Conference on MAGNETISM *and* MAGNETIC MATERIALS

HOTEL STATLER
BOSTON, MASS.
OCT. 16, 17, 18, 1956.

The second national conference sponsored by American Institute of Electrical Engineers in cooperation with the American Physical Society, The American Institute of Mining, Metallurgical and Petroleum Engineers and The Institute of Radio Engineers.

The Conference is designed to bring together people with interests ranging from basic research in magnetism, to the application of magnetic materials in equipment.

GENERAL PROGRAM

Monday, Oct. 15

8:00 P.M.	Local Committee Meeting, Hotel Statler

Tuesday, Oct. 16

8:00 A.M.	Registration, Mezzanine
9:00 A.M.	Opening Remarks by General Chairman, Georgian Room
9:15 A.M.-12:30 P.M.	Session I Magnetic Anisotropy, Georgian Room
Noon - 8:00 P.M.	Magnetics Exhibit, Mezzanine
2:00 P.M.-5:30 P.M.	Session II Permanent Magnets and Fine Particles, Georgian Room
8:30 P.M.-11:30 P.M.	Informal Get together, Bay State Room

Wednesday, Oct. 17

8:45 A.M.	Registration, Mezzanine
9:00 A.M.-12:30 P.M.	Session IIIa Magnetism and Physical Metallurgy, Georgian Room
9:00 A.M.-11:30 A.M.	Session IIIb Apparatus and Design, Bay State Room
Noon - 8:00 P.M.	Magnetics Exhibit, Mezzanine
2:00 P.M.-5:30 P.M.	Session IVa Losses in Soft Magnetic Materials, Georgian Room
3:00 P.M.-5:30 P.M.	Session IVb Ferrites, Bay State Room
6:30 P.M.	Social hour, Boston Museum of Science
7:15 P.M.	Dinner, Boston Museum of Science, Dinner speaker, Dr R. M. Bozorth, of Bell Telephone Laboratories, "A Visit to Russia"

Thursday, Oct. 18

8:45 A.M.	Registration, Mezzanine
9:00 A.M.-12:30 P.M.	Session V High Frequency Phenomena, Georgian Room
12:30 P.M.-2:00 P.M.	Magnetics Subcommittee Luncheon, Hotel Statler
Noon - 6:00 P.M.	Magnetics Exhibit, Mezzanine
2:00 P.M.-5:30 P.M.	Session VI Memory Devices and Magnetic Amplifiers, Georgian Room

Registration

Registration will be at the Hotel Statler Mezzanine from 8:00 A.M. to 5:00 P.M. on Tuesday, October 16, and from 8:45 A.M. to 5:00 P.M. on Wednesday and Thursday. Admission badges will be ready for preregistrants, without waiting. You will conserve your time and assist in conference planning by registering in advance.

The registration fee of $5.00 includes admission to the technical sessions, the magnetics exhibit, and the informal get-together Tuesday evening. Make checks payable to the Conference on Magnetism, and mail to T. O. Paine, General Electric Co., West Lynn, Mass.

Technical Sessions

The presentation of the technical papers will be rigidly limited to 12 minutes. Each paper will be followed by a 3 minute discussion period.

The meeting rooms will be provided with a standard slide projector for 3-1/4" x 4" slides, blackboard, and a reading stand. Other facilities available by special arrangement. The complete paper, for publication in the Conference Proceedings, must be handed to the session chairman at the time of the presentation.

Informal Get-together

This is scheduled for Tuesday evening in the Bay State Room to provide a gathering place to become acquainted with other registrants for informal discussions. Light refreshments will be served. Admission by registration badge. Ladies welcome.

Dinner

A roast beef dinner, preceded by a social hour, will be served in the Morse Auditorium of the Boston Museum of Science, on Wednesday evening. After dinner Dr. R. M. Bozorth of the Bell Telephone Laboratories will present a talk describing his recent visit to Russia to attend a conference on The Physics of Magnetic Phenomena. Dr. Bozorth will discuss Russian progress in magnetic research as well as the social life he and his wife observed on their trip through the country. In addition to attending the technical conference, they visited state nurseries, elementary schools, universities, an atomic power plant, and resort areas. Color slides will be shown.

Due to space restrictions, attendance is limited to 300 registrants. Tickets will be sold in advance; any tickets remaining will be sold at the registration desk on a first come - first serve basis. To be sure of attending the dinner, purchase tickets in advance.

Conference Proceedings

Proceedings containing all of the technical papers presented will be printed immediately after the conference. If ordered at the time of registration the price will be $4.00; otherwise the price will be $7.00.

Hotel Reservations

Accommodations are available at the Conference Headquarters, the Hotel Statler. (Other nearby hotels are the Sheraton Plaza, the Lincolnshire, and the Bradford.)

TECHNICAL PROGRAM

Tuesday, October 16, 1956

9:00 A.M. Opening Remarks. Georgian Room.
R. M. Bozorth, Conference Chairman

9:15 A.M. Session I Georgian Room

MAGNETIC ANISOTROPY
J. E. Goldman, Presiding

1. A Survey of the Theory of Magnetic Anisotropy (invited paper)
   J. H. Van Vleck, Harvard University

2. A New Magnetic Anisotropy
   W. H. Meiklejohn and C. P. Bean,
   G. E. Research Laboratory

3. Controlled Crystal Anisotropy of Various Mixed Ferrites
   C. M. van der Burgt, Philips Research Laboratories (Eindhoven, Netherlands)

4. Semicovalence and Anisotropy in Magnetic Oxides
   A. L. Loeb and J. B. Goodenough,
   Lincoln Laboratory, M. I. T.

10:45 A.M. INTERMISSION

5. Magnetic Annealing (invited paper)
   R. M. Bozorth, Bell Telephone Laboratories

6. Magnetic Domain Patterns on Thin Films
   R. C. Sherwood and H. J. Williams,
   Bell Telephone Laboratories

7. Magnetization of Nickel Films at Low Temperatures
   R. W. Hoffman and A. M. Eich,
   Case Institute of Technology

8. On the Determination of Magnetocrystalline Anisotropy Constants from Torque Measurements
   J. S. Kouvel and C. D. Graham, Jr.,
   G. E. Research Laboratory

2:00 P.M. Session II Georgian Room

PERMANENT MAGNETS AND FINE PARTICLES
R. M. Bozorth, Presiding

9. Fine Particle Magnets (invited paper)
   T. O. Paine, G. E. Measurements Laboratory

10. Magnetic Properties of some Iron and Iron Oxide Micropowders
    R. B. Campbell, H. Amar, A. E. Berkowitz, and P. J. Flanders, The Franklin Institute Laboratories for Research & Development

11. Determination of the Orientation of Crystallites in Elongated Particles in the Single-Domain Range
    R. B. Campbell, The Franklin Institute Laboratories for Research & Development

12. Reproducing the Properties of the Alnico Permanent Magnet Alloys with Elongated Single-Domain Cobalt-Iron Particles
    F. E. Luborsky, L. I. Mendelsohn, and T. O. Paine,
    G. E. Measurements Laboratory

13. Magnetic Anisotropy and Rotational Hysteresis in Elongated Fine Particle Magnets
    I. S. Jacobs, G. E. Research Laboratory, and F. E. Luborsky, G. E. Measurements Laboratory

14. The Relation Between Magnetic Properties and Crystal Morphology of Submicron Iron Crystals
    M. W. Freeman, M. W. Freeman Co., and John H. L. Watson, Edsel B. Ford Institute for Medical Research

3:45 P.M. INTERMISSION

15. A Contribution to the Study of Permanent Magnets of the Fe-Co-Ni-Al Type
    A. J. J. Koch, M. G. v. d. Steeg, and K. J. deVos, Philips Research Laboratory (Eindhoven, Netherlands)

16. Nucleation Experiments on Alnico 5
    E. A. Nesbitt and A. J. Williams,
    Bell Telephone Laboratories

17. Processing and Properties of Cobalt-Platinum Permanent Magnet Alloys
    D. L. Martin, G. E. Research Laboratory

18. Effects of Temperature Variations on the Remanence of Permanent Magnets
    R. K. Tenzer, The Indiana Steel Products Co.

19. Stress Corrosion in Permanent Magnets Composed of Anisotropic Powdered Manganese Bismuthide
    E. Adams, U.S. Naval Ordnance Laboratory

Wednesday, October 17, 1956

9:00 A.M. Session IIIa Georgian Room

MAGNETISM AND PHYSICAL METALLURGY
W. R. Hibbard, Presiding

20. Magnetism and Structure (invited paper)
C. Zener and R. R. Heikes,
Westinghouse Research Laboratories

21. A Neutron Diffraction Study of the Structures and Magnetic Properties of Manganese Bismuthide
B. W. Roberts, G. E. Research Laboratory

22. The Magnetic Structure of Annealed Fe_3Al
R. Nathans, M. T. Pigott, Pennsylvania State University and C. G. Shull, Massachusetts Institute of Technology

23. Some New X-ray Data on Iron-Rich Iron-Aluminum Alloys
A. Taylor and R. M. Jones,
Westinghouse Research Laboratories

24. Effect of Atomic Ordering on Magnetic Properties of 10 to 17 Per Cent Aluminum-Iron Alloys
D. Pavlovic and K. Foster,
Westinghouse Electric Corporation

10:45 A.M. INTERMISSION

25. Heat Treatment for High Initial Permeability in Binary and Complex Nickel-Iron Alloys Containing about 75% Ni
R. E. S. Walters, Post Office Engineering Dept., Research Branch, Dollis Hill, London, N.W. 2

26. Magnetostriction Measurements on Some Ordered and Disordered Fe-Pt Alloys
E. Klokholm and F. J. Donahoe,
The Franklin Institute Laboratories for Research & Development

27. Magnetic Measurements of Ni-Au Alloys
A. E. Berkowitz and P. J. Flanders,
The Franklin Institute Laboratories for Research & Development

28. Magnetization of Cr-Rich Fe-Cr Alloys from 2^oK to 300^oK
A. Arrott, Carnegie Institute of Technology

29. A Magnetic Method for the Measurement of Precipitate Particle Sizes in a Copper-Cobalt Alloy
J. J. Becker, G. E. Research Laboratory

30. Magnetic Properties of UMn_2
A. R. Kaufmann and S. T. Lin,
Massachusetts Institute of Technology

31. Strong Field Cryomagnetic Studies of Some Ferromagnetics, Ferrimagnetics and Antiferromagnetics
W. E. Henry, U.S. Naval Research Laboratory

9:00 A.M. Session IIIb Bay State Room

APPARATUS AND DESIGN
J. A. Osborne, Presiding

32. Magnetoabsorption
W. E. Bell, Varian Associates

33. Power Comparing Calorimeter
E. R. Czerlinsky and R. A. MacMillan,
Air Force Cambridge Research Center

34. Instrumentation for Magnetic Moment and Hysteresis Curve Measurements
P. J. Flanders, The Franklin Institute Laboratories for Research & Development

35. A Simple Method to Calculate Leakage Factors for Magnetic Circuits with Permanent Magnets
R. K. Tenzer, The Indiana Steel Products Co.

36. Instrumentation for and Measurement of Magnetostriction at Low Alternating Field Intensities in Silicon Iron
C. W. Little, Jr., and D. A. Wycklendt,
Allis-Chalmers Res. Lab

10:15 A.M. INTERMISSION

37. Investigation of an Alternating-Current Bridge for the Measurement of Total Core Losses in Ferromagnetic Materials at High Flux Densities
I. L. Cooter and W. P. Harris,
National Bureau of Standards

38. A New Ferroresonance Combination for Static Control Devices
A. T. Balint, University of Buffalo

39. New DC Hysteresigraph
J. D. Young, G. E. General Engineering Laboratory

40. An Automatic Torque Balance for the Determination of Magnetocrystalline Anisotropy
R. F. Penoyer, International Business Machine Corp.

2:00 P.M. Session IVa Georgian Room

LOSSES IN SOFT MAGNETIC MATERIALS
C. P. Bean, Presiding

41. The Origin of Losses in Magnetic Materials (invited paper)
    J. Goodenough, Lincoln Laboratories

42. The Effect of Impurities and Orientation on the Losses in Silicon Iron
    G. W. Wiener, Westinghouse Electric Corporation

43. The Effect of Plastic Deformation on the Core Loss of Oriented Silicon Steel
    J. K. Stanley, Crucible Steel Company of America

44. Domain Observation on Silicon-Iron
    C. D. Graham, Jr., G. E. Research Laboratory

45. Rapid Determination of Preferred Orientation in Magnetic Aluminum-Iron Alloys by Combination Etch Pit-Domain Pattern Technique
    P. Albert, Westinghouse Electric Corporation

46. The Effect of Aging on the Time Decay of Permeability in 3% Silicon Iron
    E. S. Anolick, G. E., Pittsfield

4:00 P.M. INTERMISSION

47. Magnetostriction of Aluminum-Iron Single Crystals in the Region of 6 to 30 Atomic Per Cent Aluminum
    R. C. Hall, Westinghouse Electric Corporation

48. Supermendur, A New Rectangular Loop Magnetic Material with High Flux Density and Low Coercive Force
    H. L. B. Gould and D. H. Wenny, Bell Telephone Laboratories

49. Sendust Flake - A New Magnetic Material for Low Frequency Application
    W. M. Hubbard, E. Adams, and J. F. Haben, Naval Ordnance Laboratory

50. Effects of Nuclear Irradiation on Magnetic Materials
    R. E. Fischell, D. I. Gordon, and R. S. Sery, U.S. Naval Ordnance Laboratory

51. Why Present Evaluation Methods for High Quality Magnetic Strip Materials are Inadequate
    P. W. Neurath, G. E., Pittsfield

3:00 P.M. Session IVb Bay State Room

FERRITES
V. C. Wilson, Presiding

52. New Magnetic Core Materials at Frequencies up to the UHF Band (invited paper)
    G. H. Jonker, H. P. J. Wijn, and P. B. Braun, Philips Research Laboratories (Eindhoven, Netherlands)

53. Domain-Wall Relaxation in Ferrites
    D. J. Epstein, Massachusetts Institute of Technology

54. The Remanent State in Ferrites According to the Rotation Model
    E. H. Frei and S. Shtrikman, The Weizmann Institute of Science Rehovot, Israel

55. Permalloy Characteristics in Ferrites
    D. Kooi, Lockheed Aircraft Corp.

4:30 P.M. INTERMISSION

56. Susceptibility of Normal Spinels from $2^{o}K$ to $300^{o}K$
    J. E. Goldman, Ford Motor Company, and A. Arrott, Carnegie Institute of Technology

57. Growth and Application of Ferrite Single Crystals
    W. G. Field and S. K. Dickinson, Air Force Cambridge Research Center

58. Preparation of Ferrites by the Atomizing Burner Technique
    J. F. Wenckus and W. Z. Leavitt, Lincoln Laboratories

59. Ferrite Accelerating Cavities for a 25 Billion Electron Volt Proton Synchrotron
    M. Plotkin, Brookhaven National Laboratory

Thursday, October 18, 1956

9:00 A.M. Session V Georgian Room

HIGH FREQUENCY PHENOMENA
G. T. Rado, Presiding

60. Fundamentals of Ferromagnetic Resonance (invited paper)
    N. Bloembergen, Harvard University

61. Ferromagnetic Resonance in Highly Anisotropic Crystal Metals
    J. O. Artman, Harvard University

62. Single Crystal Intrinsic Permeabilities of Ferrites
    E. G. Spencer, R. C. LeCraw, L. A. Ault, and J. E. Tompkins, The Diamond Ordnance Fuze Laboratories

63. Domain Structure Effects in an Anomalous Ferrimagnetic Resonance of Ferrites
    R. C. LeCraw and E. G. Spencer, The Diamond Ordnance Fuze Laboratories

64. Reversible Properties of Ferromagnets
    D. M. Grimes, University of Michigan

10:45 A.M. INTERMISSION

65. Microwave Applications of Magnetic Materials (invited paper)
    D. L. Hogan, Harvard University

66. A New Faraday Rotation Phenomenon and its Application to Microwave Switching
    J. A. Weiss, Bell Telephone Laboratories

67. The Production and Use of High Intensity Pulsed Magnetic Fields
    S. Foner and H. H. Kolm, Lincoln Laboratories

68. The Microwave Susceptibility of Polycrystalline Ferrites in Strong DC Fields and the Influence of Non-Magnetic Inclusions on the Microwave Susceptibility
    E. Schlömann, Raytheon Manufacturing Company

2:00 P.M. Session VI Georgian Room

MEMORY DEVICES AND MAGNETIC AMPLIFIERS
D. R. Brown, Presiding

69. High Frequency Effects in Magnetic Films (invited paper)
    R. L. Conger, U.S. Naval Ordnance Laboratory, Corona, Calif.

