$

The left hand side of this equation describes changes in flux linkages. These can come about either through changes in the value of J or H_a or through relative motion between the sample and the coil or the field and the coil.

In order to measure the magnetization of a permanent magnet in a superconducting solenoid, the arrangement shown schematically in Fig. 2(a) is used. The applied field H_a from the superconducting solenoid is constant in the region of the sample and the close fitting coil. As the permanent magnet is withdrawn from the close fitting coil, the time integrated voltage generated by the coil $\int Edt$ is measured. If the sample is completely removed from the coil, the resulting change in flux linkages is $[4\pi J]nA$. Then:

$$4\pi J = -\frac{1}{(1-N)} \frac{10^8}{nA} \int Edt \qquad (7)$$

where A is the cross sectional area of the permanent magnet. The units are gauss, cm^2, volts, and seconds.

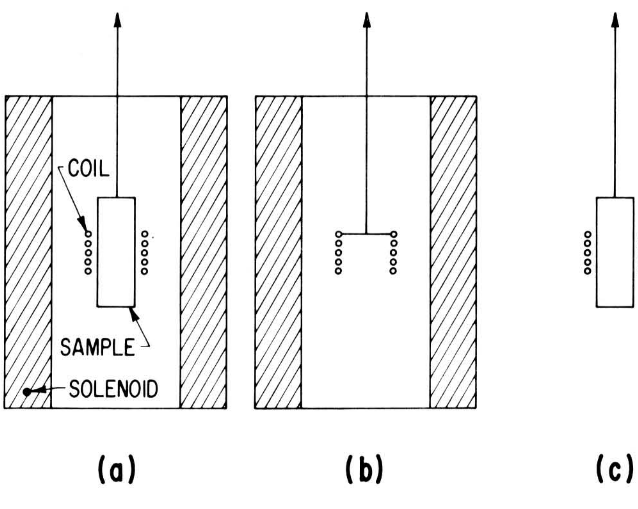


Fig. 2 Schematic representation of the use of a close fitting coil to measure $\int dB$. Fig. 2(a) Measurement of magnetization at constant applied field. Fig. 2(b) Measurement of applied field. Fig. 2(c) Measurement of open circuit induction at zero applied field.

The applied field is measured with the arrangement shown schematically in Fig. 2(b). The coil used can be the same one that was used for measuring magnetization. When the coil is completely moved from the center of the solenoid to a position of zero field, the change in flux linkages is $[H_a]nA$. In this case the time integrated voltage generated by the coil is used to determine the applied field by the relationship:

$$H_a = -\frac{10^8}{nA} \int Edt \qquad (8)$$

Where A is the cross sectional area of the coil. The units are oersted, cm^2, volts, and seconds. For a given coil, the nA is determined by experimental calibration in an applied field measured to 1 part in 10^4 with a nuclear magnetic resonance probe operating in the frequency range for hydrogen. The resonant frequency per unit of applied field is 4257.76 Hz/Oe and can be observed over the field range from 280 to 7000 Oe.

Under open circuit conditions when the applied field is zero, as shown in Fig. 2(c), the open circuit induction B_0 may be determined directly by withdrawing the permanent magnet from a close fitting coil. In this case:

$$B_0 = -\frac{10^8}{nA} \int Edt \qquad (9)$$

Where A is the cross sectional area of the permanent magnet. It should also be noted that for open circuit conditions when H_a is equal to zero, combination of equations (3) and (4) leads to the B/H load line:

$$\frac{B}{H} = -\frac{(1-N)}{N} \qquad (10)$$

And hence, the corresponding field and magnetization are given by:

$$H_0 = -\frac{N}{(1-N)} B_0 \qquad (11)$$

$$4\pi J_0 = B_0 - H_0 = \frac{1}{(1-N)} B_0 \qquad (12)$$

If the coil is not extremely close fitting for the magnetization and open circuit induction measurements [Figs. 2(a) and 2(c)], then the time integrated voltage signal $\int Edt$ generated by the sample coil for use with equations (7) and (9) should be multiplied by an experimentally determined coupling coefficient C. Open circuit induction at zero applied field is measured with the loose fitting coil and another closer fitting coil. The ratio of the time integrated voltage signals per coil turn $\int Edt/n$, close divided by loose, is equal to the coupling coefficient C.

