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TECHNICAL PROGRAM

SESSION 1

SUPERCONDUCTING DEVICES I — Chairman: R. C. Barker

1.1 Superconductors as Nonlinear Magnetic Materials (Abstract only) (Invited).
C. P. Bean, General Electric Research Laboratory, Schenectady, N. Y.

1.2 High Field-High Current Superconductivity and Superconducting Magnets (Abstract only) (Invited).
J. E. Kunzler, Bell Telephone Laboratories, Inc., Murray Hill, N. J.

1.3 Some Principles and Properties of Superconducting Thin Film Computing Devices (Abstract only) (Invited).
F. B. Hagedorn, Bell Telephone Laboratories, Inc., Murray Hill, N. J.

1.4 Applications of Superconducting Materials (Abstract only) (Invited).
T. A. Buchhold, Advanced Technology Laboratories, General Electric Company, Schenectady, N. Y.

SESSION 2

SUPERCONDUCTING DEVICES II — Chairman: L. A. Finzi

2.1 Theoretical and Experimental Aspects of the Ryotron.
J. C. Miller, C. M. Wine, and L. S. Cosentino, RCA Laboratories, Princeton, N. J.

2.2 Some Characteristics of the Steerable Persistatron Switch.
H. A. Owen, Jr., Duke University, Durham, N. C.

2.3 Magnetoresistive Amplifiers with Superconductive Elements.
T. D. English, Jr., IBM Components Division, Poughkeepsie, N. Y., and L. A. Finzi, Carnegie Institute of Technology, Pittsburgh, Pa.

2.4 Pulse and Direct Current Sources for Cryogenic Systems.
L. D. Wald and J. P. Pritchard, Jr., Texas Instruments, Inc., Dallas, Tex.

2.5 Design of a Fully Associative Cryogenic Data Processor.
J. P. Pritchard, Jr. and L. D. Wald, Texas Instruments, Inc., Dallas, Tex.

SESSION 3

RECORDING I — Chairman: C. D. Mee

3.1 Achievements and Problems in Magnetic Recording (Invited).
K. Teer, Philips Research Labs, Eindhoven, Netherlands.

3.2 Fundamental Criterion for Recording on Magnetic Surfaces.
H. J. Kump and D. E. Speliotis, IBM Data Systems Division, Development Laboratory, Poughkeepsie, N. Y.

3.3 An Investigation of Separation Losses in High-Speed, High-Density Recording Tapes.
D. E. Speliotis, G. Bate, J. R. Morrison and R. E. Braun, IBM Data Systems Division, Development Laboratory, Poughkeepsie, N. Y.

3.4 A Flux Sensitive Reproduce Head of Thin Film Construction.
P. Smaller, Ampex Corporation, Redwood City, Cal.

SESSION 4

MAGNETIC-SEMICONDUCTOR DEVICES I — Chairman: J. D. Harnden, Jr.

4.1 SCR Inverter Commutated by an Auxiliary Impulse.
W. McMurray, Advanced Technology Laboratories, General Electric Company, Schenectady, N. Y.

4.2 A Magnetic Feedback Modulator for Improved FM Carrier Recording.
R. L. Price, 3M Company, Los Angeles, Cal.

4.3 Silicon Controlled Rectifiers for High-Power Semiconductor-Magnetic Pulse Generators.
L. R. Swain, Jr. and G. T. Coate, MIT, Cambridge, Mass.

4.4 A Gate Controlled, A-C Power Switch.
H. F. Storm, Advanced Technology Laboratories, General Electric Company, Schenectady, N. Y.

SESSION 5

MEMORY SYSTEMS I

Chairman: T. R. Long

5.1 The Plated-Woven Wire Memory Matrix (Invited).
K. Futami, S. Oshima, T. Kamibyashi, Kokasai, Denwa Company, Ltd., Tokyo, Japan.

5.2 A Synopsis of Magnetic Memories.
H. Chang, IBM Research Center, Yorktown Heights, N. Y.

5.3 Analysis of 10^8 Element Magnetic Film Memories Systems.
A. V. Pohm, R. J. Zingg, J. H. Hoper, and R. M. Stewart, Jr., Iowa State University, Ames, Iowa.