70. Relation between Magnetic-Core Switching-Time and the Width of Ferromagnetic Resonance Peaks
    R. P. Coleman, Burroughs Corporation, Research Center

71. Magnetization Reversal in Thin Films
    D. O. Smith, M. I. T., Lincoln Laboratories

72. Some Switching Properties of Square Loop Ferrites
    E. M. Gyorgy and J. L. Rogers, Bell Telephone Laboratories

73. Magnetic Viscosity in 4-79 Moly Permalloy
    O. J. Van Sant, U.S. Naval Ordnance Laboratory

3:45 P.M. INTERMISSION

74. The Ferractor (invited paper)
    T. Bonn, Sperry-Rand Univac Division

75. The Crossed-Field Magnetic Amplifier and its Applications
    E. H. Frei and D. Treves, The Weizmann Institute of Science, Israel

76. The Ferrite Bead - A New Memory Device
    D. H. Looney, Bell Telephone Laboratories

77. Characteristic of a Memory Array in a Sheet of Ferrite
    R. H. Meinken, Bell Telephone Laboratories

Session I MAGNETIC ANISOTROPY
J. E. Goldman, Presiding

1. A SURVEY OF THE THEORY OF MAGNETIC ANISOTROPY*
J. H. Van Vleck
Harvard University, Cambridge, Mass.

*invited paper

2. A NEW MAGNETIC ANISOTROPY
W. H. Meiklejohn and C. P. Bean
General Electric Research Laboratory,
Schenectady, N. Y.

A new type of magnetic anisotropy has been discovered which is best described as an exchange anisotropy. This anisotropy is the result of an interaction between an antiferromagnetic material and a ferromagnetic material. A material that exhibits this exchange anisotropy is fine particles of cobalt with a cobaltous oxide shell. The material is made by electrodeposition of cobalt into mercury. The fine particles of cobalt (200 Å) are then surface oxidized to form cobaltous oxide. The resultant particles have a core of cobalt and a shell of cobaltous oxide. Above the Neel temperature (paramagnetic state) these fine particles of oxide-coated cobalt have magnetic properties as expected for pure cobalt particles. Below the Neel temperature of the cobaltous oxide, there exists an interaction between the spins of the ferromagnetic cobalt and the antiferromagnetic oxide. In order to best observe the exchange anisotropy of a randomly-oriented compact of fine particles, the material is cooled from the paramagnetic state of the oxide to the antiferromagnetic state in a saturating magnetic field. Since the Neel temperature of cobaltous oxide is 293°K, the material was cooled from 300° to 77°K in a magnetic field. The exchange anisotropy is a unidirectional anisotropy in that it produces one easy direction of magnetization. As a result, the torque curve is proportional to sin θ and not sin 2θ as in materials of uniaxial anisotropy such as pure cobalt. An anisotropy constant of 5×10^6 ergs/cm^3 has been calculated from the torque curves. Another manifestation of this unidirectional anisotropy is a displaced hysteresis loop which occurs when the specimen is cooled in a magnetic field. Both the coercive force and the residual flux density become asymmetrical along the axis of magnetization. Experimental values of 2,200-oersteds loop displacement and 5,400-oersteds coercive force have been obtained. In the case that the exchange anisotropy is along the same axis as the applied field the material acts as though the effective field (H') is

$$H' = H_a - Kx/I_s,$$

where H_a is the applied field and Kx is the exchange anisotropy constant. The displacement of the hysteresis loop was not changed even in fields of 70,000 oersteds. Another unusual property of this material is a rotational hysteresis that is substantially independent of the applied field at high fields. The rotational hysteresis was measured to be 5.7×10^6 ergs/cm^3, whereas the rotational hysteresis of pure cobalt particles at the same very high fields was essentially zero. This interaction between the ferromagnetic cobalt and the antiferromagnetic cobaltous oxide allows a measure of the lower limit of the anisotropy of an antiferromagnetic material.

3. CONTROLLED CRYSTAL ANISOTROPY OF VARIOUS MIXED FERRITES

Cornelis M. van der Burgt
Philips Research Laboratories
N. V. Philips' Gloeilampenfabrieken
Eindhoven, Netherlands

Dynamic elasticity at remanence, piezomagnetic coupling at remanence, and initial permeability of polycrystalline toroids of various cobalt-substituted ferrites were determined over the temperature range from -196°C to +120°C at least. The compositions are represented approximately by

$$(M_{1-y}\,Zn_y)_{1-x}\,Co_xFe_2O_4,$$

where M stands for $Li^{1+}_{1/2}\,Fe^{3+}_{1/2}$, Ni^{2+}, and Mn^{2+}.

The magnetocrystalline anisotropy constant K_1 of cobalt ferrite is known to be large and positive (K_1 = 2 to 3×10^6 erg/cm^3). Consequently incorporation of a small amount of cobalt ferrite in solid solution in other ferrites that have $K_1 < 0$ (ferrous, nickel, manganese ferrites, and presumably lithium ferrites) may lead to a compensation of crystal anisotropy at a transition temperature T_o depending on the amount of cobalt ferrite. The fact that the crystal anisotropy, which is positive at low temperatures, passes zero at a temperature T_o implies that around this temperature only strain anisotropy and pore shape anisotropy remain, so that there exists a small temperature range where the substance is magnetically and magnetoelastically soft. The resulting peaks in the permeability and compliance, together with the overall increase of these quantities with temperature, lead to a temperature range somewhere above T_o where the permeability and the elasticity are substantially temperature independent.

Previous experiments by Bickford et al., who measured the initial permeability and the initial slope of the magnetostriction curve, revealed that small cobalt-substitutions in ferrous ferrite ($K_1 \approx -110{,}000$ erg/cm^3) resulted in a transition temperature $T_o = 20°C$ for $x = x_{20} \approx 0.012$. This means that the compensating effect of the cobalt-substitution is 3 to 4 times as strong as expected, i.e. $\propto$ = 3 to 4 in the simple relation

$$K_1(x)=(1-x).K_1(x=o) + \propto.x.K_1(x=1).$$

Similarly the experiments on lithium ferrite, which, in view of its low permeability, presumably has a magnetic anisotropy comparable to that of ferrous ferrite, resulted in a value $x_{20} \approx 0.013$.

On the other hand, cobalt-substitutions in nickel ferrite ($K_1 \approx -60{,}000$ erg/cm^3), in equimolar nickel-zinc ferrite ($K_1 \approx -40{,}000$ erg/cm^3), and in manganese ferrite ($K_1 \approx -26{,}000$ erg/cm^3) appeared to be less effective than expected, the values of x_{20} being ≈ 0.028, ≈ 0.040, and ≈ 0.030, respectively, so that $\propto$ is about 5/6, 2/5, and 3/5. Nevertheless the curves

$$T_o \text{ vs } x_{T_o}$$

for all systems of cobalt-substituted mixed ferrites have a similar shape.

4. SEMICOVALENCE AND ANISOTROPY IN MAGNETIC OXIDES†

Arthur L. Loeb and John B. Goodenough
Lincoln Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.

In a previous paper[1] a magnetic-exchange mechanism was proposed that is consistent with ion distribution and lattice distortions as well as with the observed atomic-moment coupling in metallic oxides. From this model it follows that cation-orbital angular momentum is usually quenched. Two common cases where the orbital momentum is not quenched are Co^{2+} and Fe^{2+} in octahedral sites: In these cases spin-orbit coupling is important for the magnetic anisotropy. In other cases some other mechanism must be responsible for the anisotropy. In crystals whose atomic moments are subject to the restrictions imposed by antiferromagnetic exchange, the magnetic dipole-dipole interactions provide a magnetic anisotropy of at least the observed order of magnitude. The dipole-dipole interaction may also induce lattice distortion. These distortions are to be distinguished from those caused by covalent-bond formation. These considerations are applied to various simple and mixed oxides of manganese, iron, cobalt, and nickel. The predictions are compared to most recent neutron-diffraction results.

1. J. B. Goodenough and A. L. Loeb, "Theory of Ionic Ordering, Crystal Distortion, and Magnetic Exchange Due to Covalent Forces in Spinels", Physical Review Vol. 98, No. 2, 391-408, April 15, 1955.

† The research in this document was supported jointly by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

5. MAGNETIC ANNEALING*

R. M. Bozorth
Bell Telephone Laboratories, Incorporated,
Murray Hill, N. J.

This is a review of the results and theories relating to heat treatment of magnetic materials in a magnetic field.

These materials are of several kinds: (1) permanent magnets of the Alnico type, (2) soft alloys of the Fe-Co-Ni and Fe-Si systems, (3) thin films of alloys, and unalloyed cobalt and nickel, and (4) ferrites such as cobalt-ferrites.

Materials of kind (1) are pretty well understood as due to the growth of a finely divided precipitate, the direction of growth being influenced by the field. The fine elongated particles account for the anisotropy and the high coercive forces observed. A similar kind of growth of elongated, crystallographically oriented particles in a field has been observed in MnBi.

A number of theories have been proposed for explaining the properties of kind (2). Most of these are concerned with the production of long-range or short-range ordering, but this is somewhat difficult to apply to the binary Co-Ni alloys in which no long-range ordering has been detected.

Atomic ordering cannot explain the recent observations on materials of kind (3) in which uniaxial symmetry and square loops have been observed for films of the elements Fe, Co, Ni, and some of their alloys deposited by evaporation in a field, or annealed in a field after deposition. Theories to explain materials of kind (4), the ferrites, are much the same as for kinds (1) and (2).

An explanation that is consistent with the existence of the effect in thin films of the elements, and in other materials, is based on the influencing of the geometry of imperfections (dislocations) by the magnetic anneals. A number of consequences and tests of this theory will be mentioned.

* invited paper

6. MAGNETIC DOMAIN PATTERNS ON THIN FILMS (WITH MOVIES)

R. C. Sherwood and H. J. Williams
Bell Telephone Laboratories, Incorporated
Murray Hill, N. J.

Magnetic domain patterns have been observed on films ranging in thickness from 50Å to 12,000Å, by means of the Bitter technique. The films were made by E. M. Kelly of these Laboratories, by evaporating Fe, Ni, Co, and several alloys of these elements in a vacuum. The films were deposited in a magnetic field following the procedure of Blois and Conger to obtain a uniaxial direction of easy magnetization. It was found that the easy direction of magnetization could be changed by reheat-treating the films in a field with a new orientation.

In general, the character of the domain patterns is dependent on the thickness of the films instead of the composition. Nuclei of reversed magnetization, long curved boundaries, and zigzag boundaries which move along the easy direction when the field is applied in this direction, were observed on all the films. The boundaries of the thinner films are more irregular, and their motion is impeded by imperfections in the films.

Long slender domains were obtained on films ranging from approximately 200Å to 500Å in thickness by first saturating the film along the direction of easy magnetization and then applying a reverse field at an angle of about 30° to the easy direction. This procedure gave a pattern on a 200Å film of iron having approximately 1500 boundaries per cm. The boundaries always tend to make an angle of approximately 30° with the easy direction even though the reverse field is applied at angles considerably different from 30°. The successive application of a reverse field first 30° on one side of the easy direction and then 30° on the other side forms a rhomboid pattern.

The very thin films, approximately 150Å or less in thickness, showed very dense concentrations of boundaries and double boundaries after demagnetizing with an a-c field approximately perpendicular to the direction of easy magnetization. The tendency of the boundaries in the very thin films to aggregate is attributed to the magnetostatic energy which is decreased by aggregation.

Motion pictures of domain patterns on some of the films will be shown.

7. MAGNETIZATION OF NICKEL FILMS AT LOW TEMPERATURES

R. W. Hoffman and A. M. Eich
Case Institute of Technology
Cleveland, Ohio

The relative magnetization of evaporated nickel films has been measured as a function of thickness over the temperature range from 10°K to 300°K. The films were condensed on glass substrates held at 75°C in vacuum of 1×10^{-5} mm Hg. and were coated with SiO immediately after formation to prevent oxidation. Thicknesses were determined from electrical conductance measurements on a companion sample using a chemical mass determination for calibration. The films, 35A to 1350A thick, were annealed for 4 hours at 275°C in vacuum and then removed from the system for the magnetic measurements. The magnetization was measured with a 60 cps M-H loop tracer using a maximum field of 200 oersteds. Coercive forces for the films ranged from 10 oersteds to 35 oersteds. Klein and Glass[1] have recently calculated the M/M_o versus reduced temperature, kT/J, curves for f.c.c. films using the spin wave approach. Comparison of the experimental and theoretical curves using the value of J = 230k as deduced from low temperature measurements of M/M_o on bulk nickel by Fallot[2] yields poor agreement. If J is regarded as a parameter and a fit is made at one value of M/M_o, the experimental points agree well with the theoretical curves for any given film. The agreement holds over values of M/M_o from 0.7 to 1.0 where the spin wave approximations should be valid. Values of J found in this fashion seem to depend on the film thickness, ranging from about J = 75 k for a 35A film to J = 150 k for a 1350A film.

1. S. J. Glass, M. S. Thesis Case Institute of Technology (to be published). For a similar calculation on simple cubic films see M. J. Klein and R. S. Smith, Phys. Rev. 81, 378 (1951)

2. M. Fallot, Ann. Phys. 6, 305 (1936).

8. ON THE DETERMINATION OF MAGNETOCRYSTALLINE ANISOTROPY CONSTANTS FROM TORQUE MEASUREMENTS

J. S. Kouvel and C. D. Graham, Jr.
General Electric Research Laboratory
Schenectady, N. Y.

The results of careful torque measurements on {100} single crystal discs of 3-1/4 per cent silicon-iron were found to disagree in some respects with previous work. This has led to a reconsideration of many of the details of the theory underlying such measurements.

The maximum torque observed in a torque test has generally been found to increase with increasing field according to Tarasov's empirical relation $L_{max} \propto 1-aH^{-1}$, and this relation has been used for extrapolation to infinite field. In the present work, however, the peak torque increases as $1-cH^{-1/2}$ over the range 1000 to 10,000 oersteds. The variation of c with the shape of the disc led to a consideration of Tarasov's suggestion that the edges of a disc specimen are not saturated even in fields greater than the anisotropy field plus the demagnetizing field (computed for the inscribed oblate spheroid). For this effect to produce a torque, the magnitude of the net magnetization must depend on its direction relative to the crystal axes. Moreover, for this torque to oppose the torque resulting from crystal anisotropy, the net magnetization, I, must be largest in the hard directions and smallest in the easy directions. If I is expressed as a function of θ, the angle between I and a ⟨100⟩ direction, in such a way that the amplitude but not the shape of the L versus θ curve depends on field, it is found that a small variation of I with θ results in a large change in the torque peaks. Specifically, a 30 per cent decrease in torque peaks with a decrease in field from 10,000 to 1000 oersteds, as observed in one of our discs, can be accounted for by an increase in the fluctuation of I with θ from an extremely small value to only 1.6 per cent. Direct observation of the domain patterns on a {100} disc prove the lack of saturation at the edges of the disc, and appear to confirm the postulated variation of I with θ.

A similar analysis was applied to torque measurements on a {110} disc. It was observed for both the {100} and {110} discs that the effective anisotropy constants derived from the slopes of the torque curves differed somewhat from the values obtained from the torque peaks. Further study showed that even at fields up to 20,000 oersteds the shape of the L versus θ curve was not entirely independent of field. As a consequence, some ambiguity remains in the determination of K_1; this ambiguity may prevent the determination of K_2 when K_2 is small compared to K , as in the present experiments.

Session II PERMANENT MAGNETS AND FINE PARTICLES
R. M. Bozorth, Presiding

9. FINE-PARTICLE MAGNETS*

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The concept of the single-domain particle is briefly developed from domain theory, and a physical picture presented of the relation between particle properties and fundamental anisotropy and exchange forces. The characteristics of fine-particle magnets are then related to the basic properties of aligned and compacted single-domain particles. Permanent magnet properties that have been experimentally attained for fine particles of various materials are reviewed, and compared to the estimated maximum theoretically obtainable.

* invited paper

10. MAGNETIC PROPERTIES OF SOME IRON AND IRON OXIDE MICROPOWDERS+

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The theory of highly dilute ferromagnetic micropowders treats these powders in first approximation as a set of Stoner-Wohlfarth assemblies[1]. In each of these assemblies, the particles are, by definition, randomly oriented single-domain noninteracting ellipsoids of revolution with the same axial ratio, m, volume, v, and magnetization density, I_o.

The agreement with experiment is only qualitative; for example, the predicted value of the coercivity is usually too high, although of the correct order of magnitude. The quantitative discrepancy is, however, substantially decreased by a more rigorous computation of the theoretical values. The following scheme is suggested:

1. Determination, through careful measurements on the electron micrographs n(m,v)dmdv, fractional number of particles with elongation and volume in the respective ranges (m, m + dm) and (v, v + dv). The volume fraction of particles with elongation, m, is then

$$g(m) = \mathcal{S}_v n(m, v).v \qquad (1)$$

where $\mathcal{S}$ stands for integration or summation.

2. Starting from the Stoner-Wohlfarth[1] and Rhodes[2] tables, derive the "magnetization matrix" F(H,m), yielding the magnetization curve for an m-assembly. The magnetization curve of the actual powder is then given by

$$\frac{I_H}{I_0} \equiv f(H) = \int F(H,m)\, g(m) \qquad (2)$$

In (1), one should delete from the m-v plane of integration the area corresponding to multi-domain and superparamagnetic particles as suggested by Bean[3].

It will be shown in general that the predicted value of the coercivity is lowest when:

1. The whole distribution (and not simply its median) is considered.

2. The contribution of the superparamagnetic and multi-domain particles is taken into account.

Measurements have been made on a series of dilute iron and iron oxide micropowders in an effort to correlate their magnetic and structural properties. The magnetic measurements include magnetization and hysteresis curves for various temperatures, coercive force and remanence as functions of applied field, and preliminary torque data. The structural measurements include particle counts from electron micrographs to determine size and shape distributions, crystallite size, and composition. The influence of the distribution functions on the field and temperature dependence of the remanence, coercive force, and the ratio of remanence to saturation will be discussed.

Coercive force and remanence have been measured in the range from room temperature to liquid nitrogen temperature on samples of magnetite micropowders. These data have been obtained with and without an applied field during cooling. A change of slope in the coercive force versus temperature curve occurs at the cubic orthorhombic transformation temperature ($\sim -160^\circ C$). The increase in coercive force in the orthorhombic magnetite is in accord with the crystal anisotropy measurements of Williams, Bozorth and Goertz[4], although crystal anisotropy does not appear to determine the coercive force in the cubic region. The remanence curve obtained with a field applied during cooling shows a similar increase in slope at the transformation temperature. This behavior apparently corresponds to the establishment of an easy axis near the field direction in accordance with the mechanism proposed by several investigators[5].

1. E. Stoner and E. Wohlfarth, Trans. Roy. Soc., (London), A-240, 599 (1948).

2. Rhodes, P., Proc. Leeds. Phil. Lit. Soc., 5, 116 (1949).

3. C. P. Bean, J. Appl. Physics, 26, 1381-83 (1955).

4. H. J. Williams, R. M. Bozorth, and M. Goertz, Phys. Rev., 91, 1107 (1953).

5. Reference 4 contains references to the previous work.

+ This work was performed under the cooperatively sponsored Magnetics Research Program at The Franklin Institute Laboratories for Research and Development.