Equations (4), (7) and (8) are the basis of point by point magnetization measurements made with a high-field solenoid. In our case, we have been using a niobium-tin superconducting solenoid capable of producing an applied field of 100 kOe. The solenoid is provided with an insert dewar such that the field is available at room temperature. An integrating digital voltmeter is used to measure the time integrated voltage signal $\int Edt$ generated by the sample coil. Examples of magnetization curves measured in this manner are shown in Fig. 3. The B:H curve may be derived from these curves by use of equation (3). An example is shown in Fig. 4. Saturation magnetization for the alloy from which the magnet has been fabricated may also be derived from these data. We have taken saturation magnetization for the alloy $4\pi J_{s,\,alloy}$ to be equal to the value of magnetization $4\pi J$ measured at 100 kOe divided by the packing fraction P. Sometimes the value for saturation magnetization of the alloy

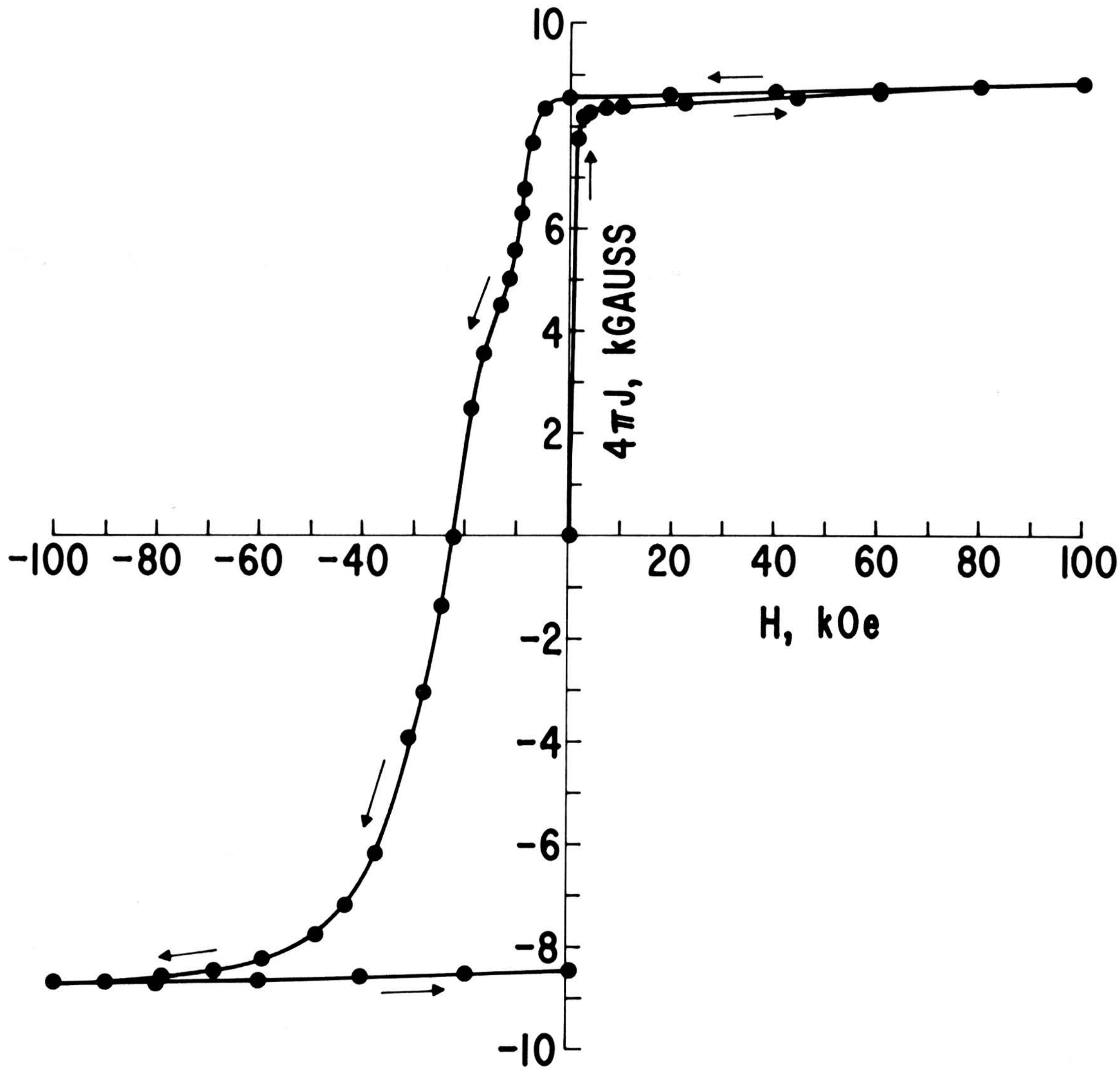
$4\pi J_{s,\ alloy}$ is referred to as the intrinsic induction for the magnetic material. In this case it is given the symbol B_s. For cobalt-samarium, P is equal to the density in gm/cm^3 divided by 8.6. An alignment factor may also be derived from these data. We have taken the alignment factor to be equal to the value of magnetization at zero field (equivalent to the remanent flux density B_r) divided by the value of magnetization at 100 kOe.

