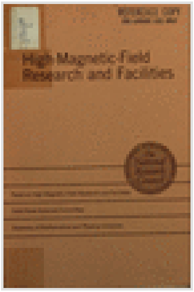

High-Magnetic-Field Research and Facilities: [Final Report] (1979)

Pages
112

Size
6 x 9

ISBN
0309304342

Panel on High Magnetic Field Research and Facilities; Solid State Sciences Committee; Assembly of Mathematical and Physical Sciences; National Research Council

High-Magnetic-Field Research and Facilities

Panel on High Magnetic Field Research and Facilities
Solid State Sciences Committee
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

NOTICE The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

The technology of resistive magnets was founded in the nineteenth century, and developments have continued, with magnetic fields of about 23 tesla (T) (1 T = 10^4 gauss) being attainable at present. In a parallel development, superconducting materials were discovered in the second decade of this century; recent advances have led to superconducting magnets affording fields up to 17 T. A melding of the two technologies allows fields of about 30 T today.

Higher fields are obtainable with pulsed conditions. Using quasi-static (up to several tenths of seconds) systems, one can achieve 40 T. For still higher fields, there are short-time pulses (of the order of microseconds) that supply fields up to 100 T in a nondestructive manner and fields above 300 T in a manner destructive of sample and coil.

Fifteen years ago the National Magnet Laboratory was commissioned and was the major facility of its type in the world. Since that time, nearly all the major high-field technology advances have occurred in the United States. However, in recent years, other countries have developed facilities, so that today major centers affording the above-mentioned field strengths are found throughout Europe and in Japan, as well as in the United States.

Believing it timely to consider where the development of this technology is leading, the Solid State Sciences Committee of the National Research Council's Assembly of Mathematical and Physical Sciences proposed a study to assess:

1. The importance of high magnetic fields to present and future research in all areas;
2. The importance of high magnetic fields to present and future technologies;
3. The identification of any areas of research that might offer major opportunities for exploitation of high magnetic fields;
4. The present and future science and technology for the generation of high magnetic fields;

5. The role of large magnetic facilities in the overall scientific and technical community.

The Committee established a panel to study these points and any others it deemed important. The panel was organized in June 1978 and at its first meeting divided its study into four parts, each to be handled by a subpanel. These four were (a) Scientific Opportunities, (b) Applications, (c) Magnet Design and Materials, and (d) High Magnetic Field Facilities and Users. Each subpanel prepared a report, which is included in this final report of the Panel.

Many questions arose during the course of the Panel's discussions. Some we were able to address, and these are covered in the report; others we could not address. It is clear that large facilities will continue to play a major role in high-magnetic-field development; however, we did not make any recommendations as to what or where these facilities should be. In addition, we did not assess the performance of the existing large facilities. Although we considered the costs associated with the attainment of higher fields, we did not specify a funding program. If our recommendations are followed, implementation will proceed with a coordinated plan for funding and for a detailed design and development of hardware and associated facilities. What we have done is to identify specific important objectives for future high-magnetic-field development and to recommend the most effective means to move toward those objectives.

I wish to thank all members of the Panel and all consultants to it for their conscientious work, which they performed in spite of the pressing obligations of their regular activities. I also wish to thank the many members of the scientific and engineering communities who responded to inquiries, for without those responses this report could not have been written. The names of those who contributed to the study appear in Appendix B to this report.

Support for this study was provided by the National Science Foundation (Contract C-310, Task Order 385), for whose interest and cooperation we are most grateful.

Seymour P. Keller, *Chairman*
Panel on High Magnetic Field
Research and Facilities

1

Introduction

High magnetic fields have played a fundamental role in research and technology. In research, such diverse disciplines as biology, chemistry, engineering, metallurgy, and physics have required the extensive use of magnetic fields. Not only has the phenomenon of magnetism itself been the basis for many fundamental investigations, but it has also led to a rich history of research on and development of magnetic materials and technology. Magnetism continues to be an active and fruitful area for research. In addition, magnetic fields play a central role in many important phenomena and research techniques including nuclear magnetic resonance (NMR) and electron spin resonance (ESR) measurements, Hall probe and Hall effect measurements, applications to superconductivity, magnetooptic spectroscopy, and tunable semiconductor lasers. A list of research areas involving the use of magnetic fields would be almost endless; however, the Panel's objective is not to provide an exhaustive listing but to give a flavor of the important research needs being fulfilled with the application of magnetic fields.