11. DETERMINATION OF THE ORIENTATION OF CRYSTALLITES IN ELONGATED PARTICLES IN THE SINGLE-DOMAIN RANGE+

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A method is described for determining the orientation of crystallites in a multi-crystalline, acicular particle by electron diffraction techniques. In a particle with oriented crystallites, all of the crystallites have a common crystallographic direction along the axis of the particle; the crystallites may be rotated randomly about the common direction. Utilizing the selected area diffraction unit of the RCA-EMU-2C electron microscope, a single particle can be isolated and its diffraction pattern obtained. At the same time, the spatial orientation of the particle with respect to the pattern is determined.

If the particle being studied is multi-crystalline with oriented crystallites, the diffraction pattern has the appearance of an X-ray rotation diffraction pattern of a single crystal; i.e., a very definite pattern of well defined spots. If, however, the crystallites are not oriented, the pattern has the usual appearance with arcs or circles. Interpreting the oriented pattern by fairly standard methods, one can show which common crystallographic direction of the crystallites is along the axis of the particle.

Initial experiments were carried out on samples of γ-Fe_2O_3 with a particle size of approximately 1 μ x 0.2 μ and with crystallite sizes ranging from 50Å to 800Å as determined by X-ray line broadening.

In general, the data indicate that a large majority of the particles have oriented crystallites. This orientation direction varies from particle to particle, but within a given particle all the crystallites usually have a common orientation axis. The crystallographic direction found is generally of low order such as 210, 221, etc. Particles have been observed in which the orientation is not perfect, with the spots being slightly elongated, and a few particles observed have shown essentially random orientation. The results will be compared with those of Osmond[1] who by an entirely different method placed the <111> direction along the axis of the particle. Implications of these results as to the relative roles of shape anisotropy and crystalline anisotropy on magnetic properties will be discussed.

Similar preliminary work on iron oxide hydrates and pure iron will also be reported.

1. W. P. Osmond, Proc. Phys. Soc., 66, 4-B pp 265 (1953).

+ This work was carried out under the cooperatively sponsored Magnetics Research Program at The Franklin Institute Laboratories for Research & Development.

12. REPRODUCING THE PROPERTIES OF THE ALNICO PERMANENT MAGNET ALLOYS WITH ELONGATED SINGLE-DOMAIN COBALT-IRON PARTICLES

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Single-domain particles of 40:60 cobalt-iron alloy have been prepared with a median diameter of 200 angstrom units, a median elongation of 5.4:1, and an intrinsic coercive force of 1900 oersteds. By compacting these particles with various degrees of alignment and packing density, shape anisotropy fine-particle magnets have been made with magnetic properties duplicating those of each of the Alnico permanent magnet alloys, including maximum energy product values above five million gauss-oersteds. It is concluded that the Alnico alloys and the cobalt-iron fine-particle magnets derive their permanent magnet properties from very similar, though not identical, shape anisotropy effects.

13. MAGNETIC ANISOTROPY AND ROTATIONAL HYSTERESIS IN ELONGATED FINE PARTICLE MAGNETS

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and
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Various aspects of the magnetic anisotropy of electrodeposited elongated single domain Fe and FeCo alloy particles are examined with a view to better understanding their process of magnetization. The initial increase of coercivity with increase of the angle between alignment direction and measuring field is in qualitative accord with the prediction of the chain-of-spheres model previously proposed and in contrast to coherent rotation models. The behavior of torque curves at high fields suggests that an anisotropy is present which is a little greater than predicted by the chain-of-spheres model but less than that predicted by the Stoner-Wohlfarth ellipsoid model, for the observed dimensional ratios. Calculations of the rotational hysteresis in single domain particles are extended to the chain-of-spheres model. A study of the rotational hysteresis enables a relatively sensitive choice between several models of the magnetization process. The results again suggest a slightly greater anisotropy than predicted by the chain-of-spheres model. Comparison of the observed and predicted values for the rotational hysteresis integral, $\int (W_R/I_s)d(1/H)$, indicates strongly that a non-uniform rotation process, like fanning in a chain-of-spheres, is operative in electrodeposited ESD particles.

14. THE RELATION BETWEEN MAGNETIC PROPERTIES AND CRYSTAL MORPHOLOGY OF SUBMICRON IRON CRYSTALS

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Detroit, Michigan

Electron Microscopic studies and magnetic measurements are being carried out on specially prepared submicron alpha iron crystals. Experimental data will be presented to illuminate the relationship between morphology and magnetic properties of submicron iron particles.

15. A CONTRIBUTION TO THE STUDY OF PERMANENT MAGNETS OF THE Fe-Co-Ni-Al TYPE

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In order to improve the magnetic properties of the Fe-Co-Ni-Al alloys a study was made of the cause of the coercive force.

This study comprises an investigation of the phase relations in these alloys as well as an extensive analysis of the heat treatment.

For the investigation of the phase relations several methods were used. Alloys of different composition were annealed to approach equilibrium and their structures examined by microscope as well as by X-rays. The course of the phase reactions was examined by dilatometric methods. In some cases also high-temperature X-ray diffraction was applied.

The heat treatments comprise the standard permanent magnet heat treatment as well as isothermal- and cyclic-treatments.

An alloy, with the composition 24% Co, 14% Ni, 8% Al, 3% Cu, 51% Fe, known as Ticonal G+, was particularly studied.

It was shown that during the standard heat treatment of this alloy two different processes are taking place.

The first reaction, the splitting up of the α matrix into $\alpha + \alpha'$ mainly takes place in the region between 850°C and 750°C.

The second one, precipitation of an f.c.c. phase in addition to $\alpha + \alpha$, can only occur below 750°C, i.e. during tempering.

After a heat treatment during which only the first reaction could occur, a coercive force of less than about 20 oersted was measured; the second reaction always gives rise to a substantial increase in the coercive force.

Similar reactions have been found in other Fe-Co-Ni-Al alloys.

Particularly in the alloy with the composition 34,0% Co, 14,5% Ni, 7,0% Al, 4,5% Cu, 5,0% Ti, bal. Fe, possessing a coercive force twice that of Ticonal G, the f.c.c. phase appears in a larger proportion.

The alloy with the composition 24,0% Co, 14,0% Ni, 8,0% Al, 3,0% Cu, 2,0% Nb, bal. Fe has a coercive force of about 850 oersted.

In this alloy, apart from the f.c.c. precipitate, an additional precipitate has been observed.

Apparently there is a correlation between the arising of the coercive force in these alloys and the precipitation phenomena during tempering.

A possible explanation of the mechanism that gives rise to the magnetic properties is offered.

\+ A similar alloy is known as Alnico 5 in U.S.A.

16. NUCLEATION EXPERIMENTS ON ALNICO 5

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Current fine particle theory is successful in accounting for the coercive force of many permanent magnets but it does not explain why certain magnets, notably Alnico 5, respond to heat treatment in a magnetic field. This work presents experimental evidence which supports the theory of Kittel, Nesbitt, and Shockley for the heat treatment of Alnico 5. In studying the effect of the magnetic field applied during the heat treatment of Alnico 5, two important ranges of temperature are visualized. First, the range of temperature of thermal nucleation of the precipitate from 890°C to 790°C and second, the range of temperature of growth of precipitate particles from 790°C to 550°C. When the field was applied only during the range of thermal nucleation and the specimen then rapidly cooled (15°C per second) to room temperature and aged at 600°C, regular Alnico 5 properties were obtained. However, when the field was applied only during the range of growth of the precipitate particles and aged at 600°C, low energy products were obtained. These results indicate that the magnetic field is effective mainly during the range of thermal nucleation of the precipitate. In addition, the results enable one to visualize a simple picture of the heat treatment of Alnico 5.

17. PROCESSING AND PROPERTIES OF COBALT-PLATINUM PERMANENT MAGNET ALLOYS

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The study of cobalt-platinum alloys has been of scientific interest since these alloys represent a kind of permanent magnet material that is different from Alnico. The controlling reaction being an order-disorder transformation.

An investigation of the structure, mechanism and kinetics of the disorder-order transformation and resulting property changes in cobalt-platinum alloys has been in progress for some time. In this report the processing and heat treatment studies on alloys in the range 40 - 60 atomic per cent cobalt are presented.

Cobalt-platinum alloys have been prepared by melting and by sintering. To obtain good working characteristics it was found that care must be taken in selecting the cobalt. Some grades of cobalt resulted in an alloy that cracked during hot swaging. It is believed that the hot-shortness observed was due to sulphur embrittlement, and by using low sulphur cobalt the effect was eliminated. The ductile alloys could be cold worked, but only after quenching from a high temperature to retain the disordering phase.

The magnetic properties have been found to be greatly influenced by the composition, by the cooling rate from the disordering treatment, and the final ordering time and temperature. Coercive force values (Hc) of 4700 and energy product values (BHm) of 9 million have been obtained by controlled cooling and ordering.

The saturation and residual induction increases with cobalt content, whereas the coercive force (Hc and Hci) is higher for platinum-rich alloys in the range 50-60 atomic per cent platinum. The energy product value peaks around the 50 atomic per cent alloy.

Density, electrical resistivity, and X-ray parameter data for the alloys are given. The density has been very useful in checking the compositions of the alloys studied.

Session II

18. EFFECTS OF TEMPERATURE VARIATIONS ON THE REMANENCE OF PERMANENT MAGNETS

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Irreversible and reversible changes of remanence with temperature between -60 and +350°C were measured on cylinder-shaped magnets of the Alnicos 3, 5, and 6, Cunife, and barium ferrite. Samples of different length:diameter ratios were investigated. The medium-sized sample always operated at the (BH)max value. The results of the measurements are presented in several graphs.

An interpretation of the reversible effects is based on the classification of the investigated materials into the following groups:

1. Materials which have one phase.

2. Materials with two phases, one of which is ferromagnetic.

3. Materials with two phases, both of which are ferromagnetic.

It appears that a knowledge of the reversible changes of remanence with temperature for different operating points can help to decide whether a permanent magnet material has one or more magnetic phases.

The interpretation of the observed irreversible losses is based on properties which determine the magnetization processes.

Materials which show irreversible losses in remanence after low temperature cycles are characterized by "anisotropic regions" in the material. The easy axis of magnetization in these regions may be due to shape or crystal anisotropy. The anisotropic regions usually comprehend many domains.

19. STRESS CORROSION IN PERMANENT MAGNETS COMPOSED OF ANISOTROPIC POWDERED MANGANESE BISMUTHIDE

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The corrosion of anisotropic ultra-fine particle permanent magnets is usually attributed to the extreme reactivity of the starting powder and the resulting porosity after compacting. In low energy systems, such as ultra-fine iron magnets of essentially spherical particles, corrosion can be effectively reduced or prevented by internal and external organic coatings. However, in high energy systems, such as Bismanol compacts of highly anisotropic particles of manganese bismuthide, the use of most protective films only delayed corrosion. A qualitative examination showed that the Bismanol magnets, upon exposure to high humidity atmospheres, developed cracks and fissures at sharp corners if flux concentrations exist. This is analogous to the stress-corrosion phenomena occurring in structural alloys. High coercive force magnets deteriorated more rapidly than low energy magnets. It was found that stress-corrosion in Bismanol can be eliminated by complete encapsulation and minimized by arranging the magnetic circuit to avoid flux concentrations.

Session IIIa MAGNETISM AND PHYSICAL METALLURGY
W. R Hibbard, Presiding

20. MAGNETISM AND STRUCTURE*

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The magnetic structure of any system, atom, molecule, or crystal, is but a reflection of the type of binding. The importance of magnetism to an understanding of structure is that a study of the magnetic properties gives a clue to the type of binding. The type of binding may in turn be correlated rather closely with structure. The purpose of the present paper is to review the information which magnetism tells us about binding type, and then to correlate this information with structure.

A review is given of the various types of binding: polar, interpenetration, metallic, covalent, double exchange, and superexchange. The influence of position in the periodic table upon the relative importance of the various types of binding is discussed. The magnetic manifestations of the various types of binding is given particular attention.

Because of their relatively simple structure, polar crystals are discussed first. Experimental evidence is cited which points to a localized model as being a better approximation than the band model in the case where the cation is a transition metal. The various consequences of such a localized model are discussed.

Typical of such examples are the magnetic behavior of the transition metal chalkogenides, the correlation between electrical conductivity and magnetic structure, and the occurrence of an activation energy associated with electron mobility. Particular attention is devoted to crystals having transition metal ions of mixed valency.

Whereas in transition metals the most appropriate model is not as unambiguous as in polar crystals, the localized model is adopted, and the consequences thereof are compared with experiment. Examples of such consequences are crystal type, anamolous thermal expansion, and phase changes.

21. A NEUTRON DIFFRACTION STUDY OF THE STRUCTURES AND MAGNETIC PROPERTIES OF MANGANESE BISMUTHIDE+

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The intermetallic compound, BiMn, has been studied by neutron diffraction techniques at temperatures from 4.2°K to 733°K (460°C). In the temperature range 340-360°C to 445°C a disordered structure with random occupation of Mn atoms on regular and interstitial lattice sites fits the data well if the Mn atoms are assumed to be in the paramagnetic state. This disordered model conflicts with the suggestion made by Guillaud[1] of an antiferromagnetic state in the above temperature range. The temperature hysteresis associated with both magnetization and the large cell distortions are qualitatively explained by the disordering and recovery at the transformation temperatures. The effective moment per Mn atom below the transformation agrees with the magnetic measurements of Heikes[2] within experimental error. Observations on spin orientation directions made at temperatures below 84°K show that only partial moment rotation occurs in zero applied magnetic field.

1. Guillaud, C., J. Phys. Radium 12, 143 (1951).

2. Heikes, R. R., Phys. Rev. 99, 446 (1955).

+ Neutron diffraction experiments were carried out at the Brookhaven National Laboratory Reactor, Upton, Long Island, New York.

22. THE MAGNETIC STRUCTURE OF ANNEALED Fe_3Al+

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Pennsylvania State University,
and
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The magnetic structure of a powdered sample of annealed Fe_3Al has been investigated by neutron diffraction techniques. Examination of the magnetic scattering in the superlattice peaks has yielded information on the values for the magnetic moments of the various iron and aluminum atoms. The results show that for those iron atoms whose nearest neighbors are all iron, a value of approximately 2.2 μ_B is observed, while for those iron atoms whose nearest neighbor environment is 50% iron and 50% aluminum, a moment of around half this amount is found. The value for the aluminum moments was found to be very close to zero. Thus, the neutron diffraction results seem to indicate a definite nearest neighbor dependence for the iron magnetic moments.

Current experiments are being carried out on a single crystal of Fe_3Al using a polarized beam of neutrons in order to improve the accuracy of the final determination of the individual moment values. In addition, measurements on quenched and cold-worked materials of similar compositions will be reported on.

+ Research carried out at the Brookhaven National Laboratory under the auspices of the U.S. Atomic Energy Commission and the National Security Agency.

23. SOME NEW X-RAY DATA ON IRON-RICH IRON-ALUMINUM ALLOYS

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and
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The constitution of high purity iron-aluminum alloys over the range 0-50 atomic per cent aluminum has been investigated by X-ray diffraction methods. New lattice parameter data on quenched and annealed alloys are presented which differ significantly from the classical results of Bradley and Jay obtained nearly 25 years ago. The new data show discontinuities which are closely associated with the magnetic properties of the alloys. Diffraction patterns taken at elevated temperatures reveal new types of order-disorder transformations and expansion phenomena which may be associated with a large volume magnetostriction. A ferromagnetic face centered cubic phase-structure with probable composition Fe_3Al is found associated with alloys over the range 18-33 atomic per cent aluminum. This structure, which is probably epitaxially related to the body-centered cubic matrix of the alpha phase, undergoes an order-disorder transformation.

24. EFFECT OF ATOMIC ORDERING ON MAGNETIC PROPERTIES OF 10 TO 17 PER CENT ALUMINUM-IRON ALLOYS+

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The aluminum-iron alloys containing 10 to 20 per cent by weight aluminum transform at temperatures above 500°C from a room temperature stable Fe_3Al ordered structure into either a random structure or a FeAl ordered structure. The structure resulting from this transformation has a marked effect on the magnetic properties of ferromagnetic aluminum-iron alloys, especially for compositions above 14 per cent aluminum. These changes in magnetic properties were studied as a function of composition and heat treatment in the alloys containing 10 to 17 per cent aluminum. The major variables in heat treatment were the rate of cooling through the temperature range of ordering, the temperature of initial annealing, and the temperature from which the final cooling proceeded. The rate of cooling is of particular interest because it has a direct bearing on the structure and thus the magnetic properties of the alloys. In the alloy range between 14 and 18 per cent aluminum, the coercive force is one to two orders of magnitude greater for the slow cooled condition than for the quenched condition. On the contrary, between 10 and 14 per cent aluminum, slow cooling is the requisite for a low coercive force. The curves of coercive force as a function of aluminum content for the two conditions of heat treatment (slow cooling and water quenching) cross at the Fe_3Al composition (13.9 weight per cent aluminum). Both curves go through a maximum near 10 and 18 per cent aluminum and pass through a minimum between these compositions. For the slowly cooled alloys, the minimum is near 12 per cent aluminum; for the water quenched alloys, the minimum is near 17 per cent aluminum. An attempt is made to correlate these magnetic changes with the constitution of the iron-rich portion of the aluminum-iron phase diagram.

+ This work has been supported by the Aeronautical Research Laboratory, Wright Air Development Center.