considered to be uniformly magnetized (J = constant, although B and H vary). For this case, the demagnetizing factor calculated by Joseph[2] can be used:

$$N_b = 1 - \frac{2p}{\pi k}\,[K(m) - E(m)] \tag{13}$$

$$\text{where } k = (1 + p^2/4)^{-1/2} \tag{14}$$

$$m = k^2 \tag{15}$$



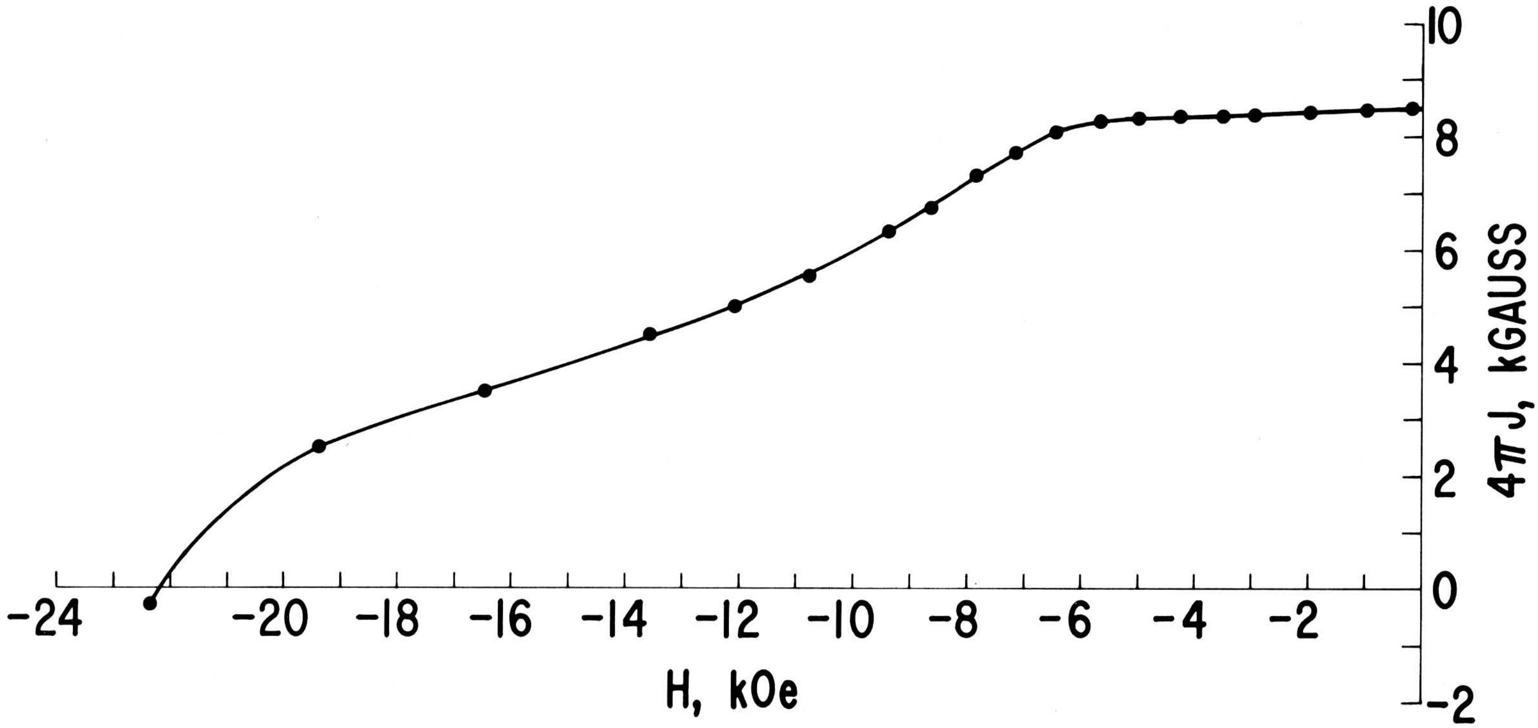
(a)

Fig. 3 Magnetization curves measured in a superconducting solenoid. Fig. 3(a) is the full curve from zero field to +100 kOe, back through zero field to -100 kOe and back to zero field. Fig. 3(b) is the second quadrant only. The magnetizing field was 100 kOe. The sample was a Co-Sm alloy. Diameter = 0.287 in., length = 1.225 in., alignment factor = 0.967, packing factor = 0.911 and saturation magnetization for the alloy = 9.70 kGauss.