5.4 Plated Wire Magnetic Film Memories.
I. Danylchuk, U. F. Gianola, A. J. Perneski, and M. W. Sagal, Bell Telephone Laboratories, Inc., Murray Hill, N. J.

5.5 System and Fabrication Techniques for a Solid State Random Access Mass Memory.
H. W. Fuller, T. L. McCormack, and C. P. Battarel, Laboratory for Electronics, Inc., Boston, Mass.

5.6 Laminated Ferrite Memory (Abstract only).
R. Shahbender, C. Wentworth, K. Li, S. Hotchkiss, and J. Rajchman, Radio Corporation of America, Princeton, N. J.

5.7 High Density Magnetic Film Memory Techniques.
T. S. Crowther, MIT, Lincoln Laboratory, Lexington, Mass.

SESSION 6

RECORDING II

Chairman: E. D. Daniel

6.1 Noise Pulses in Magnetic Recording (Abstract only).
S. R. Lambeir, Philips Research Labs, Eindhoven, Netherlands.

6.2 An Investigation of High Frequency Bias Induced Tape Noise.
U. Ragle and P. Smaller, Ampex Corporation, Redwood City, Cal.

6.3 Effects of Particle Orientation on Interaction in Magnetic Recording Tapes.
R. A. Cummings, Singermetrics, South Norwalk, Conn. and C. D. Mee, IBM Research Center, Yorktown Heights, N. Y.

6.4 Evaluation of Co-P Electrodeposits as a Recording Medium.
H. R. Allen, Honeywell Denver Division, Denver, Col., J. M. Carr and J. S. Sallo, Honeywell Research Center, Hopkins, Minn., and M. G. Peterson, Honeywell Aero Division, St. Petersburg, Fla.

SESSION 7

MAGNETIC-SEMICONDUCTOR DEVICES II Chairman: T. G. Wilson

7.1 High Frequency Time Ratio Control with Insulated and Isolated Inputs.
R. E. Morgan, Advanced Technology Laboratories, General Electric Company, Schenectady, N. Y.

7.2 A DC to DC Power Amplifier Using External Impulse Commutation.
D. L. Watrous and J. D. Harnden, Jr., Advanced Technology Laboratories, General Electric Company, Schenectady, N. Y.

7.3 Some Regulated Power Supply Apparatus Used Morgan Circuit.
S. Aoki and J. Hasegawa, Shindengen Electric Company, Tokyo, Japan.

7.4 Solid State Commutation for Direct Current Motors.
H. D. Brailsford, Brailsford & Company, Inc., Rye, N. Y.

SESSION 8

MEMORY SYSTEMS II Chairman: R. Shahbender

8.1 Woven Thin-Film Wire Memory.
H. Maeda, A. Matsushita, Toko Radio Coil Laboratories, Ltd., Tokyo, Japan.

8.2 A Noise Cancelling Two-Core-Per-Bit Nondestructive Readout Technique Operated in a Flux Rotation Mode.
H. M. Winters, Automatic Electric Laboratories, Inc., Northlake, Ill.

8.3 Transfluxor Content-Addressable Memory.
A. D. Robbi and R. Ricci, RCA Laboratories, Princeton, N. J.

8.4 An Evaluation of Design and Performance of the Permanent Magnet Twistor Memory.
L. W. Stammerjohn, Bell Telephone Laboratories, Inc., Allentown, Pa.

8.5 The Piggyback Twistor--An Electrically Alterable Nondestructive Read-Out Twistor Memory.
W. A. Baker, Bell Telephone Laboratories, Inc. Allentown, Pa.

8.6 A High-Speed Card Changeable Permanent Magnet Memory--The Inverted Twistor.
F. J. Procyk and L. H. Young, Bell Telephone Laboratories, Inc., Allentown, Pa.

SESSION 9

MATERIALS I — Chairman: F. B. Humphrey

9.1 Magnetostatic Interaction in Magnetization Reversal in Thin Ni-Fe Films (Invited).
S. Middelhoek, IBM Research Laboratory, Zurich, Switzerland.