25. HEAT TREATMENT FOR HIGH INITIAL PERMEABILITY IN BINARY AND COMPLEX NICKEL-IRON ALLOYS CONTAINING ABOUT 75% Ni

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The main purpose of the investigation has been to find out to what extent the magnetic behaviour of Ni-Fe alloys, with and without additions of Mo and Cu, can be interpreted in terms of lattice ordering. Binary Ni-Fe alloys of composition close to Ni_3Fe achieve greatest initial permeability after quenching from some temperature well above the critical point for long range ordering (490°C), and it is sometimes supposed that this type of alloy has highest initial permeability (μa) when it is "disordered". The present work shows, however, that the initial permeability of Ni_3Fe depends critically on the temperature from which it is quenched, the optimum temperature being 600°C. It is suggested that, just as in supermalloy-type (80% Ni, 14% Fe, 5% Mo) alloys maximum μa is associated with a critical degree of long-range order, so in binary alloys a critical degree of short-range order is required.

The effects of adding Mo to a binary Ni-Fe alloy are considered. As the Supermalloy composition is approached, the response of magnetic properties to heat treatment changes sharply in the region of 4.3% Mo. This is revealed by plotting μa against the temperature from which specimens are quenched. Alloys with Mo-contents lower than 4.3% have only one peak, always close to 600°C, whereas those with higher Mo-contents have two peaks, a major one below 600°C, and a minor one at about 800°C. As the Mo-content rises, the strength of the minor peak increases, and the temperature at which the major peak occurs falls. This suggests that the short-range ordering process tends to be suppressed in alloys of the Supermalloy type, possibly in favour of an atomic arrangement centred on Mo-atoms.

A quaternary alloy containing 77% Ni, 14% Fe, 5% Cu, 4% Mo responds to heat treatment very similarly to the ternary alloy 80% Ni, 15% Fe, 5% Mo. By regularly interrupting the cooling of this type of material by quenching and then determining μa, it has been shown that the amount of cooling required for μa to reach a maximum depends on the cooling rate. The faster the rate, the lower the temperature to which cooling must proceed to develop maximum μa. This result is expected if μa depends on the development of a critical degree of long-range order.

Resistance measurements have been made on

Ni-Fe, Ni-Fe-Mo, and Ni-Fe-Cu-Mo alloys, both at temperature, and after quenching. The results do not help greatly to decide what types of atomic arrangement occur. A particularly surprising result is that the resistivity of Ni_3Fe is a maximum after quenching from about 600°C, whereas alloys containing more than 1% Mo have almost minimum resistivity in this condition. Curves of resistance versus temperature show that addition of Mo to Ni-Fe alloys accelerates long-range ordering.

26. MAGNETOSTRICTION MEASUREMENTS ON SOME ORDERED AND DISORDERED Fe-Pt ALLOYS

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and
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As a continuation of a general study of the relationship between magnetic properties and the ordering process in Fe-Pt alloys, the longitudinal magnetostriction for alloys containing 24.2, 27.1, and 30%+ platinum in the ordered and disordered states has been measured. Measurements of the dependence of magnetostriction on the degree of order in this phase region are complicated by structural changes. Within the composition region for which these alloys order, there exists a martensitic type phase transformation from a high temperature face-centered cubic structure (designated as γ-phase) to a low temperature body-centered cubic structure (designated as α-phase). The transition temperatures depend markedly on the degree of order. For example, the transition temperature of the 24.2% alloy ranges from 300°K for a quenched sample to 78°K for a slowly cooled specimen. The γ-phase on ordering becomes stable at room temperature. An ordered α-phase has not been observed. The α-phase is always ferromagnetic, while the Curie temperature of the γ-phase depends on the degree of ordering[1,2].

In order to clarify the effect of the structural modifications on the magnetostriction of the ordered and disordered alloys, the magnetostriction was measured with the samples at room temperature, then at liquid nitrogen temperature, and finally after returning to room temperature. The data is summarized in the table below. The correlation with the structural changes will be discussed.

In general, the magnitude of the longitudinal magnetostriction of the γ-phase alloys increased on ordering; this is in agreement with the data of Akulov[3], et al., but not with results of Kussmann and von Rittberg[4].

THE LONGITUDINAL MAGNETOSTRICTION AT MAGNETIC SATURATION ($\lambda \times 10^6$)

Alloy %(Pt)	Quenched from 1000°C, measured at: Room Temp.	80°K	Room Temp. after 80°K	Ordered, measured at: Room Temp.	80°K	Room Temp. after 80°K
24.2	25.3	10	60	58	270	40.3
27.1	29.7	18.3	26.6	73.5	108	57
30.0	78	105	76	77	167	80

1. A. E. Berkowitz, F. J. Donahoe, A. D. Franklin, R. P. Steijn (to be published in Acta Metallurgica).

2. A. Kussman, G. G. v. Rittberg Metallkunde 41, 470 (1950).

3. N. S. Akulov, Z. I. Ali-Zade, K. P. Belov Proc. Acad. Sci. (U.S.S.R.) LXV, 815 (1949).

4. A. Kussmann, G. G. v. Rittberg Annalen der Physik, 7, 173 (1950).

+ All alloy compositions are specified as atomic percentages.

27. MAGNETIC MEASUREMENTS OF A Ni-Au ALLOY+

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and
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The Ni-Au system has a broad solubility gap in which two f.c.c. phases are present: one, Ni-rich and ferromagnetic; the other, Au-rich and not ferromagnetic. Single crystal samples of an alloy containing 23.6 atom per cent nickel have been examined after successive anneals at 400°C (in the two phase field). Torque curves have been obtained as a function of applied field in the (110) plane at room temperature and liquid nitrogen temperature for the early stages of precipitation. The field dependence of the rotational hysteresis has been determined from these data.

Since measurements were made when < 0.5% of the equilibrium amount of nickel precipitate had been developed, it was assumed that this precipitate consisted principally of single-domain nickel particles. Accordingly, the Stoner-Wohlfarth[1] tables were used to analyze the torque and rotational hysteresis measurements. This method yielded satisfactory qualitative agreement with the field dependence of the torque and rotational hysteresis data. These latter quantities increased rapidly from zero values at low fields to maxima between 600 and 900 oersteds (depending on temperature), and decreased more slowly with increasing applied field. The torque curves had no angular dependence in the low field range, but developed an increasingly prominent sin 2θ dependence with increasing applied field. The torque and rotational hysteresis amplitudes were substantially higher at low temperatures.

The principal lack of agreement with the Stoner-Wohlfarth approach was twofold. First, the ratios of the applied fields corresponding to maximum and zero rotational hysteresis were considerably different from that predicted from the Stoner-Wohlfarth method. Second, the total volume of precipitated single-domain nickel as derived from a suitable integration of the rotational hysteresis curve did not agree with the volume determined from more direct measurements. Similar divergencies have been noted by other investigators[2].

The details of the torque and rotational hysteresis data, and their field and temperature dependence will be discussed in terms of pertinent structural features of the precipitate particles. These include orientation, size and shape distributions, and coherency strains.

1. E. Stoner and E. Wohlfarth, Trans. Roy. Soc., A-240, 599 (1948).

2. C. P. Bean and W. H. Meiklejohn, Bull. A.P.S., 1, #3, 148 (1956).

+ Supported by the Office of Naval Research.

28. MAGNETIZATION OF Cr-Rich Fe-Cr ALLOYS FROM 2°K TO 300°K+

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Measurements of magnetization vs. field from 2°K to 300°K have been carried out on Cr-rich Fe-Cr alloys of compositions 1%, 5%, 10%, and 15% Fe. All of these alloys remain paramagnetic to 2°K. Assuming the moment to be associated with Fe atoms only, the moment per Fe atom increases from 2 Bohr magnetons in the dilute alloys to over 3 Bohr magnetons in the 15% alloy. The interaction between the Fe atoms is negative at 1%, zero at 5%, and positive for 10% and 15%.

The 10% and 15% alloys show a behavior which corresponds to a Stoner collective electron gas without quite enough exchange interaction to go ferromagnetic. The 15% alloy shows a marked effect of aging at 500°C with the susceptibility at 300°K and 90°K increasing with time. A slight effect was observed on holding the 10% alloy at 500°C for 4 hours. No effect was observed for the 5% alloy.

Present address Ford Motor Company

+ Supported by the U.S.A. Signal Corp

29. A MAGNETIC METHOD FOR THE MEASUREMENT OF PRECIPITATE PARTICLE SIZES IN A COPPER-COBALT ALLOY

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Ferromagnetic particles in a non-magnetic matrix show three types of magnetic behavior as a function of decreasing particle size:

1. Particles large enough to contain many ferromagnetic domains magnetize initially by the motion of domain walls.

2. Particles smaller than a critical size, which depends on their magnetic anisotropy, contain no domain boundaries, are always spontaneously saturated, and reverse their magnetization only by a rotation of their entire magnetic moment. These single-domain particles may have very high coercive forces if their anisotropy is high.

3. Particles which are still smaller continue to be single-domain, but the direction of their magnetization fluctuates thermally. These "super-paramagnetic" particles behave like a paramagnetic substance of very large moment. They follow a classical Langevin function:

$$\frac{I}{I_o} = \coth \frac{MH}{kT} - \frac{kT}{MH},$$

where M is now the entire moment of the particle and thus very much larger than the usual values for paramagnetic substances. Such particles have no remanence, no coercive force, and no hysteresis; yet they saturate in small fields.

All the above kinds of behavior can be observed in precipitation alloys. In particular, magnetization curves in the early stages of precipitation can be used to measure the particle sizes and size distributions when the particles are still in the super-paramagnetic range. By this means, the precipitation of cobalt in a 2 per cent cobalt-copper alloy has been followed, the measured average particle radius growing from 12 to 70 Angstrom units with increasing annealing time. Their paramagnetic nature is confirmed by the fact that their magnetization curves at different temperatures superpose perfectly when plotted against H/T.

The size at which permanent-magnet properties begin to appear gives an upper limit for the anisotropy. It follows that the cobalt particles are face-centered-cubic, and either almost spherical or decidedly plate-shaped.

The presence of a ferromagnetically "dead" surface layer several atoms thick, devoid of ferromagnetic coupling, has frequently been postulated. A comparison of particle size with saturation in these experiments indicates that no such layer is present.

30. MAGNETIC PROPERTIES OF UMn_2

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and
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The magnetic properties of UMn_2 have been studied from room temperature down to liquid helium temperature. The value of magnetic susceptibility in the range of temperatures investigated is about the same order of magnitude as that of ordinary paramagnetics but is highly field dependent. Above 185°K the curve of reciprocal susceptibility against temperature is hyperbolic and below that temperature it shows peculiar anomalies. At low fields (up to about 2000 oersteds) the susceptibility-temperature curves show maxima and minima which are more or less smoothed out at high fields (above 2000 oersteds). Small spontaneous magnetization and hysteresis have also been observed. For the purpose of analyzing the complex behaviors, quite a number of magnetization curves for the temperature range from 4.2°K to 200°K have been determined. By using the simple method of separating the ferro- and antiferromagnetic parts, the following results have been obtained.

1. The curve of spontaneous magnetization against temperature shows a broad maximum at about liquid nitrogen temperature.

2. The susceptibility is almost independent of temperature from about 185°K to 50°K.

3. Below 50°K, the susceptibility increases with decreasing temperature.

Three hysteresis curves at 152.6°K, 77°K and 4.2°K have been obtained, which are different in appearance from those of ordinary ferromagnetics. From the magnetic properties described above, it seems that UMn_2 is a kind of ferrimagnetic material and that Neels theory of ferrimagnetism and antiferromagnetism for ferrites has received a good confirmation from another kind of substance.

31. STRONG FIELD CRYOMAGNETIC STUDIES OF SOME FERROMAGNETICS, FERRIMAGNETICS AND ANTIFERROMAGNETICS

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In fields up to 60,000 gauss and at low temperatures, a study has been made of certain effects of exchange interactions, especially as they manifest themselves through ferromagnetism, ferrimagnetism and antiferromagnetism. Some of the ferromagnetic substances which have been studied are: iron, cobalt, uranium hydride, uranium deuteride and certain complex compounds. In the case of iron, measurements of the intra-domain magnetization in the saturation range have established a lower limit of the molecular field (about 3×10^6 gauss). The ferromagnetism of beta uranium hydride occurs at 173°K and is interesting in that it has a high residual magnetism in zero magnetic field. This remanence, as a function of temperature precipitously drops to zeromagnetization at the Curie temperature. The saturation magnetization of beta uranium hydride has been measured at liquid helium temperatures and at 60,000 gauss and found to be 1.15 Bohr magnetons per atom of uranium, which is in agreement with results of neutron diffraction studies carried out by Shull and Wilkinson. The saturation magnetization of uranium deuteride is apparently somewhat lower than that of the hydride.

Some of the antiferromagnetic substances studied are ytterbium sesquioxide, manganous chloride tetrahydrate[1], manganous bromide tetrahydrate[1], copper chloride dihydrate and uranium dioxide.

Through magnetization studies of manganous chloride tetrahydrate and the corresponding bromide, molecular fields corresponding to antiferromagnetic exchange interactions have been determined and are respectively, 14,000 gauss and 17,500 gauss. Using the same techniques, it has been shown that for ytterbium oxide, the molecular field is found to be of the order of 35,000 gauss. In the case of $CuCl_2.2H_2O$, the magnetization results indicate that the molecular field is probably much greater than 60,000 gauss and perhaps at least 100,000 gauss. Some of the substances which we have found to be antiferromagnetic have been confirmed by neutron diffraction studies at Oak Ridge.

The studies of ferrimagnetics have included cobalt carbonate, which exhibits a double Curie temperature; i.e., remanence and ferrimagnetic exchange interaction first show up at about 10°K. When the magnetization is plotted against the temperature, there seems to be a change in the sign of the second derivative of magnetization with respect to temperature at about 3°K. At 1.3°K and 60,000 gauss, the moment is only about 0.05 Bohr magnetons per atom of cobalt. An analysis is made in terms of departures from the Brillouin function and in terms of various theories[2]. The observation of ferrimagnetism is also interpreted on the basis of predictions which could be made from recent high temperature susceptibility measurements of Bizette[3].

1. W. E. Henry, Phys. Rev. 94, 1146 (1954).

2. J. H. Van Vleck, J. Phys. rad 12, 262 (1951); Rev. Mod. Phys. 25, 220 (1953); L. Neel, Proc. Phys. Soc. (London) A64, 869 (1952); C. J. Gorter, Physica 18, 861 (1952); Y. Yaffet and C. Kittel, Phys. Rev. 87, 290 (1952).

3. H. Bizette, Compt. rend. 241, 546 (1955).

Session IIIb APPARATUS AND DESIGN
J. A. Osborn, Presiding

32. MAGNETOABSORPTION

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This paper describes a new technique which is useful for the measurement of magnetoresistance phenomena in conductors or nonconductors. The apparatus measures the radio-frequency absorption in the test specimen as a function of magnetic fields and is, therefore, described by the term "magnetoabsorption".

It is well known that the apparent Q of an inductor can be changed by the losses occurring in a core placed within the coil. The change in Q will be a direct measure of the imaginary component of the complex magnetic susceptibility at a given frequency. Very small changes in the Q of a coil produced by a paramagnetic core may be observed with great amplification by the use of the simple oscillating detector Q-meter. Since sensitivities are obtainable which are the order of one part in 10^6, one may employ small samples or observe minute effects and still maintain excellent signal-to-noise ratios.

An apparatus has been constructed which displays the radio-frequency absorption of the core as a function of magnetic field on an oscilloscope screen or traces a curve on a strip chart recorder.

This apparatus has been used to observe magnetoabsorption effects in a large number of paramagnetic systems. Magnetoabsorption curves are, in general, uniquely determined by the type of sample and by its physical state. Paramagnetic metals, in general, show a fairly simple line structure while ferrites often times may have structure in the curves. The extreme sensitivity of the apparatus makes it possible to observe the absorption in the magnetite naturally occurring in rock samples, and to measure small traces of paramagnetic impurities in lubricants. An important field of application is the measurement of surface phenomena. The high resolution and variable skin depths offered by the radio frequency detection field permit detailed studies of strain, grain orientation and oxidation.

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Museum of Science
Science Park
Registry of Motor Vehicles
Boston
NASHUA
FITZGERALD
BRIDGE
(CLOSED) WARREN
BRIDGE
CHARLESTOWN
Boston Garden and N. Station
COMMERCIAL
CHARTER ST.
HULL
Copp's Hill Burrying Ground
Old North Church
PRINCE
ENDICOTT
WASHINGTON ST.
THACHER ST.
Paul Revere House
Haymarket Square
SALEM
CROSS
HANOVER
RICHMOND
FIRST
COMMERCIAL AVE.
NORTHERN TRAFFIC ROUTE
River
Swimming Pool
CHARLES ST.
BRIGHTON
CHAMBERS
LEVERETT ST.
POPLAR
ALLEN
Baker Mem. Hosp.
Mass. Gen. Hosp.
Eye & Ear Hosp.
FRUIT ST.
Suffolk County Jail
BLOSSOM ST.
Harrison Grey Otis House
LYNDE ST.
Hotel Manger
CAUSEWAY
FRIEND
CANAL
HAVERHILL
PORTLAND
TRAVERSE
MERRIMAC
GREEN
PITTS ST.
STANIFORD
CHARDON ST.
SUDBURY ST.
BLACKSTONE ST.
UNION
NORTH
CLINTON
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MARKET
LONGFELLOW BRIDGE
CAMBRIDGE ST.
EMBANKMENT ROAD
GROVE
ANDERSON
GARDEN
HANCOCK
BOWDOIN
HOWARD ST.
Suffolk County Court House
Old State House
Boston Massacre
STATE
REVERE ST.
MYRTLE ST.
PINCKNEY ST.
CEDAR ST.
DERNE ST.
JOY
SOMERSET ST.
COURT ST.
Boston Athenaeum
King's Chapel
City Hall
KILBY
BOAT HAVEN
Edward Hatch Mem. Shell
MT. VERNON ST.
CHESTNUT ST.
BRIMMER ST.
OTTER ST.
BEACON ST.
WALNUT ST.
State House
Bellevue Hotel
SCHOOL ST.
Parker House
Granary Burying Ground
Park Street Church
PARK ST.
WATER ST.
CONGRESS
P.O.
MILK
OLIVER ST.
PEARL
BROAD
Orpheum Theatre
Old South Meeting House
FRANKLIN ST.
HIGH
The Lincolnshire
Soldiers Mon.
BOSTON COMMON
PUBLIC GARDEN
Washington Mon.
ARLINGTON ST.
TREMONT ST.
WINTER ST.
TEMPLE PL.
WEST ST.
SUMMER ST.
ARCH ST.
FEDERAL
Chamber of Commerce
AVON ST.
BEDFORD
Keith Memorial Theatre
AVERY ST.
R.K.O. Boston Theatre
Astor Theatre
CHAUNCY ST.
PURCHASE
ATLANTIC
Emerson College
CLARENDON ST.
BERKELEY ST.
Ritz Carlton Hotel
BOYLSTON ST.
Touraine Hotel
ESSEX
Colonial Theatre
Plymouth Th.
Majestic Theatre
Wilbur Theatre
Shubert Theatre
Met. Theatre
BEACH ST.
KNEELAND ST.
South Station
DARTMOUTH
Boston Summer Theater
Mass. Division
New Eng. Mutual Bldg.
PROVIDENCE
ELIOT ST.
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Tufts Med. & Dental School
HARVARD ST.
HARRISON
WASHINGTON
OAK ST.
DORCHESTER
Copley
C1
C9
C28
C37
28
38

33. POWER COMPARING CALORIMETER

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This calorimeter and its techniques of operation were developed for the purpose of measuring heat quantities generated inside a mass, such as transformer cores.