In the above, the appropriate demagnetizing factor N is the one determined for the midplane of an axially magnetized cylinder of length L and diameter D. This is referred to as the ballistic demagnetizing factor N_b. For the cobalt-rare earth magnets, with susceptibility very close to zero, the cylinder can be

$$p = L/D \tag{16}$$

and where K(m) and E(m) are complete elliptic integrals of the first and second kind, respectively. The ballistic demagnetizing factor may also be approximated, as shown in Table I, for L/D = 0.3 to 4.0 by



(b)

Fig. 3 (contd)

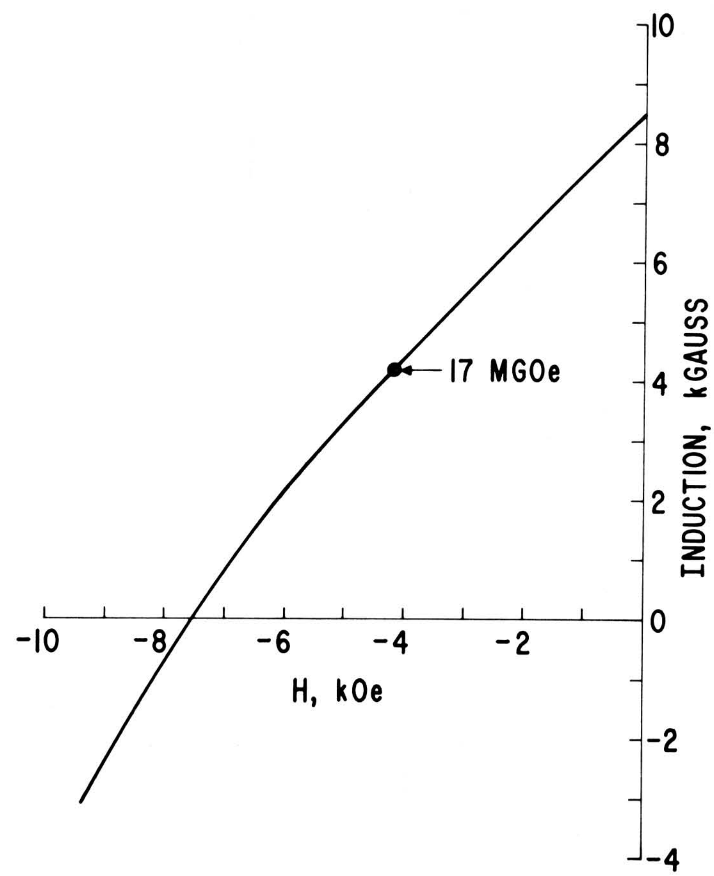


Fig. 4 B:H curve calculated from the magnetization data presented in Fig. 3 by use of equation (3).

TABLE I

Demagnetizing Factors for Finite Circular Cylinders of Uniform Magnetization, Magnetized Longitudinally

Dimension Ratio L/D	$N_b(I)$	$N_b(II)$	N_m
0.1	0.7845	(0.8203)	0.7967
0.2	0.6565	(0.6788)	0.6802
0.3	0.5604	0.5685	0.5947
0.4	0.4842	0.4823	0.5281
0.5	0.4221	0.4142	0.4745
0.6	0.3705	0.3597	0.4303
0.7	0.3273	0.3156	0.3933
0.8	0.2905	0.2793	0.3619
0.9	0.2592	0.2493	0.3349
1.0	0.2322	0.2240	0.3116
2.0	0.0935	0.1006	0.1819
3.0	0.0480	0.0593	0.1278
4.0	0.0287	0.0400	0.0984
5.0	0.0189	(0.0293)	0.0799
6.0	0.0133	(0.0226)	0.0673
7.0	0.0099	(0.0181)	0.0581
8.0	0.0076	(0.0149)	0.0511
9.0	0.0061	(0.0126)	0.0456
10.0	0.0049	(0.0108)	0.0412

$N_b(I)$ is the ballistic demagnetizing factor calculated using equation (13) [See Ref. (2)]. These values are preferred over $N_b(II)$.

$N_b(II)$ is the ballistic demagnetizing factor calculated using equation (18). Values in parentheses are not considered sufficiently accurate and should not be used. [See Ref. (3)].

N_m is the magnetometric demagnetizing factor calculated using equation (21). [See Refs. (2) and (5)].