If we turn from research to technology and practical applications, we quickly see here, too, the diverse uses to which magnets have been applied. A partial list includes such varied applications as transformers, motors, generators, audio and video recording, computer technology, radar, television, fusion experiments, measuring probes, and mass spectrometers. The application of magnetism to human needs and uses is an unending story, as we continuously find new and important usages such as magnetic bubbles for information storage, linear motors and levitation for moving vehicles, and microwave ovens.

Many of these research and technology applications have been achieved with modest fields [up to 1 or 2 tesla (T); 1 T = 10^4 gauss]. As fields of greater magnitude became available, the utilization of magnetism became more widespread and its applications in research and technology more diverse.

A brief comment on the history of the development of magnets is in order. The basic building block of a high-field magnet is a multiturn coil of conducting material containing an electrical current. This nineteenth century invention led to the modern electrical industry through the work of Faraday, Maxwell, and others. Later it was found that the magnetic field generated by the coil could be enhanced by inserting a strongly magnetic material such as iron in the coil. The resulting fields were limited to about 2 T. The first fields above 3 T were achieved with iron-free high-power solenoids as early as 1914. Major advances took place in the 1930's in the United States with Giauque's work on kerosene-cooled solenoids at Berkeley (resulting in 10-T steady-state fields) and Bitter's work on water-cooled solenoids at Massachusetts Institute of Technology (MIT). Bitter's design has endured, and today modifications of it are used in most high-magnetic-field facilities.

Magnets of this type are relatively inexpensive (about $20,000); the main capital cost of a facility is the cost of the power supply and cooling system. Hence, most high-field facilities in the world have a number of solenoid magnet stations that can be connected to a large power supply. Magnets of this type now produce fields up to 23 T.

In 1911, in a parallel development, Kamerlingh Onnes discovered superconductivity. For some time it was thought that superconductors could be used as windings for high-field magnets. Unfortunately, these pure metal superconductors become resistive in modest magnetic fields of about 0.1 T. In 1961, Kunzler and his associates found a new class of superconductors (Type II) that remain in the superconducting state even in extremely high fields exceeding 15 T. With this discovery, the avenue for attaining high fields with superconducting coils was opened. Recent rapid advances have led to a substantial number of superconducting magnet systems producing fields greater than 12 T (the current world's record is 17.5 T) distributed worldwide.

These two technologies, the resistive magnet and the superconducting magnet, have been joined to produce even higher fields in the range of 25-30 T. Such hybrid magnets afford experimenters the highest dc fields.

Still higher magnetic fields have been achieved on a pulsed basis. Quasi-static (up to several tenths of seconds) systems have attained fields of about 40 T. Short-pulse systems provide fields up to 100 T, in a nondestructive fashion, for durations up to milliseconds. Fields above 300 T can be generated for microseconds, but coil and sample are destroyed.

Fifteen years ago the Francis Bitter National Magnet Laboratory was commissioned at MIT and was the major facility of its type in the world. Since that time, nearly all high-field technology advances have occurred in the United States. Today major U.S. facilities are located at the National Magnet Laboratory at MIT, the Naval Research Laboratory, the University of Pennsylvania, and the University of California at Berkeley. Major facilities have also been built all over the world: in France, England, Germany, Holland, Poland, Russia, and Japan.

The questions we now face are these: How high a magnetic field is it practical to strive for? What are the scientific opportunities in research if we attain higher magnetic fields? What are the technological and developmental opportunities if we have higher magnetic fields? What is the status of the current magnet facilities in the United States? What is the status of current ideas on magnet design for the generation of higher magnetic fields?

The objectives of this report are to consider these questions, present pertinent information, and attempt to arrive at answers. Accordingly, the report is divided into five additional chapters. Chapter 2 contains the conclusions of the Panel and its recommendations. Chapter 3 deals with scientific opportunities for research using high magnetic fields. Chapter 4 treats applications using high magnetic fields. Chapter 5 is concerned with magnet design and materials work related to the generation of high magnetic fields. Last, Chapter 6 reports on high-magnetic-field facilities and their use in both the United States and abroad.