The heat quantity to be determined is generated at a constant rate inside a Dewar jar, and the temperature rise vs. time is recorded by means of thermocouples.

In order to avoid reference to the detailed caloric data of the masses involved in the heat exchange process, recordings are taken under two conditions:

1. With a known amount of heat supplied at constant rate to the calorimeter by means of an electric heater, and later

2. With the unknown amount of heat to be determined supplied at constant rate to the same jar by the material under test.

The rates of change of temperature recorded for these two conditions are compared to determine the power lost as heat.

Novel features of this calorimeter which account for the heat leakage are:

1. A special method of operation, and original procedure for

2. Subsequent evaluation of recordings,

3. Repetitive measurements in rapid sequence are hereby possible.

This is accomplished as follows:

1. By means of a cold gas cooling system, the contents of the jar are cooled below the temperature of the environment, e.g., room temperature. Whereupon heat is supplied at constant rate from the heater or the source to be determined, until a discrete temperature above environment temperature is obtained or exceeded.

2. At the instant, when the temperatures inside and outside of the vessel are equal, no heat leakage can occur, and the rate of change of temperature is an exact measure of the rate of heat supplied. However, it is not feasible to read this value from the recordings with adequate accuracy. Therefore, a practical method of evaluation was conceived. Mathematical analysis of the problem is discussed together with the construction and operation of such a device.

The results of the practical applications of the Power Comparing Calorimeter prove the value of this device for the reliable determination of internal losses of ferromagnetic materials.

34. INSTRUMENTATION FOR MAGNETIC MOMENT AND HYSTERESIS CURVE MEASUREMENTS+

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The magnetic balance operates on a null balance principal and automatically records weight changes. Since the sample is in vacuum, susceptibility and saturation moment measurements can be made over a large temperature range. The sensitivity of the instrument is > 0.1 mg.

The problems of interaction of the magnet field with the balance sensing magnet, and of the sample pulling into the pole pieces are adequately solved. Temperatures are measured at the sample.

Hysteresis loops and magnetization curves are measured by vibrating a sample in a uniform field at fifteen cycles. Measurements are made in the temperature range from 700°C to -190°C. Samples are either solid rods or powder compacts in the form of cylinders 1/8 diameter x 1" long. Specimens containing < 0.5 volume per cent iron can be accurately measured.

The method is equivalent to a ballistic point by point measurement, but has the advantages that the applied field can be varied continuously, and the moment can be read on a meter or recorded. The technique is rapid and facilitates observation of moment changes with time at a fixed field.

Some applications of these instruments will be discussed.

+ This work was performed under the cooperatively sponsored Magnetics Research Program at the Franklin Institute Laboratories for Research and Development.

35. A SIMPLE METHOD TO CALCULATE LEAKAGE FACTORS FOR MAGNETIC CIRCUITS WITH PERMANENT MAGNETS

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A type of magnetic circuits is considered where one or more permanent magnets and soft steel parts are arranged in series and placed symmetrically in relation to an air gap. As basic arrangement, we use a circuit of square shape in which permanent magnets and soft steel parts are used interchangeably. We assume the total leakage flux (ϕ_L) to follow three basic paths: ϕ_a between the parts adjacent to the air gap, ϕ_b between the side parts, and ϕ_c along the part opposite the air gap.

The following simplifications are introduced:

1. If ϕ_a or ϕ_b emanates from soft steel, we obtain $mmf_a = mmf_b = mmf_g$ by neglecting the reluctance in soft steel.
2. If ϕ_a or ϕ_b emanates from permanent magnets, we obtain for the average values $\overline{mmf_a} = \overline{mmf_b} = 2/3\ mmf_g$. This relation is based on experimental results.
3. Simplified approximations for calculation of the three basic permeances are given.
4. The fact that permanent magnets have a neutral zone which does not contribute to leakage is taken into account by using only two-thirds of the magnets' total length when calculating their leakage permeance.

These simplifications are introduced into the leakage factor, which, for expediency, is written as $\sigma = 1 + (k_aP_a + k_bP_b + k_cP_c)/P_g$. The factors (k) stand for mmf ratios and P signifies permeances.

Several examples are given on how to apply the simplifications also to modified circuits of the type described at the beginning, e.g. ring magnets with air gap, U-shaped magnets with soft iron pole pieces and air gap. Leakage of tapered pole pieces is also easily calculated. The gain in gap flux density due to the application of tapered pole pieces instead of cylindrical ones is given by a simple ratio which defines a gain factor.

The accuracy of leakage factors calculated according to the given rules was checked by comparison with measured values on many different magnetic circuits. Deviations were less than $\pm$ 6%.

36. INSTRUMENTATION FOR AND MEASUREMENT OF MAGNETOSTRICTION AT LOW ALTERNATING FIELD INTENSITIES IN SILICON IRON

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During an extensive study of transformer noise energy sources, the desirability of instrumentation which could rapidly measure the alternating magnetostriction caused by 60 cps sine wave magnetization of Epstein strip samples soon became apparent. Existing instrumentation required too much time per sample to permit reasonably extensive surveys of materials used in manufacture. The initial part of this paper describes the equipment developed for this purpose.

The instrument, which does not involve an amplifier, produces an output of one volt for each microinch per inch magnetostrictive strain and the sensitivity is uniform from d-c to 20,000 cycles per second. It has needed recalibration three times during the last three years, and was operated 24 hours a day for eight months with no apparent change in sensitivity. The range was adjusted to cover, continuously, 1×10^{-8} inches per inch to 8×10^{-5} inches per inch. The expected error is $\pm 1 \times 10^{-8}$ inches per inch or $\pm$ 2 per cent, whichever is greater.

The sample magnetization range of peak flux density is two kilogauss to 18 kilogauss for a 60 cps sinusoid.

There are no attachments to the sample. Samples can be mounted or changed in less than a minute, and the series of measurements can be made in less than a quarter hour. The mechanical impedance of the sample is reproducible.

Much work dealing with the magnetostriction of grainoriented silicon iron sheet has been reported in the literature. However, information on the magnetostriction characteristics of this material for low-field intensities seems to be sparse. Knowledge of the magnetostriction characteristics in this range of field intensity is of value not only in further research but also in the transformer engineering art, where the noise produced by magnetostrictive effects is important.

This paper condenses the information obtained in tests of magnetostriction characteristics of 5000 specimens of grainoriented silicon iron of one quality grade. Magnetostriction for peak inductions of 15,000 gauss (60 cps excitation) in the rolling direction of the sheet was of primary interest.

At 15,000 gauss peak induction, the peak magnetostriction in the field direction ranged from -1×10^{-6} to 10×10^{-6}. More than half of the specimens had low negative magnetostriction. Wide variations (± 50 per cent) in the magnetostriction were found in strip samples representing an area as small as three square feet of a single sheet.

From the predominance of the relatively low magnetostriction and slightly negative magnetostriction, it can be inferred that the domain magnetization preferentially lies parallel to the rolling direction in (110) (001) textured silicon iron. For the great many specimens which exhibited slightly negative magnetostriction, it can be inferred that the relative volume of domains oriented transverse to the field increases somewhat in the course of magnetization below technical saturation.

37. INVESTIGATION OF AN ALTERNATING-CURRENT BRIDGE FOR THE MEASUREMENT OF TOTAL CORE LOSSES IN FERROMAGNETIC MATERIALS AT HIGH FLUX DENSITIES

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The use of bridge methods for measuring the total core losses of ferromagnetic materials has been restricted in the past to those flux densities where the effects of distortion in the magnetizing current were negligible. However, if a correction term is applied for the effect of the harmonic components of the current, the bridge measurements may be extended into the region of high flux density with an accuracy comparable to that obtained with the wattmeter. Furthermore, the bridge method has better sensitivity and is also useful over a wider range of frequency. The correction term is derived by considering the ferromagnetic material to absorb energy from current and voltage of the fundamental frequency and to return energy to the circuit at harmonic frequencies. The actual energy dissipated in the ferromagnetic material is the difference between those two quantities. In order to calculate the harmonic power delivered by the iron, the harmonic currents and the resistance of the current mesh involved must be known. This requires that the resistance of the power source be determined. A circuit was also devised by which the total core loss of a ferromagnetic sample can be measured by means of a Maxwell-Wien bridge and by a wattmeter simultaneously. Excellent agreement is obtained between the two methods.

38. A NEW FERRORESONANCE COMBINATION FOR STATIC CONTROL DEVICES

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Author describes his method of non-linearly combining a pair of dissimilar ferromagnetic core-elements with a condenser of predetermined value in a differential transformer so as to obtain the stabilized secondary voltage of a static voltage and current regulator.

One or both of the core-elements which can be built of any commercially available standard lamination size or of wrapped cores, operate in their saturated regions and the output is derived from the differentially connected two secondaries or from a single secondary which is wound across the differentially coupled two fluxes.

The regulated flat region of output voltage is obtained by taking advantage of the substantial core-losses which resistively dampen the LC-ferroresonance, at the same time the resonance is tuned to smooth the output wave-shape and filter out a major part of the distortions usually present in the output of saturated core devices. On the other hand, the ferroresonance can be predetermined for a combination in which the fundamental is suppressed and a selected higher or subharmonic frequency is reinforced. Also, by the proper selection of the dissimilar core materials and a tuning condenser, a sharply differentiating relay application is available with the known jump-phenomena of certain ferroresonant combinations.

Author lists the design data and performance characteristics of a 250-watt, self-regulating power-supply transformer of 115 ± 15% input-voltage with ± 1% output error in each of the multiple secondary B+, grid, and filament voltages for various electronic equipment.

The design is very simple and almost completely symmetrical as to core sizes, windings, etc. so that its application is quite flexible.

A particularly valuable characteristic is the fact that all the ferromagnetic core-components are symmetrically loaded and actively participating in the energy transfer which accounts for the high electric and magnetic efficiencies at a high power-factor. These features result in a relatively small size and weight which is almost as small as that of an unregulated ordinary power-supply transformer of the same output.

Author suggests a new three-dimensional method of empirical-graphical study of the dynamic behavior and transfer characteristics of ferromagnetic materials which he calls "dynamic-phase-related B-H-theta curves", and he suggests the use of a dimensionless complex ratio number "m" called "variable mutual-inductance factor" which can be easily derived for any selected core-materials in a prototype design.

39. A NEW DC HYSTERESIGRAPH

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and
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The paper "A New DC Hysteresigraph", by R. E. Tompkins and J. D. Young, describes the development of an accurate and reliable instrument for measuring the flux of magnetic materials. The development of this instrument contributes to modern flux measuring devices by combining R. F. Edgar's null detection method of measuring flux with R. H. Dicke's R-C integrator.

The instrument consists of two photoelectric fluxmeters, their associated power supplies and an X-Y recorder, all mounted in a single cabinet. The cabinet has space for the control circuit of an external power source, which supplies excitation to the specimen under test. The search coil is placed in series with the galvanometer and the resistor of the R-C circuit. Voltage induced in the search coil by changing flux interlinkages causes the galvanometer to begin to deflect, and changes the division of light between the two phototubes. This produces a change in the amplifier output voltage. The resulting flow of current into or out of the capacitor produces a voltage drop across the resistor which is opposite in direction and very nearly equal in magnitude to that induced in the search coil. Thus, the galvanometer is used as a null detector and the flux change is continuously balanced and recorded on the X-Y recorder.

The paper describes the necessary precautions taken in the construction of the R-C circuit, the temperature stability and the shock mounting of the galvanometer box. Photographs and description of the principle of operation, compensation circuits, control circuits and amplifier and electronic circuits are included in the paper. The paper concludes with the application of the DC Hysteresigraph and shows typical curves of B versus H for high permeability material, demagnetization with minor loops and the second quadrant demagnetizing for a permanent magnet material.

40. AN AUTOMATIC TORQUE BALANCE FOR THE DETERMINATION OF MAGNETOCRYSTALLINE ANISOTROPY

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Anisotropy constants of ferromagnetic single crystals may be determined accurately from curves of torque on the test specimen as a function of direction of saturation magnetization relative to the crystallographic axes. An automatic torque balance, consisting of a D'Arsonval movement - light beam - split photocell network, has been developed and is described herein. The principal advantage of this system is that complete torque curves may be taken over a wide temperature range in a very short time. It is therefore particularly suitable for studies of anisotropy as a function of temperature. The anisotropy constant, K_1, may be determined with this apparatus if its value lies within the range

$$\frac{10^2}{\text{Volume of sample(cc)}} \text{ to } \frac{4 \times 10^4}{\text{Volume of sample(cc)}} \text{ erg/cc.}$$

This range, however, is a limitation only on the existing equipment and may be expanded as desired.

Session IVa LOSSES IN SOFT MAGNETIC MATERIALS
C. P. Bean, Presiding

41. LOSSES IN MAGNETIC MATERIALS *
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Current concepts of the physical origin and mechanisms of losses in magnetic materials are reviewed under three traditional categories: hysteresis losses, eddy-current or dielectric losses, and residual losses. The residual losses include ferromagnetic resonance, rotational damping, and spin-wave resonance. The phenomenological Landau-Lifshitz equation is used to quantitatively express the various manifestations of rotational damping. Possible physical mechanisms responsible for this damping and some of the difficulties associated with the Landau-Lifshitz equation are qualitatively indicated.

* invited paper

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42. THE EFFECT OF IMPURITIES AND ORIENTATION ON THE LOSSES IN SILICON IRON
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If the effect of impurities and orientation on the magnetic properties are to be studied, it is important that each be controlled with a minimum of variation in other factors. Accordingly such variables as chemical composition, sheet thickness, internal strain and grain size had to be indistinguishable among the samples used in this investigation. This was achieved by starting with a three per cent silicon commercially melted material taken from a single ingot. Microscopic and chemical analysis of the hot band showed excellent uniformity. This material was processed to three different thicknesses at two impurity levels, and three levels of orientation at a single thickness. All heat treatments were the same with regard to heating time, temperature and cooling rate. The impurity levels reflected the difference in heat treating atmosphere, while the orientation was controlled by the initial starting structure and minor variations in the cold processing. This resulted in a product where impurities and orientation could be studied independently of each other. The basic

orientation studied was (110) [001].

The major effect of the impurities on the d.c. magnetic properties was to decrease the remanence, increase the coercive force, decrease the maximum permeability, and significantly increase the field required to reach 15 kilogauss. Compared to a sample of similar orientation but at a lower level of impurities the induction at 10 oersteds was the same. However, the total hysteresis loss was increased by a factor of three over the high purity sample. The effect of orientation on the d.c. properties was to decrease the remanence, increase the field required to reach 15 kilogauss, and decrease the maximum permeability. The coercive force was essentially independent of orientation over the range studied. The hysteresis loss was a function of orientation increasing with decreasing degree of perfection. The maximum hysteresis loss of the poorest oriented sample was less than that obtained on the impure samples.

The a.c. tests of 60 cycles showed that equivalent losses could be obtained either with impurities or by varying the orientation. This was most interesting when it is considered that the hysteresis loss for the impure sample was at least a factor of two higher than the poorly oriented case. This is a clear indication of the structural dependence of the a.c. losses. Further evidence of this was reflected by studying the a.c. losses as a function of frequency from 60 to 360 cycles. A plot of loss/cycle versus frequency showed characteristic differences among the samples. The structural dependence of the a.c. properties emphasizes the need for a theoretical treatment of this problem including reference to the structure and process of magnetization. If this view is considered, then the question of "anomalous" or "extra" loss no longer exists.

43. THE EFFECT OF PLASTIC DEFORMATION ON THE CORE LOSS OF ORIENTED SILICON STEEL
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The influence of slight plastic deformation (2 to 10%) by elongation on the core loss of oriented silicon steel has been determined on material of various grain sizes.

Deformation by elongation, of course, increases core loss of annealed steel but for equivalent cold work more harm (greater increase in loss) is done to material with fine rather than coarse grain. Cold work produces lattice deformation thereby increasing the losses but crystal orientation is unaffected.

An anneal of slightly deformed strip does not result in recovery of the initial magnetic properties. With a deformed fine grain size (> 500 grains per sq. mm.), the preferred orientation of the strip is destroyed on annealing. With a deformed coarse grain (< 10 grains per sq. mm.), the material does not recrystallize on heating. Deformation of large grained material results in Neumann band formation and annealing the material causes an absorption of the deformation twins. Absorption of the twins improves, but does not result in full recovery of magnetic properties.