9.2 Easy Direction Resilience of Permalloy Films.
H. J. Kump, IBM Data Systems Division, Development Laboratory, Poughkeepsie, N. Y.

9.3 Anisotropy Control of Ni-Fe Films Through Sequenced-Field Deposition.
W. T. Siegle and W. R. Beam, Rensselaer Polytechnic Institute, Russel Sage Laboratory, Troy, N. Y.

9.4 Scratch Induced Anisotropy.
Y. Gondo, Yokohama National University, Yokohama, Japan, B. E. Gran and R. J. Prosen, Honeywell Research Center, Hopkins, Minn.

9.5 A General Frame of the Displacement Model of Magnetization in Ferromagnetics and Some Consequences of It.
A. Goral, Warsaw Technical University, Warsaw, Poland.

9.6 Certain New Aspect of Rotational Switching in Policrystalline Bulk Ferromagnetics.
A. Goral, Warsaw Technical University, Warsaw, Poland.

SESSION 10

MAGNETIC AMPLIFIERS Chairman: H. F. Storm

10.1 Flux Resetting Characteristics Pertinent to the Triggering Phenomena of Magnetic Amplifier.
Tadashi Kikuchi and Takashi Kikuchi, Tohoku University, Sendai, Japan.

10.2 Two Aspects of Magnetic Amplifier Nonlinearity by a Unique Approach.
A. Goral, Warsaw Technical University, Warsaw, Poland.

10.3 Polyphase Double Frequency Magnetic Amplifier.
K. Harada, Kyushu University, Fukuoka, Japan.

10.4 High Performance, High Reliability Via Magnetic Amplifiers in the Apollo Guidance Temperature Control System.
T. L. Shuck, MIT, Instrumentation Laboratory, Cambridge, Mass.

10.5 Precision AC Welding Supply with Program Control.
N. J. Normando, Air Reduction Company, Murray Hill, N. J.

10.6 Static Logic Power Control System with Solid State and Magnetic Devices.
B. R. Shelar, International Research Associates, Franklin Park, Ill.

SESSION 11

LOGIC I Chairman: R. M. Brownell

11.1 The Storage and Gating of Information Using Balanced Magnetic Circuits.
J. N. Brown, Bell Telephone Laboratories, Inc., Burlington, N. C. and E. E. Newhall, Bell Telephone Laboratories, Inc., Murray Hill, N. J.

11.2 Microcore-Backward Diod Shift Register.
G. R. Briggs, RCA Laboratories, David Sarnoff Research Center, Princeton, N. J.

11.3 Two-Phase, All-Magnetic Shift Registers That Can Be Operated with a Single Pulse Driver in the 0-5 KC Range.
K. V. Mina and E. M Walters, Bell Telephone Laboratories, Inc., Murray Hill, N. J.

11.4 Magnetic Film Phase Locked Oscillators.
A. R. Johnson, IBM General Products Division, Development Laboratory, Endicott, N. Y.

11.5 A Magnetic Film Adaptive Linear Decision Array.
A. V. Pohm, G. R. Allen, and J. W. Nilsson, Iowa State University, Ames, Iowa.

SESSION 12

MATERIALS II Chairman: H. P. Louis

12.1 Effects of Chemical Purification on Physical Properties of Magnetic and Other Compounds (Invited).
E. G. Spencer and J. P. Remeika, Bell Telephone Laboratories, Inc., Murray Hill, N. J.

12.2 Magnetic Properties of Multilayer Films of FeNi--Mn--FeNiCo and of FeNi--Mn.
O. Massenet, R. Montmory, L. Neel, D. Paccard, and C. Schnaider, Centre National de la Recherche Scientifique, Grenoble, France.

12.3 Magnetic Properties of Co-Ni-P Thin Films by Electroless Deposition.
J. O. Holmen and J. S. Sallo, Honeywell Research Center, Hopkins, Minn.

12.4 Pulse Measurements on a Ferromagnetic Thin Film at Liquid Helium Temperature.
P. I. Bonyhard, International Computers and Tabulators, Ltd., Stevenage, England.