Evershed's polar radiation model, as discussed by Parker[3]. For a cylinder of length, L, cross sectional area A and total surface area 2S:

$$N_b = \frac{1}{1 + (L/A)(\pi S)^{1/2}} \qquad (17)$$

or in terms of length L and radius R

$$N_b = \frac{1}{1 + (L/R^2)(R^2 + RL)^{1/2}} \qquad (18)$$

MEASUREMENT OF A B:H CURVE WITH A HYSTERESIGRAPH USING AN IRON YOKE ELECTROMAGNET

Once saturated, a long cylindrical sample may be measured with a conventional hysteresigraph. We have used a 100 kOe superconducting solenoid to saturate most of our samples. Full saturation is only observed for samples with an alignment factor in excess of 0.95. We have also used a 25 kOe pulsed field to magnetize samples. Over 90% of saturation is observed in most cases.

After saturation, the following procedure is used: Measure the open circuit induction B_0 as outlined in the previous section (equation (9)). Calculate the corresponding H_0 with equation (11). Insert the permanent magnet in a close fitting coil of known nA. Establish a slight positive field in the iron yoke electromagnet. Place the permanent magnet with close fitting coil in the electromagnet with the same polarity. Adjust the pole faces of the electromagnet so that they touch the ends of the permanent magnet. Clamp the electromagnet securely. Establish a negative field equal to the open circuit H_0 previously calculated. The field H is measured with a very small Hall probe placed so that it touches the close fitting coil that goes around the sample. The field measured in this position can be assumed to be equal to the internal field. Now, set the pen on the x-y plotter down at B_0, H_0. Change the field to zero to determine the remanent flux density B_r. Then sweep the field slowly in the negative direction in order to plot the B:H curve. Such a plot is shown in Fig. 5.

The induction B is measured with the close fitting coil and an integrating fluxmeter (a time integrating voltmeter). In this case, one is measuring the change in B from the B_0 condition initially established. (Equation (2) is the basis of this

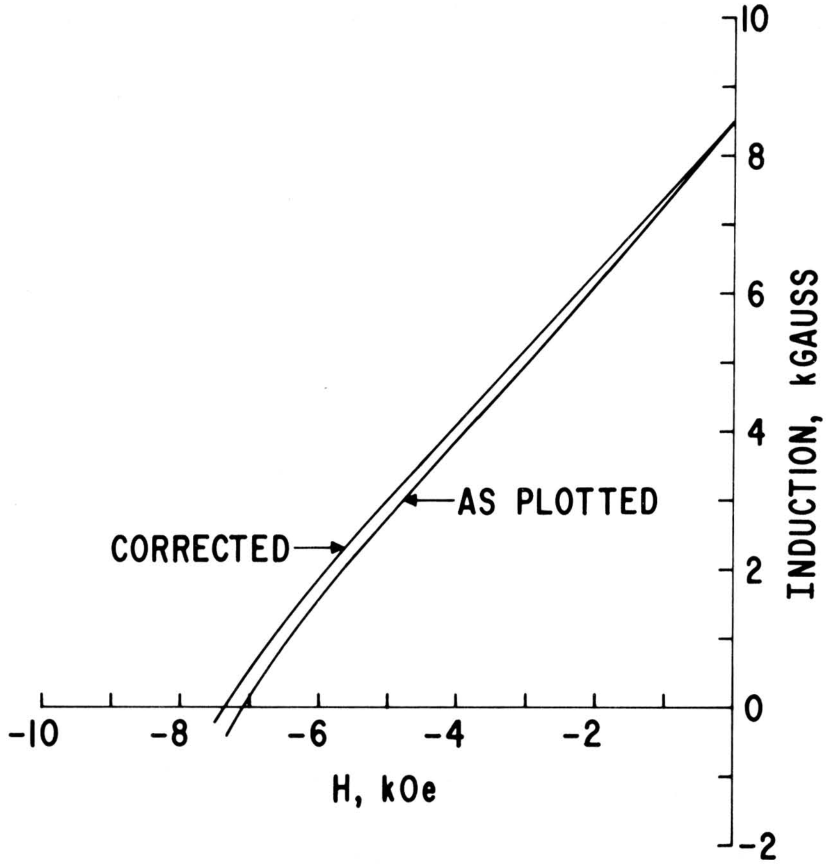


Fig. 5 B:H curve measured with a conventional hysteresigraph using an iron yoke electromagnet. The sample was magnetized at 100 kOe before this measurement. The corrected curve takes into account the effect of the air space between the measuring coil and the sample. The sample is the same sample that was measured with the superconducting coil (Figs. 3 and 4).

measurement.) Since there is always a slight air space between the close fitting coil and the permanent magnet, the coil also measures the change in field in this area. To correct for this, the induction value at a given field must be increased by the quantity $-H(A_c-A_m)/A_m$ where A_c is the cross sectional area of the coil and A_m is the cross sectional area of the magnet. Since the field is negative, the correction is positive, thus the value of induction is increased. The corrected curve on Fig. 5 was calculated in this manner. Careful calibration of the Hall probe and drift free operation of the integrating fluxmeter are essential for reliable measurements using this technique. Once demagnetized, the sample must be remagnetized in a high field solenoid before the procedure may be repeated for a second measurement.