44. DOMAIN OBSERVATIONS ON SILICON-IRON

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Ferromagnetic domain walls possess a surface energy which acts to make the wall area as small as possible. Therefore, if a single grain extends entirely through the thickness of a strip sample, the 180° domain walls in the grain tend to lie in planes perpendicular to the surface. However, crystal anisotropy forces act to keep domain walls lying in certain crystallographic planes. In silicon-iron, these favored planes are {100} for 180° walls. In {110} ⟨100⟩ grain-oriented steels, the important {100} planes are not perpendicular to the strip surface, but are inclined at 45°. The 180° walls therefore take up a position intermediate between the {100} plane and the surface normal. A calculation shows that the equilibrium angle is about 32° from the surface normal. Domain photographs are presented to show that in an isolated {110} ⟨100⟩ grain the domain walls are not perpendicular to the surface. By assuming the calculated angle of 32°, a three-dimensional domain structure can be deduced which gives a zero net magnetization for the grain. When domains are continuous across several grains of varying orientation, the requirement that the walls be plane surfaces acts to bring all the walls into one plane, which in this case lies perpendicular to the strip surface. This behavior is also illustrated.

Domain photographs are presented to show the occurrence of "lozenge" domains in several arrangements, and to demonstrate their behavior during magnetization.

45. THE RAPID DETERMINATION OF PREFERRED ORIENTATIONS IN MAGNETIC ALUMINUM-IRON ALLOYS BY COMBINATION ETCH PIT-DOMAIN PATTERN TECHNIQUES

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Techniques have been developed for the production of both discrete etch pits and domain patterns on polished surfaces of aluminum-iron alloys. The simultaneous existence of etch pits and domain patterns has been found useful for the rapid evaluation of degree and type of preferred orientations in these alloys, particularly in the large grain size ranges, where X-ray techniques are not suitable.

The procedure used for optimum production of etch pits consists of the following:

a) Mechanical polishing through 4/0 paper.

b) Electropolishing.

c) Washing in water and alcohol, re-dipping into the polishing bath with no current applied, and re-washing and drying.

d) Immersion for periods of 1-3 minutes in a room temperature solution of 100 g. of ferric sulfate and 10 cc. of concentrated sulfuric acid per liter of water.

Domain patterns are produced by permitting a suspension of fine magnetite particles to dry on the sample surface after the etch pits have been produced, thus forming semi-permanent patterns. This technique permits metallographic observation of both etch pits and domain patterns under incident illumination and at high magnification.

Aluminum-iron single crystals were polished parallel to specific crystallographic planes. Etch pits and domain patterns were produced on these planes and photographic records made. By using these as an index, it is possible for inexperienced observers to readily identify similar patterns on polycrystalline surfaces.

Representative photographs of some single crystal surfaces are presented together with some taken on polycrystalline samples.

46. THE EFFECT OF AGING ON THE TIME DECAY OF PERMEABILITY IN 3% SILICON IRON
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A study is made of the effect that aging, caused by the slow precipitation of carbon and nitrogen in silicon iron, has on the time decay of initial permeability. Following Snoek[1] and Neel[2], the time decay of initial permeability depends on the presence of and amount of solute carbon and nitrogen in the ferromagnetic material under consideration. Consequently, removal of solute carbon and nitrogen from the lattice by aging should have an effect on the time decay characteristics.

The time decay of permeability is measured by keeping a constant field of 2.6 milli-oersteds in the sample and measuring the decrease of flux density as a function of time. All measurements are made in an alternating field at a frequency of 100 cycles per second and the samples are kept at a temperature of -40°C. Aging is carried out for 300, 600 and more hours at a temperature of 150°C in air.

The time decay characteristics show a marked change after aging. The relationship of loss aging to "decay aging" is discussed.

Aging is further carried out as long as necessary to reach the point of "complete aging". The disappearance of the time decay phenomena is looked for at the point of "complete aging".

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47. MAGNETOSTRICTION OF ALUMINUM-IRON SINGLE CRYSTALS IN THE REGION OF 6 TO 30 ATOMIC PER CENT ALUMINUM
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Magnetostriction was measured on single crystals of the ferromagnetic aluminum-iron alloys in the composition range from 6 to 30 atomic per cent aluminum. Both the spontaneous saturation magnetostriction and the "forced" magnetostriction were evaluated. The single crystals for these measurements were grown from the melt, cut with the (110) plane parallel to the faces of the discs, then annealed at a high temperature and slowly cooled.

Magnetostriction was measured in the [100] and [111] directions by means of the strain gauge technique[1]. Curves of the magnetostriction versus field strength were directly plotted on an X-Y recorder[2] to a field strength of 10,000 oersteds.

Values of the spontaneous saturation magnetostriction were obtained by extrapolation back to zero field strength of the part of these curves past "saturation". In all cases, measurements were made as a function of field direction[3,4]. From an analysis of the possible errors in the determinations[5], a two-constant (h_1 and h_2) expression of magnetostriction as a function of field direction[6] was considered to be sufficient. The magnetostriction constants h_1 and h_2 were evaluated and corrected for the form effect[3]. From the corrected constants, calculations were made of the values of saturation magnetostriction in the [100], [110], and [111] directions and in polycrystalline material of random crystal distribution.

The first spontaneous magnetostriction constant, h_1, at 6 atomic per cent aluminum was similar to that of silicon iron[3]. At increasing aluminum contents, this constant rose rapidly to values over 100×10^{-6}; however, near 30 atomic per cent the value dropped sharply to a lower magnitude than that of iron. The second constant, h_2, was found to be small and negative at 6 per cent aluminum. It slowly increased, became positive at 16 or 17 per cent, and reached a maximum of less than 40×10^{-6} at the higher percentages of aluminum.

The "forced" magnetostriction was evaluated for these single crystals from the same curves of magnetostriction versus field strength. The forced effect is obtained from the slope of the magnetostriction versus field strength curve past the "saturation" field strength. As described by Calhoun and Carr[7], however, corrections must be made for the lack of true saturation and for the magnetoresistance effect of the strain gauges.

Below the Fe_3Al composition, isotropic forced strains were found to be lower than those determined for silicon iron but equal to or slightly higher than those determined for iron[7]. Above the Fe_3Al composition, the isotropic forced strain increased rapidly until at 30 atomic per cent it was approximately five times that of iron.

The anisotropic forced strains in the 30 atomic per cent alloy were found to be fairly large and clearly defined; the anisotropic constants of forced magnetostriction, h_1 and h_2, were readily evaluated. At lower aluminum contents, the anisotropic effect was generally less well defined because the corrections to the data, in some instances, were of the same order of magnitude as the data itself and apparently because the anisotropic constants were smaller. These anisotropic constants at lower aluminum contents were evaluated but the accuracy was lower.

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7. B. A. Calhoun and W. J. Carr, Jr., "Magnetostriction of Iron and Some Silicon-Iron Alloys in High Fields", Conference on Magnetism and Magnetic Materials, Oct. 1955, pp. 107-111.

48. SUPERMENDUR, A NEW RECTANGULAR LOOP MAGNETIC MATERIAL WITH HIGH FLUX DENSITY AND LOW COERCIVE FORCE

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and
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Supermendur is a new material with magnetic properties that are outstanding in high flux density performance. This material is a purified alloy with a nominal composition of 2% vanadium, 49% iron and 49% cobalt. The magnetic properties obtained after heat treatment in a magnetic field are: maximum permeability - 66,000 at 20,000 gausses, remanence - 21,150 gausses, coercive force - .26 oersted and saturation - 24,000 gausses. In contrast to other iron-cobalt alloys, Supermendur possesses unusual malleability which permits cold reductions of over 99%, making it available in strip, a few thousandths of an inch thick. Supermendur can be used advantageously to decrease the weight and size of coils already reduced to the limit obtainable with magnetic materials previously available. These coils include power transformers, pulse transformers, and magnetic amplifiers. This material promises to be of value in telephone receiver diaphragms, miniaturization, high temperature operation, and switching and memory devices.

49. SENDUST FLAKE - A NEW MAGNETIC MATERIAL FOR LOW FREQUENCY APPLICATION

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A high permeability, low loss core was prepared by compacting Sendust flakes, which were produced by warm rolling Sendust powder. Sendust, a brittle magnetic alloy of iron, silicon and aluminum, was discovered by the Japanese in 1936 and is used extensively by them in cast and powder form. The low permeability values (70-80) of Sendust powder cores precluded their acceptance in this country to any extent. The improved magnetic properties of the new flake cores, called Flakenol I, make them an attractive non-strategic substitute for applications which now require powdered high nickel alloys. The permeability values as measured on compacts of this new flake core ranged from 150-230 with electrical losses as low as present powder cores. The very low eddy-current loss coefficient value measured on Sendust flake cores indicates their usefulness at higher frequencies than possible for present high permeability powder cores. The flake cores, which have a negative temperature coefficient of permeability, were stabilized by the addition of Alfenol flake material. The comparatively simple techniques for processing Sendust flake cores from the cast alloy are described, along with the factors which most influence their ultimate magnetic characteristics.

50. EFFECTS OF NUCLEAR IRRADIATION ON MAGNETIC MATERIALS

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Because of the growing military and commercial interest in the effects of nuclear radiation on the behavior of electronic systems and materials, an investigation was made of radiation effects on the magnetic characteristics of seven representative core materials. The materials studied are: 50-50 nickel-ferrite, 2-81 Molybdenum Permalloy (powder core), 5-79 Molybdenum Permalloy, 3.5 silicon-iron, Orthonol, 16-Alfenol, and Vanadium Permendur. The samples were all in the form of laminated toroids of approximately 1-5/8 inch ID and 2 inch OD, with the exception of the 50-50 nickel-ferrite and 2-81 Molybdenum Permalloy which were both solid toroids, and the Orthonol which was a toroidal tape wound core.

The materials were placed in the nuclear reactor at Brookhaven National Laboratory where they were irradiated for approximately seventeen days at a neutron flux of 3×10^{12} neutrons per square centimeter per second. Magnetic measurements were made before, during, and after irradiation. The magnetic properties obtained are: a.c. hysteresis loops and magnetization curves at both 60 cps and 400 cps, d.c. magnetization curve, maximum permeability, residual and saturation flux densities, and coercive force. Before and after irradiation, loss measurements were made on the 50-50 nickel-ferrite and 2-81 Molybdenum Permalloy powder core, and magnetostriction measurements were made on the 50-50 nickel-ferrite and 16-Alfenol.

Because many materials, such as Bakelite core boxes and Formvar magnet wire, ordinarily used in the fabrication of magnetic core assemblies, would deteriorate rapidly at the neutron flux level within the reactor, it was necessary to use special core boxes, wire insulation, and interlamination insulation containing minimum amounts of organic materials in order to retain their desirable properties during the irradiation.

The paper describes the magnetic core assemblies, gives the details of the experiments, and presents tables and graphs illustrating effects of nuclear radiation on magnetic core materials.

51. WHY PRESENT EVALUATION METHODS FOR HIGH QUALITY MAGNETIC STRIP MATERIALS ARE INADEQUATE

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At present the so-called Epstein Test for Alternating Current Core Loss of Magnetic Materials (ASTM A 343-54) is standard for grain-oriented 3% Si-Fe strip. This test is elaborate, time consuming and therefore costly. In normal use its error is characterized by a standard deviation of approximately 9 milliwatts per pound (mwpp). Usually only one or two Epstein Samples weighing 1 lb. each are taken from one (or both) ends of a 5000 pound coil of steel.

It is demonstrated that the variability within this amount of steel corresponds to a standard deviation of the order of 25mwpp with additional systematic differences between the center and the end of the coil. Hence the accuracy of the a.c. core loss test estimated in the ASTM standard as being "within 2 per cent" is not at all applicable to the estimate of coil quality obtained from it.

From these data two conclusions can be drawn:

1. If it is desired to know the average watt loss of a 5000 pound of steel with an accuracy corresponding to the Epstein test method, frequent sampling is necessary.

2. If the information obtained by the present sampling methods suffices, a less expensive test, even if it had a slightly larger error associated with it, would be much more appropriate.

A single sheet tester, similar to one developed by the General Electric Transformer Laboratories is proposed as an accurate and economical replacement of the standard Epstein test for end sampling. Possible test methods employing more frequent sampling will also be discussed.

Session IVb FERRITES
V. C. Wilson, Presiding

52. NEW MAGNETIC CORE MATERIALS AT FREQUENCIES UP TO THE UHF BAND*

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Ever since the early days of radio communication the upper useful frequency limit of ferromagnetic core materials has been constantly advanced. Although magnetic materials find ready application in radio communication circuits, it has been the history of the science that the progress of radio to higher frequencies has taken place without the benefit of essentially new magnetic materials. The first major "break-through" into the higher frequency region came in the former decade with Snoek's invention of the high permeability ferrites. Since then Philips has maintained an active interest in magnetic materials which can be used successfully at higher and higher frequencies. In recent months interesting and important results have been obtained at the Philips Research Laboratories in the investigation of magnetic materials that have still useful properties as core materials at frequencies in the range above that where the normal ferroxcube materials are used. The theoretical background of the origin of the magnetic losses in ferrites will be discussed again, but now also with respect to the properties of the new materials.

* invited paper

53. DOMAIN-WALL RELAXATION IN FERRITES

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Temperature dependent relaxation effects have been studied in nickel-zinc and magnesium ferrites containing excess divalent iron. In the radio frequency region, the relaxation manifests itself as a peak in the magnetic loss when the complex permeability is measured as a function of temperature at constant frequency. Measurements have been made at temperatures from -195°C to +20°C using frequencies in the range of 50 KC to several megacycles. An increase in the measuring frequency shifts the loss peak to higher temperature according to an activation law. The activation energy is the same as that for electric conduction, and ranges from ca 0.07 to 0.2 ev depending on the material.

The relaxation is identified as a domain-wall effect and is analyzed in terms of a model involving a distribution of relaxation times. For polycrystalline materials, the distribution of time constants covers more than two decades; for a single crystal, less than one. Analysis of the relaxation reveals that in the ceramic nickel-zinc ferrites studied here, 60 to 75% of the initial permeability is due to wall displacements.

At temperatures of liquid nitrogen and below, the wall relaxation has been studied by observing the response of the magnetization to a step function of magnetizing force. The switching process is slow. In some cases several minutes are required for the magnetization to attain one-half its final value. The change of induction with time depends linearly on log t over a range of about two decades. A model which leads to this behavior is discussed.

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54. THE REMANENT STATE IN FERRITES ACCORDING TO THE ROTATION MODEL

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It is assumed with others that the behavior of certain polycrystalline ferrites in small fields can be accounted for by assuming spin rotation. However, a distribution of domain vectors has been assumed which differs from the distribution obtained by taking into account only crystal anisotropy. In this paper, 3 relations for such a model are developed for the general remanent state (H = 0). The relations are found to be independent of the distribution of domain vectors, and they contain the remanent and saturation magnetization, the tensor-components of susceptibility and the derivatives of these components with respect to the field.

It is shown that the first four coefficients of the distribution function, expanded into a Fourier series, can be calculated from the above magnetic parameters. Published experimental data for ferrites allowed us to check one of the above relations. Rough agreement was found.

55. PERMALLOY CHARACTERISTICS IN FERRITES
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The interesting properties of the permalloys have been studied for a long time and are well known[1]. These properties include a constricted hysteresis loop and a low initial permeability when the material is cooled slowly while a normal hysteresis loop and a high initial permeability is obtained if the material is cooled rapidly. In addition a magnetic field applied during cooling parallel to the direction of measurement yields a high permeability while a field applied during cooling perpendicular to the direction of measurement yields a lower permeability. This behavior is most pronounced at the composition Ni_3Fe.

Recently almost identical properties have been found in certain nickel and nickel-zinc ferrites containing small amounts of cobalt or manganese[2,3]. We have investigated the dependence of u' and u" and the hysteresis loop shape on heat treatment of some of these ferrites including a commercial ferrite "Ferramic Q".

A rapid cooling from above the Curie temperature produces a high u' and u" and a normal hysteresis loop. A very slow cooling from above the Curie temperature produces a low value of u' and u" and a constricted hysteresis loop. These phenomena are strongly dependent on the percentage of cobalt present.

In analogy to the work done on the permalloys[4] which ascribes this type of behavior to uniaxial anisotropy due to long range ordering it is suggested that the cobalt becomes ordered on the B-sites when the ferrite is cooled slowly. This gives uniaxial anisotropy in the direction of the magnetization. This uniaxial anisotropy then gives rise to the foregoing magnetic properties as shown by various workers[4].

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56. SUSCEPTIBILITY OF NORMAL SPINELS FROM 2^oK TO 300^oK
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Magnetic isotherms have been determined for the normal Spinels $ZnFe_2O_4$, $ZnCr_2O_4$, $CdFe_2O_4$, $MnAl_2O_4$, and $CoAl_2O_4$ from 2^oK to 300^oK. The data can be interpreted to give the moments of the magnetic ions. In the case of $ZnFe_2O_4$ and $CdFe_2O_4$, the Fe ions appear to have a spin of 2 indicating Fe^{++} and Fe^{++++} rather than Fe^{+++} as would be expected and as is observed for Cr in $ZnCr_2O_4$. The interaction between Fe ions in $ZnFe_2O_4$ is larger than in $CdFe_2O_4$ and of opposite sign ($\Theta = +100$ in $ZnFe_2O_4$ vs. $\Theta = -40$ in $CdFe_2O_4$). $ZnCr_2O_4$ and $CoAl_2O_4$ appear antiferromagnetic. The behavior of $MnAl_2O_4$ is anomalous with a transition observed at 200^oK and strong deviation from Curie-Weiss behavior below 60^oK in the direction to be expected for Ferrimagnetism. The effect of a small degree of inversion on the magnetic properties of these salts will be discussed.

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\+ Present Address Ford Motor Company

57. GROWTH AND APPLICATION OF FERRITE SINGLE CRYSTALS
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The role of ferrite single crystals in the field of magnetics is an important one, for it is from their study that fundamental knowledge is obtained. This data is essential to understanding and improving polycrystalline materials. The single crystals, per se, may find applications in this field.