12.5 Measurement of Anisotropy Dispersion and Coercive Force within Small Areas of Permalloy Films Using a Magneto-Optic Technique.
D. B. Dove and T. R. Long, Bell Telephone Laboratories, Inc., Murray Hill, N. J.

12.6 A Magnetic Amplifier for the Visual Presentation of Low-Frequency Hysteresis Loops of Very Small Ferromagnetic Samples.
H. van der Heide, Philips Research Labs, Eindhoven, Netherlands.

SESSION 13

MAGNETIC FREQUENCY CONVERTERS — Chairman: E. T. Hooper

13.1 Power Transfers in Nonlinear Frequency Converters with Three Commensurable Frequencies.
L. A. Finzi, Carnegie Institute of Technology, Pittsburgh, Pa., and R. W. Snelsire, Westinghouse Electric Corporation, Baltimore 3, Md.

13.2 A New Type Magnetic Modulator.
S. Ohteru and H. Kobayashi, Waseda University, Tokyo, Japan.

13.3 Stabilized 400 to 3600 CPS Magnetic Frequency Multiplier.
W. A. Geyger, U. S. Naval Ordnance Laboratory, Silver Spring, Md.

13.4 On the Mechanics of Vector Reactor Type Frequency Multiplier.
H. Kobayashi and S. Ohteru, Waseda University, Tokyo, Japan.

13.5 Dynamic Behavior of the Controlled Ferroresonance Regulators.
A. Lavi, Carnegie Institute of Technology, Pittsburgh, Pa.

SESSION 14

LOGIC II — Chairman: E. E. Newhall

14.1 Discrete Data Acquisition and Processing System.
G. A. Bailey, G. C. Marshall Space Flight Center, Huntsville, Ala.

14.2 Sequential Multiplexing Scheme.
R. Braasch, Sandia Corporation, Albuquerque, N. M.

14.3 Decimal Matrix Memories Utilized Incremag.
K. Moriya and K. Inaba, Nippon Signal Company, Ltd., Tokyo, Japan.

14.4 Magnetic Timing and Delay Circuitry as Applied to a Relay Test Facility.
S. D. T. Robertson, R. N. Basu, G. R. Slemon, and P. P. Biringer, University of Toronto, Toronto, Canada.

14.5 Programmable Timer: Utilizing Feedback Shift Registers and Sequence Detectors.
R. H. Braasch, E. J. Bernard, and T. A. Howard, Sandia Corporation, Albuquerque, N. M.

SESSION 15

MATERIALS III — Chairman: F. J. Friedlaender

15.1 Ferrite H-Cores. Components for Miniaturised Transformers.
E. Olsen, N. V. Philips, Eindhoven, Netherlands.

15.2 The Reproducibility of Variability Measurements of Potcores.
E. Olsen, N. V. Philips, Eindhoven, Netherlands.

15.3 The Characteristics of Ferrite Cores with Low Curie Temperature and Their Application.
K. Murakami, Tohoku University, Sendai, Japan.

15.4 Cross-Field Effects in Tape Cores.
F. J. Friedlaender and J. D. Gassaway, Purdue University, Lafayette, Ind.

15.5 The Method of Measuring the Frequency Characteristics of Rectangular Hysteresis Core Materials.
T. Kusuda and Y. Sakurai, Osaka University, Osaka, Japan.

15.6 An Experimental Study on Flux Presetting-Resetting Characteristics of Magnetic Cores with Rectangular Hysteresis Loop.
K. Murakami, Tohoku University, Sendai, Japan.

15.7 Test and Evaluation of Large Magnetic Tape-Wound Cores Used in the Astron Accelerator.
R. L. Sewell, Lawrence Radiation Laboratory, University of California, Livermore, Cal.

SESSION 16

MEMORY DEVICES — Chairman: G. C. Feth

16.1 A Coupling Phenomenon between the Magnetization of Two Thin Ferromagnetic Films Separated by a Thin Metallic Film; Applications to Magnetic Memories.
J. C. Bruyere, O. Massenet, R. Montmory, and L. Neel, Centre National de la Recherche Scientifique, Grenoble, France.