MEASUREMENT OF OPEN CIRCUIT MAGNETIZATION WITH A TORQUE MAGNETOMETER

The previously outlined methods work very well for well defined shapes that are long relative to the close fitting coil used for measuring. For thin disks, or odd shapes, or for shapes immersed in fluids maintained at temperatures other than room temperature, such measurements become difficult and the measurement of open circuit magnetization with a torque magnetometer becomes an extremely useful measurement to make. The magnetometer is shown schematically in Fig. 6. It is a modification of one designed by Becker[4]. The torsion suspension is a 0.009 inch diameter tungsten wire. The suspension and strain gauge transducer are calibrated by dead weight loading in the horizontal mode of operation.

The torque T at angle θ is produced by an interaction of the magnetic moment M of the permanent magnet and the applied field H_a such that:

$$T = MH_a \sin\theta \qquad (19)$$

Since the magnetic moment M is J times the volume V, equation (19) may be rewritten

$$4\pi J = \frac{4\pi T}{VH_a \sin\theta} \qquad (20)$$

The units are gauss, dyne-cm, cm^3, and oersted. A plot of T vs θ for a thin disk of Co-MM-Sm is shown in Fig. 7. The applied field was 100 Oe. The open circuit magnetization may be taken as the average of the peak values for $\sin\theta = 1$ and $\sin\theta = -1$. ($H_a = \pm 100$ Oe.) This averaging is valid for these materials as over the small change in field, the magnetization does not change significantly.

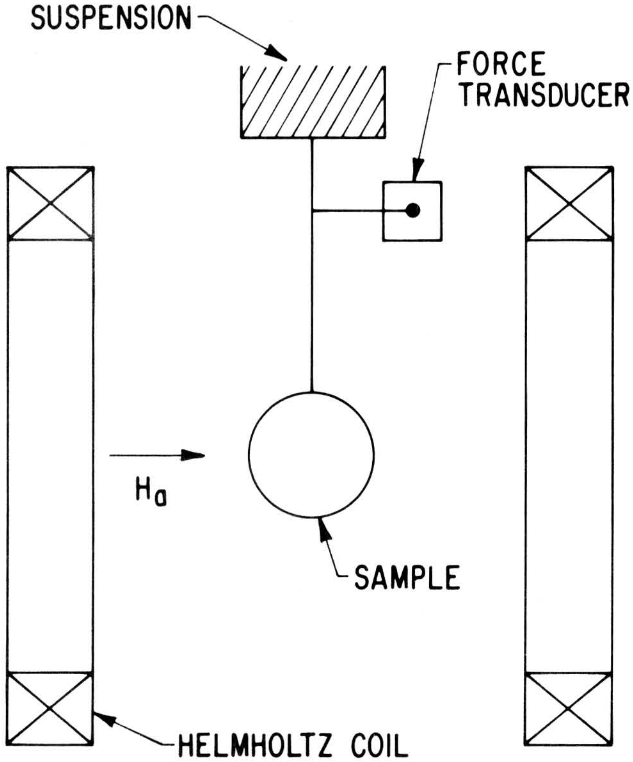


Fig. 6 Schematic view of the torque magnetometer. The angle θ is the angle between the magnetic moment of the sample and the applied field H_a.

$$m = k^2 \quad (23)$$

$$p = L/D \quad (24)$$

and where K(m) and E(m) are complete elliptic integrals of the first and second kind, respectively.

The results calculated using these equations are also listed in Table I. They are in agreement with those listed by Brown[5]. Hence, from the open circuit magnetization $4\pi J_0$ one can calculate the open circuit induction B_0 and field H_0 using equations (11) and (12).

As a check of the foregoing methods and calculations, a cylindrical rod was measured by the ballistic method and by the magnetometric method. The results are listed in Table II and show agreement within one percent.