In part because of the severe time limitation—the interval between initiation of the study and its completion being some six months—the Panel did not study a number of important issues. We do not address questions about the funding of the current national facilities, their operational practices, and the caliber of the work performed at them. We did not address questions of whether there should be new national facilities or of where current efforts should be expanded. Where we recommend increased support, we mean either the opening of new facilities or increasing the operation of present facilities or both; we do not make the judgment on which alternative should be chosen. Similarly, we have not considered the possibility of contracting selected activities. Although it was suggested that the Panel attempt to handle the zero-based budgeting questions, we did not consider ourselves prepared to do so, nor did we recommend a specific level of funding for those programs that we believe should be expanded or initiated. Further, when we recommend work aimed at obtaining higher fields than are now extant, we do not lay out a specific program for achieving this goal.

2

Conclusions and Recommendations

There has been increasing progress in most areas of research and technology involving magnetic fields. In addition, we can point to investigations in which higher magnetic fields will be critical to the advancement and attainment of knowledge. Hence, we believe that the generation and use of high magnetic fields in the study of the properties of matter is of great importance to the national program in research and technology. Examples of opportunities span such diverse studies as transitions to lower dimensionality and Wigner crystallization, metallurgical phase transitions, and antibody–antigen interactions (thus the field of immunology, probably the most fruitful area of cancer research).

Because of (a) the pervasive role magnetic fields have played, (b) the generally proven validity of extrapolating future advances from past progress as field strengths were increased, (c) the breadth of interest, application, and potential, and (d) the many exciting scientific opportunities, we *recommend* increased work toward the attainment of higher magnetic fields.

The combined weight of the scientific and technical opportunities in many disciplines, rather than a single, pressing argument, justifies this recommendation. For this reason, and because of the apparent technical and economic problems, we do not recommend a "crash" program, but instead we recommend a sustained and orderly approach to the attainment and utilization of higher magnetic fields.

In Chapter 3, on Scientific Opportunities, we have identified a large class of experiments that become feasible as magnetic fields are increased by factors of 2 or 3 above today's limit (approximately 30 T). Although scientific opportunities increase as available magnetic field strengths are increased, scientific thresholds appear to exist in the vicinity of 75 T (e.g., nuclear magnetic resonance becomes comparable in frequency, hence sensitivity, to X-band electron spin resonance). This calls for a long-range effort to generate steady-state, high-homogeneity fields of that magnitude. Unfortunately, current cost estimates for construction of such a facility (see Chapter 5) are prohibitive. We propose below a program of study to identify practical means to achieve that goal, as well as intermediate steps of lower fields, perhaps through the use of techniques and materials not yet available.

While steady-state fields are most desirable, quasi-static fields (duration times greater than tens of milliseconds) should be vastly less expensive and yet promise significant payoff (e.g., de Haas-van Alphen experiments near 100 T). We shall, therefore, propose that a program be started to design and construct such facilities. Indeed, diagnostic techniques developed at such fields will be of great value to a static high-field facility.

Finally, short-pulse (of the order of microsecond duration) fields of 1000 T can be generated with present technology. A smaller, but nevertheless exciting, subset of unusual opportunities exists in the field regime between 100 T and 1000 T. This is a largely unexplored region of research and may well produce unusual and unexpected results. The relatively low cost and potentially high scientific payoff have led us to propose a program that will lead to experiments in this field range.

The scientific, technical, and economic considerations detailed in the subsequent chapters lead us to the following recommendations:

I. *A design program should be started to determine appropriate methods for producing steady-state, highly homogeneous magnetic fields up to 75 T.*

The design program will involve the study of high-field, superconducting materials and magnets, as well as the study of new approaches to the design of resistive and hybrid magnets. Although the attainment of 75-T fields is the eventual goal of this recommendation, fields of 45 T and 60 T, steps along the way to 75 T, will help to provide the technology necessary for higher-field-magnet development. Significant scientific opportunities exist at these intermediate fields, and their scientific potential should be exploited.