16.2 Measurement of Trapped Flux Relaxation and Ground Plane Current Effects.
V. T. Shahan and C. J. Townsend, IBM Components Division, Poughkeepsie, N. Y.

16.3 Sensing a Magnetic Memory Using Magnetic Circuitry.
W. D. Farmer, Bell Telephone Laboratories, Inc., Murray Hill, N. J.

16.4 Some Anomalies in Multiaperture Ferrite Device Behavior.
G. E. Lynn and R. J. McGee, Westinghouse Electric Corporation, Baltimore, Md.

16.5 Dynamic Behaviour of Multi-Aperture Devices.
Th. Holtwijk, S. J. Valkenburg, and N. F. Verster, Philips Research Labs, Eindhoven, Netherlands.

16.6 Magnetic Field Measurements on Twistor Wire Magnetized by Small Magnets.
R. L. Call, Bell Telephone Laboratories, Inc., Holmdel, N. J.

SESSION 1

Superconductors as Nonlinear Magnetic Materials

Charles P. Bean

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Superconductivity occurs in a wide variety of metallic elements and compounds - twenty-five elements and about four hundred alloys and stoichiometric compounds at last count[1]. The highest temperature that marks the transition from superconductivity to normal behavior is a little over 18^oK (Nb_3Sn) and since for most purposes one must work well below this critical temperature, almost all experiments and devices employ liquid helium. Since this refrigerant is now widely available at about six dollars a quart together with rugged containers that evaporate two quarts/day in normal heat leak, the main economic barrier to the use of the unique properties of superconductors has been lowered if not eliminated.

These unique properties[2], as exemplified by lead, include the property of zero resistance (an induced current in a lead toroid flowed for over two years with no detectable diminution) as well as the fact that no flux will enter the bulk of a superconducting sample (Meissner effect). These properties can be summarized by the equations $\rho = 0$ and $B = 0$ where ρ and B are the resistivity and flux density respectively.

These two properties are at the base of all applications of superconductors. Zero resistivity (or at least very low loss) gives interest to the high-field superconductors discussed by Kunzler while this zero resistance coupled with the switching to normal resistance in a magnetic field accounts for the unique properties of superconducting switching, logic and storage elements described by Hagedorn. Buchhold's applications of bearings and gyros depend on the complete diamagnetism implied by $B = 0$.

We now distinguish two types of superconductors, type I and type II. The type I superconductor (most pure superconducting elements are of this type) has a particularly simple magnetic behavior. In a macroscopic specimen, the flux density is zero for fields less than the critical field, H_c, that marks the limit of the superconducting state. Above this field the specimen has all the properties of a normal metal including the property that

the field is essentially equal to the applied field. So, in summary, the type I superconductor is either completely superconducting or completely normal. (This statement is strictly true only for a long thin specimen in a field that is parallel to the axis of the specimen. With other geometries one finds a gross mixture of superconducting and normal regions called the intermediate state that is created by the field concentrations associated with specimen shape.) In recent years it has been appreciated[3] that there is another class of superconductor - usually an alloy or compound - in which, for a bulk specimen, flux is completely excluded for fields less than H_{c1}, but above this field flux penetration is partial and increases with applied field until bulk flux penetration is complete at an upper critical field, H_{c2}. Since this field is generally larger than the equivalent H_c of type I superconductors, these type II superconductors are known as high-field superconductors. The region between H_{c1} and H_{c2} is known as the mixed state which is not to be confused with the shape dependent intermediate state mentioned earlier. We made the proviso above that H_{c2} denotes the field limit of bulk flux rejection since it has been found recently that a very thin film of superconducting electrons coats the surface of the material until a higher field H_{c3}, where $H_{c3} \approx 1.7\ H_{c2}$.[4]

The present conception of the mixed state pictures the flux as entering in the form of quantized current vortices. The total flux contained in each vortex is 2×10^{-7} gauss-cm^2. In equilibrium these vortices repel one another to form a lattice that compresses as the field is increased from H_{c1} to H_{c2} and finally all flux variation in the bulk of the specimen smoothly disappears at H_{c2}. Magnetization measurements on homogeneous alloys show good agreement with this theory.[5]