Since the term "ferrite" has become rather ambiguous, it is necessary to define it as it shall be used in this paper. A ferrite is a compound which crystallizes according to the spinel structure and which has the chemical formula, $MeO.Fe_2O_3$, in which Me stands for any of several divalent metals such as iron, manganese, magnesium, cobalt, zinc and nickel either as single components or in various combinations as mixed components. The ferrites exhibit resistivities in the megohm range, saturation magnetizations much lower than iron and high initial permeabilities.

Several ferrites are known to occur in nature. They are magnetite (FeO), magnesioferrite (MgO), jacobsite (MnO), trevorite (NiO), and franklinite (ZnO). All appear to be high temperature deposits which form near magmatic sources. The factors which are important in the natural processes are proposed as the factors which would be important to laboratory synthesis. Therefore, it is through the study of the natural occurrences coupled with a complete evaluation of all types of laboratory crystallization processes that clues to productive methods of synthesis are obtained.

The numerous types of laboratory processes which are applicable to crystal growth of any substance can be divided into three general types of reactions:

1. Liquid-state reactions.
2. Solid-state reactions.
3. Vapor-state reactions.

A cursory inspection of this list, keeping in mind the necessary set of conditions, immediately eliminates most of the methods. Somewhat more analysis narrows the possibilities down to four major categories. These are the gaseous diffusion technique, the flame fusion techniques, the melt crystallization methods and the hydrothermal solution processes. These methods are being employed at various laboratories throughout the eastern United States with varying degrees of success.

The research of the Magnetics Section of the Cambridge Research Center includes attempts at growth with the flame fusion, the gaseous diffusion and the hydrothermal methods. Growth of several ferrites has been achieved by each of these with the best results being obtained from flame fusion. However, several problems remain to be solved such as the maintenance of stoichiometry throughout the crystal and the elimination of various imperfections such as cracks, bubbles, and inclusions. These same problems are being incurred at the other laboratories and must be eventually solved.

After the "perfect" crystals have been fabricated, the work of analysis begins. The first of these is the chemical analysis and the determination of certain physical quantities. After that goniometric and X-ray studies are made to resolve the crystallography. Magnetic measurements include determinations of anisotropy constants, resistivity, resonance phenomena, and domain studies. The resolution of these properties has a direct bearing on the applications of the ferrites as single crystals and as polycrystalline cores.

58. PREPARATION OF FERRITES BY THE ATOMIZING BURNER TECHNIQUE

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and
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A new process for the preparation of ferrite powders having well defined and reproducible chemical and physical properties as well as a high degree of homogeniety is disclosed. The technique involves the preparation of alcohol solutions of various metallic nitrates, mixing these solutions to produce a feed solution having the desired stoichiometry, atomizing the feed with oxygen through a two-fluid nozzle and igniting the resultant dispersion. The products of combustion are extremely fine ferrite powders having the desired spinel structure, water vapor, and various gases. A small cyclone separator was used to collect the ferrite powder and is described in detail. Chemical analyses of the feed solutions and the resultant powdered products reveal no change in stoichiometry. It is possible therefore to prepare accurately laboratory quantities of a wide variety of reproducible ferrites knowing merely the chemical analysis of the feed solutions. X-ray diffraction studies of the powders (average particle size approximately 0.5 microns) have shown that the structure is entirely spinel. Extensive investigation of the nickel-zinc ferrite system, including elemental analyses, valence state, atomic structure, lattice parameter determination and saturation magnetization measurements, are presented along with preliminary results of a study involving the manganese-magnesium ferrite system.

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59. FERRITE ACCELERATING CAVITIES FOR A 25 BILLION ELECTRON VOLT PROTON SYNCHROTRON+

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In order to develop a high resonant impedance in each of twelve accelerating cavities for a 25 BeV accelerator, ferrite loading is used. The radio frequency varies from 1.4 to 4.5 mc/sec over a one second period and the cavity is kept tuned with approximately constant impedance by means of d.c. saturation of the ferrite. The voltage required at each accelerating gap must stay fixed at 8,000 volts peak, equivalent to an rf flux density of 160 gauss at the low frequency. This relatively severe service requires a ferrite with high performance, that is low losses at these flux densities and a permeability high enough to permit easy saturation tuning.

Two commercial ferrites have been found which meet our specifications:

1. Q greater than 12 at 100 gauss peak rf flux density 1.5 mc/sec

2. μ_o greater than 350 at 1.5 mc/sec, zero rf flux density

3. A saturating flux density less than 12 amp turns/cm for a ten to one reduction in μ.

A suitable cavity has been designed capable of handling the problems of rf and d.c. feeds, cooling and mounting. The ferrite is being used in rings 35 cm O.D., 20 cm I.D. and 2.1 cm thick, probably some of the largest single pieces ever made.

+ Work carried out under contract with U.S. Atomic Energy Commission.

Session V HIGH FREQUENCY PHENOMENA
G. T. Rado, Presiding

60. MAGNETIC RESONANCE IN FERRITES*

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The physical principles of ferromagnetic resonance in ferrites are reviewed. The concept of tensor permeability, the influence of magnetic anisotropy, demagnetizing fields and damping mechanisms are discussed. The effective magnetic permeability tensor is of great importance in many microwave circuit applications. Its physical dependence on temperature, external magnetic field and composition is briefly described.

* invited paper

61. FERROMAGNETIC RESONANCE IN HIGHLY ANISOTROPIC SINGLE CRYSTAL METALS

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Cambridge, Mass.

Microwave susceptibility expressions for ferromagnetic resonance have been derived for metal single crystals possessing magnetocrystalline anisotropy. When the magnetization M is aligned with the applied field H the results are equivalent to those of Kittel[1]. When M is not aligned with H more complicated expressions are found. In many instances simple multi-domain structures occur on the crystal face. Under these circumstances the microwave resonances are found to be related to the ratio of skin depth to domain width in addition to the expected dependence on H,M, and anisotropy papameter K/M. Thus domain spacings can be inferred from microwave measurements. Such results are of great interest particularly when interpreting the results of resonance observations at low or elevated temperatures when optical examination of the crystal face may not be feasible. The ferromagnetic resonance observations taken on Fe by Kip and Arnold[2] are shown to be consistent with the predictions of this analysis. Domain spacings are derived from their data which are in good agreement with powder pattern observations reported in the literature. Resonance effects found in Ni by Reich[3] can also be attributed to a multi-domain structure. The results of experiments in progress on (110) and (100) plane samples of Fe and (110) plane samples of Ni will be discussed.

1. C. Kittel, Phys. Rev. 73, 155 (1948).

2. A. F. Kip and R. D. Arnold, Phys. Rev. 75, 1556 (1949)

3. K. H. Reich, Phys. Rev. 101, 1647 (1956) and private communication.

62. SINGLE CRYSTAL INTRINSIC PERMEABILITIES OF FERRITES

E. G. Spencer, R. C. LeCraw,
L. A. Ault, and J. E. Tompkins
The Diamond Ordnance Fuze Laboratories
Washington, D. C.

A derivation has been made of the general intrinsic permeability tensor of single crystal ferrites in terms of the net magnetization $M = M_\alpha + M_\beta$, net anisotropy constant $K_\alpha + K_\beta$, and effective gyromagnetic ratio γ. Subscripts α and β refer to the two sublattices of the antiferromagnet. A single relaxation term is assumed to account for the effects of both lattices. In general the tensor results in the form,

$$(\mu) = \begin{pmatrix} \mu_x & -i\kappa & 0 \\ i\kappa & \mu_y & 0 \\ 0 & 0 & \mu_z \end{pmatrix}$$

where the components μ_x, μ_y and κ are given in detail for any arbitrary orientation of the applied d.c. field with respect to the crystallographic axes. The intrinsic line shape through magnetic resonance is given for these cases, with the rf fields circularly polarized. The rf magnetic properties of the single crystal are completely specified if the tensor is determined along the three principal magnetic axes. Measurements on single crystal manganese and nickel ferrites are presented with the d.c. magnetic field along these axes. Intrinsic permeabilities are calculated from measured data on spheres and disks. Line shapes and intensities are compared with the derived equations.

63. DOMAIN STRUCTURE EFFECTS IN AN ANOMALOUS FERRIMAGNETIC RESONANCE OF FERRITES

R. C. LeCraw
and
E. G. Spencer
The Diamond Ordnance Fuze Laboratories
Washington, D. C.

Measurements of intrinsic tensor permeability of unsaturated nickel ferrite at 9340 mc, using cavity perturbation techniques, have revealed an anomalous resonance for negative (anti-Larmor) circularly polarized rf fields. The resonance occurs at an internal d.c. field approximately equal to the coercive force, which is 13 oersteds. The usual resonance for positive (Larmor) circularly polarized fields occurs for this frequency at an internal d.c. field of approximately 2750 oersteds. At this point the ferrite is essentially saturated. Below saturation, because of the low field resonance, the intrinsic loss term for negative circularly polarized fields, $\mu''_- = \mu'' - \kappa''$, is greater than that for positive circularly polarized fields, $\mu''_+ = \mu'' + \kappa''$, where $\kappa = \kappa' - i\kappa''$ is the off-diagonal component of the permeability tensor. This results in a negative value of κ''. Above the knee of the magnetization curve μ''_+ is greater than μ''_-, and κ'' is normal and positive. It is shown that the negative κ'' does not violate energy considerations. Both the anomalous resonance and negative κ'' have been observed on a number of different type ferrites.

A theory explaining these effects is presented based on a model involving a physically probable domain structure. The theory is developed from a consideration of rf demagnetizing poles on Bloch walls for the condition of circularly polarized rf fields. It is applicable to all ferrites, both single-crystal and polycrystalline, having domain walls which are free to move to any appreciable extent in d.c. fields of the order of the coercive force.

64. REVERSIBLE PROPERTIES OF FERROMAGNETS+

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University of Michigan

Theoretical expressions have been developed for the variation of the reversible susceptibility with magnetization in a polycrystalline material. The expressions are based upon models assuming two different origins for the susceptibility - domain wall motion and domain rotation[1]. The expected results from each model are similar for susceptibility measurements parallel with the gross magnetization level, but the susceptibility normal to the magnetization for increasing M is expected to decrease for domain wall motion and, so long as H is much smaller than the anisotropy field, increase for domain rotation. The latter result essentially arises because the susceptibility by rotation is considered zero parallel with the moments of the domains. As M increases the normal component averaged over a polycrystalline sample must increase.

Experimental data will be shown on two selected specimens chosen to represent examples of each of the two susceptibility types considered. A specimen showing the behavior expected for predominate wall motion is a high density magnesium ferrite made by D. Fresh, the same type of material as reported by Rado to show frequency dependence indicating wall motion and of the same material for which he measured the magnetic anisotropy[2]. The material showing behavior expected of domain rotation is a nickel-cobalt-zinc ferrite made in this laboratory.

An expression will be shown for the expected variation of the differential magnetostriction with magnetization when the susceptibility is due to domain wall motion. The results are in qualitative agreement with the experimental data of Bozorth and Williams[3] on 45 permalloy.

An expression is given for the susceptibility matrix arising from domain rotation as a function of magnetization. The matrix is proportional to the unit matrix for $M = 0$ and goes to the usual matrix for saturated material when $M = M_s$. The off diagonal terms are found to be proportional to M/M_s, as was previously given by Rado[4].

1. Grimes, D. M., Thesis, University of Michigan, 1956; Bull. Am. Phys. Soc. 1, 25 (1956); Grimes, D. M. and D. W. Martin, Phys. Rev. 96, 889 (1954).

2. Rado, G. T., Rev. Mod. Phys. 25, 81 (1953); Rado, G. T. and V. J. Folen, Bull. Am. Phys. Soc. 1, 132 (1956).

3. Bozorth, R. M. and H. J. Williams, Rev. Mod. Phys. 17, 72 (1945).

4. Rado, G. T., Phys. Rev. 89, 529 (1953).

+ This work was supported in the earlier stages by the United States Army Signal Corps and in the latter stages by the United States Air Force through the office of the Air Force Office of Scientific Research of the Air Research and Development Command.

65. MICROWAVE APPLICATIONS OF FERROMAGNETICS*

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In the past few years a large number of new and important applications of ferromagnetic materials in the microwave frequency region have been proposed. The ability to reduce these proposals to practice has been greatly enhanced by our ability to produce almost at will special ferromagnetic materials with the properties needed for these particular applications.

This paper will review the present status of microwave ferromagnetic devices, giving an elementary introduction to the basic theory of operation of the devices. The so-called material problems will be discussed and the needs of the microwave engineer will be enumerated in terms of the fundamental properties of the materials.

* invited paper

66. A NEW FARADAY ROTATION PHENOMENON AND ITS APPLICATION TO MICROWAVE SWITCHING

Jerald A. Weiss
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Murray Hill, N. J.

A microwave switch based on the principle of Faraday rotation differs from the arrangement usually used in the experimental study of the Faraday effect itself in that the rectangular waveguide at the output end of the cylindrical rotator section is not always oriented relative to the input guide in such a way as to permit complete transmission. Under these conditions a portion of the radiation is trapped in the junction. If the losses are small, the section exhibits some rather surprising transmission characteristics which point the way to a novel mode of switching operation. The performance is most easily understood by regarding the junction as a bridge whose two arms are identified with the components of the radiation which are so polarized as to be transmitted or reflected, respectively, at the input and output planes. The analysis shows that there exists a condition of balance, or interference, between these two components which is practically independent of the amount of rotation and is determined almost exclusively by the propagation constant of the loaded cylindrical guide for the (rotating) linearly polarized radiation. When this balance condition is used to initiate the open (reflecting) state of the switch, the device goes into the open state for an amount of rotation much less than 90°.

If this effect is used in conjunction with the conventional 90° rotation, the open state can be made to persist over an extremely wide range of rotations. The balance condition is, of course, much more frequency-sensitive than the conventional 90° rotation. The performance of a typical model of the Faraday rotation switch shows excellent agreement with the predictions of the analysis.

67. THE PRODUCTION AND USE OF HIGH INTENSITY PULSED MAGNETIC FIELDS+

Simon Foner
and
Henry H. Kolm
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The problem of producing extremely high magnetic fields is briefly reviewed in the light of modern technique. The design, performance and application of a pulsed field system capable of more than 750,000 oersteds at room temperature is described. The coil comprises a suitably supported machined beryllium copper helix having an inside diameter of 3/16 in. and a length of about 1/2 in.; it is connected directly to a 2,000 mfd, 3 kV bank of surge capacitors by means of a triggered spark gap. The discharge is oscillatory with a half-period of 120 sec. Design data and performance characteristics are presented for several modified coils which provide increased volume at a sacrifice in field intensity. A coil providing transverse access to the field and one suitable for operation in liquid helium are also described. Pulsed field measurements of galvanomagnetic effects in semiconductors, antiferromagnetic resonance at 4 mm wavelength and cyclotron resonance and magneto-band effects in semiconductors at infra-red frequencies are described briefly, illustrating the capabilities and limitations of pulsed field technique. Finally, the feasibility of extending the pulse duration to the order of one second is discussed.

+ The research reported in this document was supported jointly by the Army, Navy, and Air Force, under contract with Massachusetts Institute of Technology.

Session V

68. THE MICROWAVE SUSCEPTIBILITY OF POLYCRYSTALLINE FERRITES IN STRONG DC FIELDS AND THE INFLUENCE OF NONMAGNETIC INCLUSIONS ON THE MICROWAVE SUSCEPTIBILITY

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The microwave susceptibility of polycrystalline ferrites is calculated with the assumption that the applied d.c. magnetic field is strong enough to approximately align the magnetization vectors of all grains. The Landau-Lifshitz Equation is used as the equation of motion for the magnetization vector of each grain. The crystalline anisotropy is equivalent to an additional d.c. field, whose strength varies from grain to grain due to the random orientation of the crystallites. By way of approximation the magnetic interaction between the grains of a polycrystalline sample is replaced by the interaction of a representative grain with the average magnetization of the sample. The resultant susceptibility can be conveniently expressed in terms of two distribution functions u(A) and v(C), which are proportional to the number of grains in which the crystalline and shape anisotropy are equivalent to additional d.c. fields of strength A and C, respectively. The distribution function u(A) is calculated for the case of first order cubic anisotropy. It is asymmetric and has a logarithmic singularity a distance $-K_1/2M_s$ from its center of gravity. If u(A) is approximated by a Lorentz distribution, the susceptibility becomes independent of the distribution of the shape anisotropies v(C), and a very simple formula is obtained. In this approximation, the susceptibility of the polycrystalline sample is a weighted average of the single-crystal susceptibility, where u(A) is the weighting function.

The principal results are:

1. The resonance condition for a sphere in a d.c. field H_o is

$$\omega = \gamma\,(H_o + H_i),$$

where H_i equals the anisotropy field

$$H_a = -K_1/2M_s.$$

2. The absorption versus field curve is broadened by an amount proportional to the absolute value of the anisotropy field, independent of frequency.

3. A secondary absorption peak, a factor

$$\frac{24}{35}\left(\frac{H_a}{H}\right)^2 \quad (H = \text{internal d.c. field})$$

smaller than the primary peak, is predicted for the "wrong" sense of circular polarization.

An approximate theory of the effect of pores and other nonmagnetic inclusions on the microwave susceptibility of ferrites is developed.

Nonmagnetic inclusions give rise to free magnetic poles inside the material and, thus, to an additional magnetic field. This additional field has a d.c. component and an rf component. It can be shown, in simple cases, that the rf component does not appreciably influence the susceptibility. Therefore, only the influence of the d.c. component of the additional field is taken into account.