TABLE II

Open Circuit Magnetic Properties Determined Ballistically and Magnetometrically*

	Ballistic Method	Magneto-Metric Method
$4\pi J$ at H_0 (Magnetometric), kGauss	8.45	8.36
B at H_0 (Magnetometric), kGauss	7.68	7.59
H_0 (Magnetometric), kOe	-	-0.77
H_0 (Ballistic), kOe	-0.22	-

*Sample diameter = 0.287 in. and length = 1.225 in.

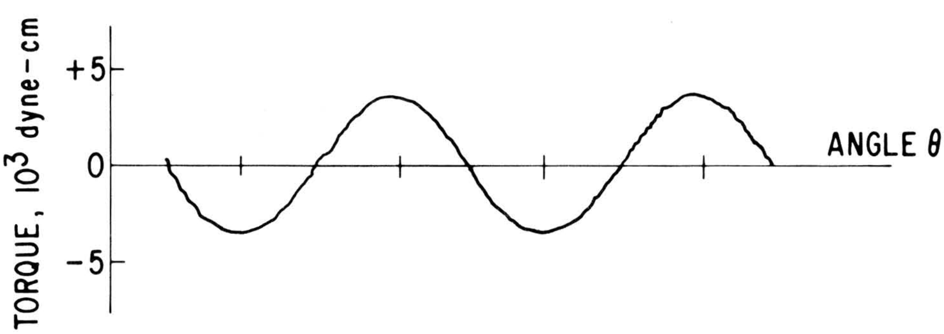


Fig. 7 Plot of torque as a function of the angle θ for a thin disk sample. The sample was a Co-MM-Sm alloy. The applied field was 100 Oe. Sample dimensions were: diameter = 0.266 in., length = 0.0613 in. The torque at Sin θ = 1 is 3330 dyne-cm. Hence, the magnetization is 7.49 kGauss at a field of -4.88 kOe.

The appropriate demagnetizing factor for this case is the magnetometric demagnetizing factor N_m. This has been treated by Joseph[2] for cylinders of uniform axial magnetization $4\pi J$. As uniform axial magnetization is very nearly the case for cobalt-rare earth magnets, this calculation can be used:

$$N_m = 1 - \left(\frac{4}{3\pi p}\right)\left\{(1+p^2)^{1/2}[p^2K(m)+(1-p^2)E(m)]-1\right\} \quad (21)$$

where $k = (1 + p^2)^{-1/2}$ (22)

Immersion of the sample in liquid nitrogen or hot oil has allowed one to measure the magnetization at different temperatures and hence derive the reversible and irreversible temperature loss coefficients.

Odd shapes such as a half-ring TWT magnet may also be measured with the torque magnetometer. It is difficult to estimate the demagnetizing factor for such a shape under open circuit conditions. The demagnetizing factor calculated with equation (17) is in considerable error (5 to 15% has been observed). Thus one is limited to a comparison of relative magnetization at a fixed but unknown load line $4\pi J/H$. For magnets of a specific size and shape, however, such a measurement is ideally suited for determination of temperature coefficients, stability and lot uniformity.

MEASUREMENT OF THE AXIAL FIELD IN A PERIODIC FOCUSING STRUCTURE FOR A TRAVELING WAVE TUBE

Half-ring magnets have been measured under open circuit conditions with the torque magnetometer as indicated in the previous section. The particular magnet under consideration is shown in Fig. 8. The magnetization $4\pi J$ under open circuit conditions was 8.19 kGauss. Fourteen magnets were placed in the circuit shown in Fig. 9. A plot of axial field as measured with a Hall probe vs axial position is shown in Fig. 10. The peak field observed was 2.99 kOe. Using a calculation developed by Grant[6], the geometry of the circuit is such that the internal field in the permanent magnet is -1.815 times the peak axial field. The corresponding B/H loading of the permanent magnet is equal to -0.473. This would correspond to a B = 2.57 kGauss, H = -5.43 kOe, and $4\pi J$ = 8.00 kGauss. With this particular geometry therefore, the value of magnetization for the magnet in the final structure is almost the same as the value for open circuit magnetization of the half-ring magnet alone.