If the type II superconductor is inhomogeneous, there may be impediments to the motion of these flux lines. In this event there will be a gradient of flux[6] as the flux is driven into the specimen. This gradient of flux lines is equivalent to a macroscopic current density by Ampere's Law, curl $\underline{H} = 4\ \underline{J}/10$. This observation allows one to calculate the magnetic behavior of these superconductors in terms of only one parameter, the critical current density, $J_c(H)$[7] - the same critical current density that is measured in current transport measurements. The magnetic behavior deduced from this approach and measured experimentally includes size dependent magnetization properties and a hysteresis loop that is the precise diamagnetic equivalent of the Rayleigh hysteresis loop for ferromagnets. This last nonlinear effect gives rise to calculable losses in alternating fields as well as generation of harmonics of the exciting frequency.

In summary, superconducting materials show nonlinear magnetic properties that are closely analogous to those of ferromagnets. The diamagnetic equivalents of square-loop magnets as well as Rayleigh loop magnets exist and are quite well understood - these properties, coupled with the phenomenon of zero resistance, may form a new area for the application of the concepts of nonlinear magnetics.

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HIGH FIELD-HIGH CURRENT SUPERCONDUCTIVITY AND SUPERCONDUCTING MAGNETS

J. E. Kunzler*

Considerable effort is being directed toward the construction of superconducting magnets, as well as toward increasing our understanding of high field superconductivity.[1] This increase in activity has followed the unexpected discovery, nearly three years ago, that Nb_3Sn could remain superconducting in a magnetic field of 88 kgauss while sustaining a current density in excess of 10^5 amps/cm^2. The hope of constructing a superconducting magnet capable of generating magnetic fields of strengths near 100 kgauss is not new; Onnes suggested this possibility[2] soon after he discovered superconductivity in 1911.[3] However, his dreams ended when he found that a magnetic field of a few hundred gauss destroyed superconductivity in the materials known at that time.[4] In the 1930's the possibility of using Pb-Bi alloys for superconducting magnets which were expected to be capable of a more modest field of about 20 kgauss was suggested.[5] However, the idea was abandoned after some discouraging observations[6] and the widespread impression developed that superconducting magnets, capable of even as much as a few kilogauss, were not practical;[7] it is now known[8] that Pb-Bi could be used for superconducting magnets having capabilities approaching those suggested. Progress toward practical superconducting magnets was made in 1955 when an iron core electromagnet using windings of superconducting niobium was reported to generate a field of about 7 kgauss.[9] In 1960, Autler reported[10] an air core solenoid, constructed of hard-worked niobium wire, that produced a field of 4.3 kgauss. A little later, a superconducting solenoid constructed of a Mo-Re alloy and capable of a field of 15 kgauss was reported.[11] The phenomenal properties of Nb_3Sn were reported in early 1961 and it then became apparent that superconducting magnets capable of fields approaching 100 kgauss would become a reality.[1] Results of investigations that showed that Nb-Zr alloys were also useful for superconducting magnets were quick to follow.[8, 12, 13] Activity mushroomed and by late 1961, other potential materials were reported;[14] in addition several laboratories reported superconducting solenoids capable of fields near 70 kgauss.[15, 16, 17] Since then feasibility models of solenoids, capable of fields as large as 100 kgauss, have been constructed[18] and operational magnets capable of fields at least this high seem likely by the time of this conference.

The problem of generating high magnetic fields with solenoid magnets constructed of ordinary conductors are formidable; magnetic materials, such as iron, are of little assistance above 30 kgauss.[19] It requires about 2 megawatts of power, about 1000 gallons per minute of cooling water, and costs a substantial fraction of a million dollars to produce a few cubic inches of continuing field at 100 kgauss. There are less than about 2 dozen installations known that have this capability in the world; furthermore, higher fields are rare since the power requirements increase more rapidly than the square of field. However, once a magnetic field is established, in principle, no power should be required to sustain it; the electrical power is converted to heat due to the resistance of the windings. Since superconductors have no resistance, their use eliminates this problem.