In this approximation, the susceptibility of the porous material is a weighted average of the susceptibility of the nonporous material. The weighting function W(H)dH is proportional to the fraction of the total volume in which the additional field is in the region between H and H + dH. The weighting function is calculated exactly for a special case: a sphere with a spherical pore at the center. It is argued that this single pore weighting function is approximately equal to the weighting function appropriate for a sample with many pores, if the same ratio of pore volume to ferrite volume is used. If the single pore weighting function is further approximated by a Lorentz distribution, the susceptibility of the porous ferrite differs from that of the nonporous ferrite only in the width of the resonance. The pore contribution to the line widths is

$$(\Delta H)_{pores} = 1.5\ 4\pi M_s \cdot \frac{v}{V}$$

where V is the total volume of the sample and v the volume of all pores.

A qualitative result of the theory is that in porous ferrites the absorption versus field strength curve should be steeper on the low-field side than on the high-field side. The point of maximum absorption is shifted toward the low-field side by an amount

$$H = \frac{4\pi M_s}{3}\frac{v}{V}.$$

Session VI MEMORY DEVICES AND MAGNETIC AMPLIFIERS
D. R. Brown, Presiding

69. HIGH FREQUENCY EFFECTS IN MAGNETIC FILMS*

Robert L. Conger
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Corona, Calif.

Ferromagnetic resonance was chosen as a tool for an investigation of the mechanism of magnetization reversal because the technique is quite sensitive and also interpretation of the results of the resonance experiments is not complicated by the domain boundary effects which confuse the results of direct reversal time experiments. The vacuum evaporation technique has been found to be very convenient for preparing alloy samples for resonance measurements since alloy films can be produced from the separate metallic ingredients in a few minutes time with relatively simple equipment. It is this ease of preparing films by evaporation that has made it possible to measure the resonance line widths of many different film compositions in this study of magnetization reversal.

Crossed coil experiments indicate that for fields several times the coercive force magnetization reversal in thin films takes place by domain rotation. A phenomenological theory based on a modification of the Landau-Lifschitz equation of motion shows that the reversal time for this type of magnetization reversal will be proportional to the damping constant of the modified equation of motion. This damping constant is in turn proportional to the ferromagnetic resonance absorption line-width. Experimental measurements on evaporated films of several different alloy compositions demonstrate this predicted proportionality of the reversal time and the resonance line width.

It is known that the addition of a few per cent of chromium or vanadium to an iron-nickel alloy will decrease its saturation magnetization by a large amount. The effect of these additions on the resonance line width of evaporated films is among the things being investigated.

* invited paper

70. RELATION BETWEEN MAGNETIC-CORE SWITCHING-TIME AND WIDTH OF FERROMAGNETIC RESONANCE PEAKS

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Paoli, Pa.

A rotation model is proposed for the mechanism of switching of a magnetic-core in the fast-switching range. Using the well-known dynamical equation for the magnetization vector,

$$\frac{dM}{dt} = \gamma \underline{M} \times \underline{H} - \frac{\lambda}{M^2} \underline{M} \times (\underline{M} \times \underline{H}),$$

the equation for the component determining flux changes through a toroidal core is obtained in the form

$$\frac{dM_H}{dt} = \lambda \left(1 - \frac{M_H^2}{M^2}\right) H.$$

The voltage waveform is given essentially by

$$\frac{dM_H}{dt} = \lambda H \operatorname{sech}^2\left(\frac{\lambda Ht}{M}\right),$$

and the switching coefficient

$$HT_s = 3.64 \frac{M}{\lambda}.$$

For 4-79 molypermalloy, the value of the relaxation frequency

$$(\lambda = 5 \times 10^9 \text{ cps})$$

obtained from the width of the ferromagnetic resonance peak by John Blades (reported at Armour Research Foundation Symposium, April 4-6, 1956) leads to a predicted switching coefficient $HT_s = 5.1 \times 10^{-7}$ oe-sec. in close agreement with data published by Menyuk and Goodenough (J. A. P. 26, 8, 1955). Effects which might account for coercive force are not considered.

71. MAGNETIZATION REVERSAL IN THIN FILMS

Donald O. Smith
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The magnetization reversal of thin films ($\approx$ 1000 Å thick) of 80-20 Permalloy has been studied in a strip transmission line. These films are evaporated onto a heated glass substrate in the presence of an orienting field. Coercivity and magnetization-reversal times vary with the angle between the driving field and the axis of initial orientation. Magnetization-reversal times less than 20 mμsec in any reversing field large enough to overcome the orienting energy have been observed. The switching coefficient $S_w \equiv H_m \tau$ is found to be $S_w < 2 \times 10^{-8}$ oe-sec. with a reversing field $H_m = 1$ oe. and a reversal time $\tau < 2 \times 10^{-8}$ sec. These low values of S are consistent with a model of flux reversal by rotation of the magnetization as a whole in the plane of the film. The longer reversal times which can also be observed are consistent with a model of flux reversal by domain-wall creating and motion. Measurements of the initial permeability perpendicular to the orientation axis will also be reported. An expected frequency dispersion of the initial permeability should give the actual low-value S_w for the domain-rotation process.

The research in this document was supported jointly by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

72. SOME SWITCHING PROPERTIES OF SQUARE LOOP FERRITES

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and
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Murray Hill, N. J.

The rate of change of magnetization of a "thin walled" toroid of square loop manganese magnesium ferrite has been studied. When rectangular current pulses are applied to a primary winding it is found that, except at very low driving currents, the magnetization reversal can be adequately described by the relationship.

$$\dot{M} = \frac{H - H_o}{S} F(M)$$

where M is the toroidal magnetization, H the applied field and H_o and S are constants of the material. This dependence of the rate of magnetization reversal on the applied field and the magnetization has been explained by Goodenough on a model of expanding and colliding domains of reverse magnetization. The number of domains is required to be independent of the applied field in the region where the above expression is applicable.

However, when a more complicated current pulse sequence is used, the above expression is not obeyed. Some simple relationships are obtained which, it appears, cannot be explained on any simple model of domain wall motion.

73. MAGNETIC VISCOSITY IN 4-79 MOLY PERMALLOY
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U.S. Naval Ordnance Laboratory
Silver Spring, Maryland

In the process of analyzing the behavior of the magnetic shift register, it was found that an important and useful relation exists between B, H, and time. When 4-79 Mo-permalloy is operating in a reversible region of its hysteresis loop, this relationship between B, H, and time is

$$\mu_r b \frac{d}{dt}(\Delta B) + \Delta B = \mu_r H \qquad \text{(emu)} \qquad (1)$$

where B is defined as the magnetic viscosity coefficient (which is a constant essentially independent of frequency and slightly dependent on B) and $_r$ is the reversible permeability. Also, it is shown that when a toroid contains a core of laminations or tape of a sufficient number of wraps,

$$N \frac{d\phi}{dt} = L \frac{di}{dt} - N\mu_r (b + \sigma T^2) \frac{d^2\phi}{dt^2} \qquad (2)$$

is valid to within a few per cent when $b > 2\sigma T^2$, where σ is the conductivity and T is the thickness of the tape or lamination. By using equation (1) and Maxwell's equations, an expression is derived for the core loss factor ($R/\mu Lf$) of a toroid having a laminated or taped core, and from this expression and experimental data, it is shown how the magnetic viscosity coefficient can be calculated. Then, again by using equation (1) and Maxwell's equations, another expression is derived by which the viscosity coefficient can be calculated from step-function current measurements (an entirely different measuring technique). The cores used to obtain experimental data were toroids containing cores of tape having thicknesses of 0.11, 0.23, 0.32, and 0.51 mils. The results of measurements made by both the $R/\mu Lf$ vs f method and the step-function current method give the same value for the viscosity coefficient. Measurements made by the step-function current method (while involves measuring amplitudes of transient voltage pulses having time constants in the millimicrosecond region) predict to within 6% the slope of $R/\mu Lf$ vs f measurements made at relatively low frequencies in the Kilocycle region. Conversely, from the slope of $R/\mu Lf$ vs f measurements made at low frequencies, one can easily predict the shape, amplitude, and time constant of the transient voltage pulse occurring across the toroid winding when the core is driven by a step-function current. From the theoretical and experimental material contained in this paper, equation (2) is also proven. The effect of the ends of the tape in a tape core is also discussed and a method is described by which one can determine when a tape has a sufficient number of wraps so that it can be treated as a laminated one.

74. THE FERRACTOR*+
Theodore H. Bonn
Sperry Rand Corporation
Philadelphia, Pa.

This paper contains a review of the Ferractor design philosophy. The basic circuit is described and methods of calculating power gain, turns ratio, power level, etc. are discussed. Many of the factors presented and much of the analysis have wide application to other high-frequency magnetic devices.

The Ferractor is a high-frequency pulse magnetic amplifier designed to replace vacuum tubes in digital data handling applications. Information rates as high as 2-1/2 megacycles have been achieved. A general purpose digital computer, the Univac Magnetic Computer, which contains fifteen hundred 660 kilocycle Ferractors has been constructed and is in operation at the Air Force Cambridge Research Center. This machine has only about twenty vacuum tubes.

The high speed and high gain of the Ferractors is due to a combination of improved circuitry and improved core design. A new core construction which uses thin wall stainless steel bobbins (instead of ceramic as heretofore used) to support 1/8 mil 4-79 molybdenum permalloy results in a greatly improved space factor. The development of improved toroidal winding techniques also increases the space factor. A number of circuit developments contribute to the performance of Ferractors. A series-type circuit allows the use of a single low-impedance pulse power supply which can be much more efficiently generated and distributed than the high-impedance multiple pulse sources of the shifting register type circuits previously reported by others. Effective means are described for suppressing zero signals and backward flow of information. Some computer circuits using Ferractors are described.

+ Trademark of Sperry Rand Corp.

* invited paper

75. THE CROSSED-FIELD MAGNETIC AMPLIFIER AND ITS APPLICATIONS

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and
D. Treves
The Weizmann Institute of Science
Rehovoth, Israel

The crossed-field magnetic amplifier, which is of the second harmonic type, is described and discussed. In this amplifier the exciting flux is perpendicular to the signal flux, and the latter links the output coils. There is therefore no mutual inductance between exciting and output coils, thus avoiding direct coupling. In this kind of amplifier only one core is necessary but this core is usually hollow in order to accommodate the exciting windings. The hollow toroid is discussed as an ideal example.

Using this amplifier, a clip-on d.c. milliammeter was designed. Another application is a static reproducing head.

The behavior of the magnetic amplifier under different conditions is analyzed, and instability phenomena are described.

76. THE FERRITE BEAD - A NEW MEMORY DEVICE

D. H. Looney
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Murray Hill, N. J.

A memory device, to be used in large scale high speed computors, must be simple in operation, easy to test, low in cost, and reliable. The use of toroids of ferrite material in coincident current memories has been successful and indicates that modifications of the ferrite toroid would be very valuable. The requirements for such a device may be formulated as:

1. Amenable to large scale automatic production.
2. Minimum testing required.
3. Drive current and power low.
4. Signal to noise ratio high.
5. Faster switching time.

These objectives can be achieved only if the memory system and the memory device are carefully tailored to one another. As an example, the use of coincident current operation restricts the available switching speed of any ferrite and

imposes severe testing requirements on each individual toroid.

The ferrite bead is a device which is capable of automatic production, low current drive, high output voltage and fast switching time. The device consists of a mixture of ferrite powders fired directly on the current carrying wires. Wire size may be as small as two mils with a spacing of one half a mil between wires. As a result the current necessary to switch a given ferrite material is reduced by a factor five or ten. The bead is usually formed as an ellipsoid about 1 mm in length and approximates a column rather than the disc of the usual toroid. Thus large output signals are obtained using low current drives. Many beads can be closely spaced and fired simultaneously on any array of wires.

A large number of experimental beads have been made. Two structures have been investigated, a bead containing a group of parallel wires and a bead containing wires spaced at 45° and 90°. A typical parallel wire bead gives an output of 50 mv at a speed of 1 μs for a driving current of 100 ma. The cross wire beads require a higher driving current and have a smaller flux change. The flux versus current characteristic, switching behavior and other electrical properties will be discussed.

77. CHARACTERISTIC OF A MEMORY ARRAY IN A SHEET OF FERRITE

R. H. Meinken
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Murray Hill, N. J.

A memory array can be contained in a sheet of ferrite by drilling many small holes in the ferrite; the material immediately surrounding each hole acts as a memory center. This type of device offers certain advantages:

1. Small holes furnish low current devices without sacrificing speed.
2. Many memory centers can be contained in a small area.
3. Small flux changes can be employed permitting the memory to be driven by commercial size cores.
4. The possible economy in manufacturing.

The disadvantages are:

1. Ferrite outside the switched volume

contributes to the reversible permeability noise signal.

2. When the flux change is small, precautions have to be taken to minimize the air flux pickup to maintain a high signal to noise ratio.

3. The memory centers in an array must be magnetically uniform to permit economy in manufacture.

Preliminary work indicates that wiring the array by evaporating on the conducting leads may economize the manufacture of the device and considerably reduce the air flux pickup.

With high coercive force material (> 1 oersted) the particle size is small compared to hold size and the uniformity of memory centers is good. With low coercive force material, hole size and particle size become comparable and therefore the uniformity within the array is decreased.

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MAGNETICS EXHIBIT

A magnetics exhibit has been arranged with some of the country's outstanding firms engaged in research, manufacture, and application of magnetic materials, components, and equipment. These include:

Arnold Engineering Company, Marengo, Ill.
Magnetic materials: permanent magnets, high permeability cores

Bell Telephone Laboratories, Inc., Murray Hill, N.J.
Magnetic materials in communications equipment

The Carpenter Steel Company, Reading, Pa.
High nickel alloy parts for: temperature compensator alloys, low expansion alloys, glass sealing alloys

Crucible Steel Company of America, Pittsburgh, Pa.
Magnets, magnet assemblies, precision instrument castings

General Electric Co., Metallurgical Products Dept.
Permanent magnets, thermistors, thyrites

General Electric Co., Research Laboratories
New scientific equipment, properties of new materials

General Magnetic Corporation, Detroit, Mich.
Alnico magnets

The Indiana Steel Products Company, Valparaiso, Ind.
Permanent magnets, non-metallic ceramic permanent magnets, speaker magnets

Instruments Publishing Company, Pittsburgh 12, Pa.
"Instruments and Automation" magazine, "Instrument and Apparatus News", technical book

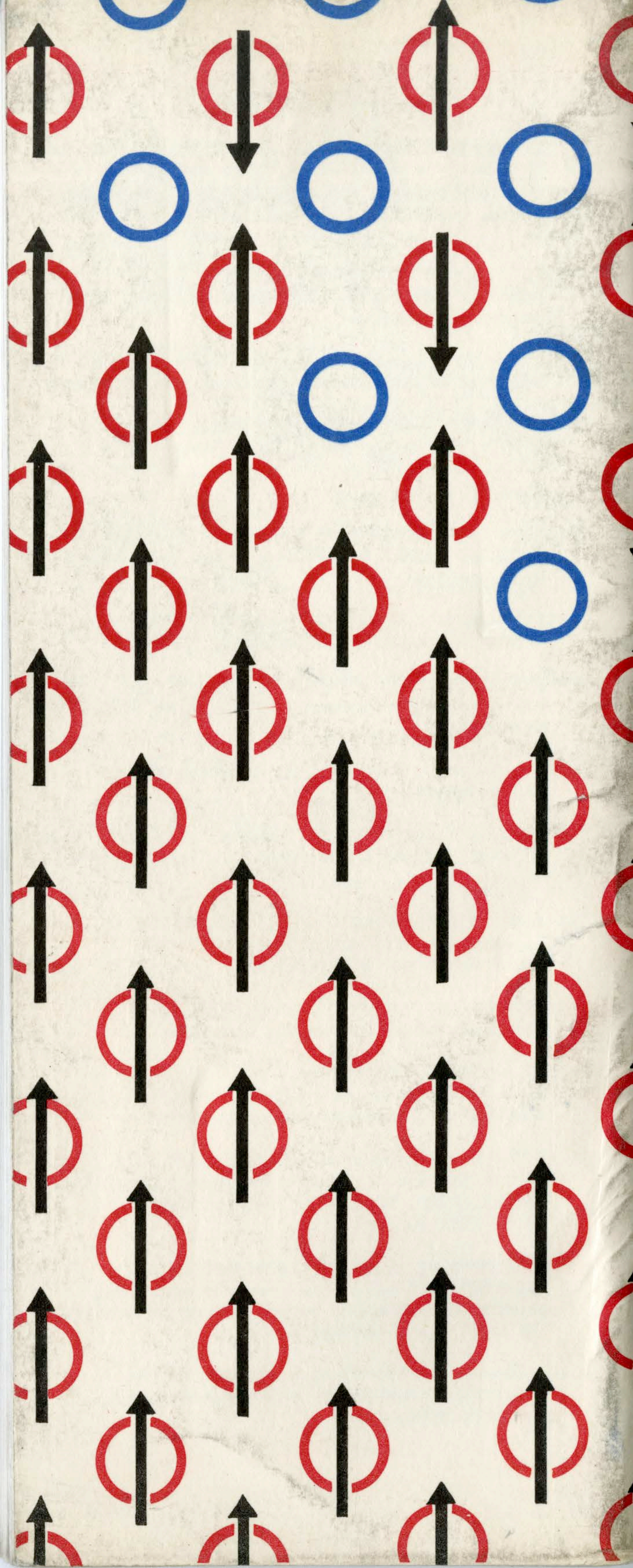
Magnetic Metals Company, Camden, N.J.
Electromagnetic core parts and shields

Magnetics, Inc., Butler, Pa.
Tape wound cores, ultra-thin cores, shields, laminations, powdered permalloy cores

Radio Frequency Laboratories, Boonton 6, N.J.
Models 942 and 107 Magnet chargers, Model 889 Magnetreater, Model 206, Booster Unit, Model 1221 Charger

Rese Engineering, Inc., Philadelphia 6, Pa.
Magnetic core pulse analyzer for analyzing square-loop magnetic cores, automatic handler for high speed testing of cores

Westinghouse Electric Corp., Pittsburgh, Pa.
Specialty Transformers and Hipersil cores, magnetic materials



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