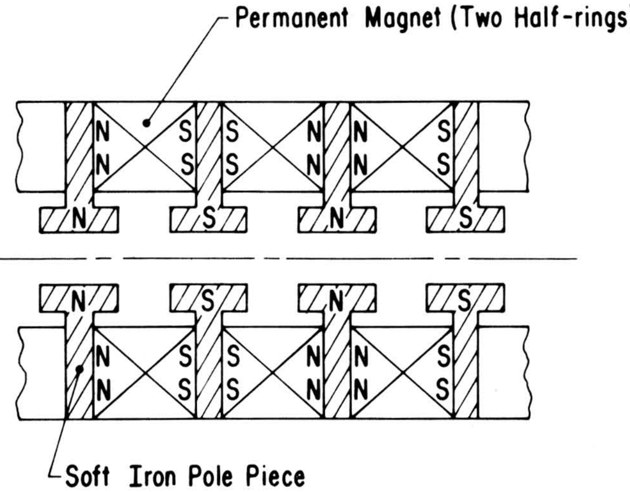


Fig. 9 Cross section of a periodic focusing structure for a traveling wave tube. The dimensions of the permanent magnets are as listed in Fig. 8. The dimensions of the pole pieces are: ID = 0.259 in., ferrule OD = 0.319 in., ferrule length = 0.022 in., disk OD = 1 in., disk thickness = 0.065 in.

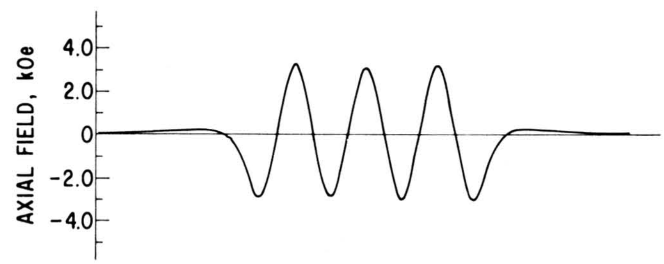


Fig. 10 Plot of axial field as a function of position.

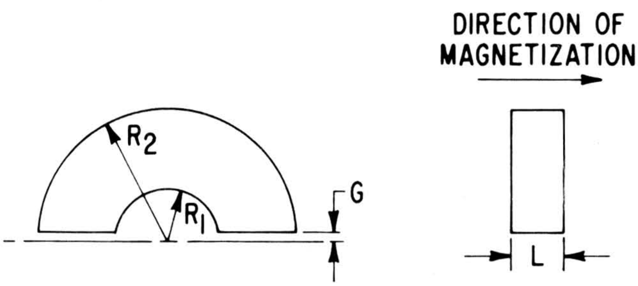


Fig. 8 Half-ring magnet for a traveling wave tube periodic focusing structure. R_1 = 0.165 in., R_2 = 0.500 in., G = 0.020 in., and L = 0.138 in.

CONCLUSIONS

Magnetic measurements of cobalt-rare earth magnets can be made with equipment readily available. A means of providing a magnetizing field in excess of 50 kOe has been found to be necessary to fully saturate these materials. Superconducting solenoids and also pulsed field solenoids have been used to provide these fields. Torque magnetometry is useful for measuring thin shapes. Meaningful demagnetizing factors may be calculated for cylindrical shapes with these materials. Demagnetizing factors for shapes such as half-ring traveling wave tube magnets are not readily estimated. However, for a specific geometry, open circuit magnetization may be directly correlated with the peak field observed in the final magnetic circuit.

ACKNOWLEDGMENTS

The authors would like to acknowledge the assistance of J. T. Geertsen, R. P. Laforce, and R. T. Laing for the preparation of samples and data; R. I. Joseph of Johns Hopkins University for comments relative to the use of his equations for calculation of demagnetizing factors; J. E. Grant of the Electron Dynamics Division of Hughes Aircraft Company for providing a computational technique for calculation of peak fields and B/H load line in the periodic focusing structure for a traveling wave tube, and also J. J. Becker and R. J. Charles for their critical review of the manuscript.

Some of the cobalt-samarium samples examined as part of this study were prepared under a manufacturing methods program sponsored in part by the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Contract No. F33615-70-C-1098.

REFERENCES

1) D. L. Martin and M. G. Benz, "Magnetic Properties of Cobalt-Rare Earth Magnets for Microwave Applications," IEEE Conference on Electron Device Techniques, New York, September 23-24, 1970. Also submitted for publication in IEEE Trans. Magnetics.

2) R. I. Joseph, "Ballistic Demagnetizing Factor in Uniformly Magnetized Cylinders," J. Appl. Phys., 37, 4639 (1966).

3) R. J. Parker and R. J. Studders, Permanent Magnets and Their Application, John Wiley and Sons, Inc., New York, 1962, pp. 163-168.

4) J. J. Becker, unpublished, U. S. Patent 3,464,003.

5) W. F. Brown, Jr., Magnetostatic Principles in Ferromagnetism, North-Holland Publishing Company, Amsterdam, 1962. See the Appendix and Table A3.

6) J. E. Grant, Electron Dynamics Division, Hughes Aircraft Co., private communication.