*Bell Telephone Laboratories, Inc., Murray Hill, New Jersey

Our understanding of high field superconductivity has advanced considerably during the past three years. Superconductors can be divided into two types: Type I and Type II. Type I superconductors have low critical magnetic fields, tend to have reversible properties, and are not suitable for high field magnets. As a result of considerable work by Russian theorists[20] and others[21] (known as the GLAG theory in honor of its originators), an ideal reversible state of Type II superconductivity can be accounted for in high fields. However, these ideal Type II superconductors cannot sustain a transport current and require "flux pinning,"[22, 23] obtained by introducing defects or inhomogeneities into the material, before they are useful for magnets. Most properties, such as the magnetization of high field-high current superconductors are highly irreversible.[24] Bean[25] and Berlincourt[26] have recently published good reviews of the physics of high field superconductors.

At the present, two materials, ductile Nb-Zr alloys and the brittle compound Nb_3Sn, are being used extensively for superconducting magnet fabrication. Nb-Zr has the advantage of ductility but it also suffers from some disadvantages. It has a lower critical field[27] (about 70 kgauss for the composition most commonly used); wire in magnets is unable to sustain as much current as in short lengths,[15, 16, 17, 28] and solenoids are subject to "training" and "proximity" effects.[29] In general, the critical magnetic field is independent of the mechanical state of Nb-Zr alloys while the critical current density increases significantly with increased deformation.[8, 30] However, it has been shown that the critical current can also be increased by appropriate heat treatment.[31, 32] Nb-Zr magnets are being produced commercially by organizations such as Avco, Linde, Magnion, Westinghouse, Varian Associates, etc.

Nb_3Sn is brittle and thus requires special techniques for its fabrication into magnets. RCA has described a process[33] which relies on the existence of some degree of ductility in thin layers of Nb_3Sn deposited on a ductile substrate. The National Research Corporation has developed a similar structure. Bell Telephone Laboratories has developed a process[1, 34] in which unreacted niobium and tin powders are enclosed within the core of a "wire" which is reacted by heating to near 1000°C to produce brittle Nb_3Sn in the core of the wire after the solenoid is wound. The process has proven to be more successful than might have been expected for such a complex configuration; many continuous lengths of wire, each over 10,000 feet long, have been produced. The characteristics of Nb_3Sn cored "wire" are sensitive to such parameters as particle size of the Nb powder, initial composition, time and temperature of the reaction, etc.[35, 36] The performance of Nb_3Sn cored "wire" magnets has been very satisfactory; none have failed due to use or thermal cycling. It appears that this process will be useful for magnets capable of field strengths approaching the critical field of Nb_3Sn which is 200 kgauss or above.[27, 37]

There are many problems associated with the use of superconductors for generation of magnetic fields. They include, refrigeration of the solenoid to liquid helium temperature (4.2°K), removal of heat and the avoidance of instability when the magnetic field strength is changed (due to the irreversible magnetization of the superconductors), prevention of flux jumping which originates from the same source, handling of the energy of the magnetic field when the solenoid "goes normal," avoidance of shock waves and high voltages resulting from rapid collapse of the magnetic field, structurally restraining the magnet against the mechanical forces on the windings (there is a radial force at the midsection of a solenoid resulting from the "pressure of the magnetic field" which varies as the square of the field and is approximately equal to 6000 psi at 100 kgauss).

Some of these problems are new and some become formidable when the volume or the strength of the field becomes large. However, they all appear to be capable of reasonable solutions.

High field-high current superconductors are too new for many of their potential applications to be apparent. Until the advent of these materials, it was generally not realistic for an engineer to think of devices requiring magnetic fields of 50 or 100 kgauss. Some of the more obvious potential applications include high magnetic fields for a wide variety of research activities, magnets for particle accelerators and bubble chambers, magnets for controlled thermonuclear fusion (in the event it proves to be feasible), magnets for magnetohydrodynamic power generation, high field-high current superconductors for high power dc transmission systems, and the shielding and shaping of magnetic fields.

The discussion and references are intended to be illustrative rather than complete. More details and additional references can be found in the references cited.

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