Superconducting magnets will play a fundamental role in the attainment of higher steady-state fields and technological applications. Hence, in addition to an increased commitment to basic research in superconducting materials, there should be increased funding for materials processing and magnet technology, so that some of the known higher-field superconductors might be fabricated into practical magnets.

A facility affording a higher magnetic field, as discussed above, whether it be 75 T or an intermediate field, achieved on the way toward the long-range goal of 75 T, would be of inestimable value to the high-field superconductivity and magnet development communities. The variety of materials for which critical current densities and critical magnetic fields are measurable would be considerably extended, with the consequent acquisition of information essential to the effort to utilize advanced high-field superconductive materials for the construction of magnets.

II. *The design and construction of a quasi-static pulse magnet with fields approaching 100 T should be undertaken.*

Increased support should be given to one or more centers for the generation of quasi-static fields of about 100 T. Scientific opportunities supporting this recommendation are detailed in Chapter 3. In addition, the development of such facilities will contribute to the technology necessary for attaining higher steady-state fields.

III. *The design and construction of short-pulse magnets affording fields greater than 1000 T is feasible and should be undertaken.*

Increased support should be given to one or more centers where fields of about 1000 T can be generated so that experimental work and development of the facilities are stimulated. This ultrahigh field use and development can be implemented immediately, for the technology currently exists (see Chapter 5). In choosing a facility to fund, the quality and breadth of the scientific support must be taken into account.

As corollaries to these principal recommendations, we add the following:

- As a necessary concomitant to the above recommendations, we *recommend* the allocation of research support sufficient to allow the exploitation of high magnetic fields.
- We *recommend* that facilities receive sufficient funds so that the necessary supporting equipment (e.g., optical spectrometers, ESR and NMR spectrometers) be available.
- Because large energy sources and technology exist at facilities for fusion research, weapons technology, and high-energy physics, we *recommend* that incremental funds be allocated to adapt these major resources for high-field research.

Finally,

IV. *Because we feel that small regional facilities containing magnets with field strengths less than 15 T are not in sufficient demand to justify capitalization and operating costs, we recommend that additional general facilities with less than 15 T not be established at this time; however, we* *do recommend the continued support of such magnets for in-house research projects.*

The chapters that follow provide the background and rationale for the recommendations presented in this section.

3

Scientific Opportunities

INTRODUCTION

This chapter is based on the many responses from members of the scientific community to a letter of inquiry (see Appendix A). We are grateful for the responses and wish to thank all those who spent so much time and effort to help in formulating this report. Their names are listed, together with those of others who participated in this study, in Appendix B.

Because the availability of high magnetic fields affects a wide range of research, it was necessary to select examples from among a large number of suggestions. The final selection for inclusion represents the judgment of the members of the Panel.

The Panel adopted a specific definition of a high magnetic field. We concentrated on the scientific opportunities provided by (1) continuous uniform magnetic fields up to 75 T; (2) quasi-static pulse fields up to 100 T (duration, hundreds of milliseconds); (3) nondestructive fields up to 250 T (durations of milliseconds); (4) very-short-pulse destructive fields up to 2500 T (duration of tens or hundreds of nanoseconds). The feasibility of generating such fields is discussed in Chapter 5 on Magnet Design and Materials.

Significant scientific opportunities exist over the entire field range greater than 30 T. As the available field strengths are increased, the number of opportunities increases. Certain unique experiments require steady-state fields of the order of 75 T. Examples are experiments employing nuclear magnetic resonance (e.g., biology and chemistry), where the resonance frequency is comparable to X-band electron spin resonance, leading to comparable sensitivity; de Haas-van Alphen and cyclotron resonance in concentrated alloys and "dirty" compounds (A15 superconductors); and atomic spectroscopy, where study of low-quantum-number atomic levels becomes possible. We, therefore, set steady-state, high-homogeneity fields of 75 T as our principal objective. Unfortunately, technology appears to make this goal prohibitively expensive. We are forced, therefore, to recommend a detailed study of methods (perhaps novel) that can generate these fields. We suggest that a staged program of high static field development, with intermediate levels of 45 T and 60 T, may emerge as the most likely method for achievement of this goal. A number of opportunities do exist at these intermediate fields.

The Panel notes that present technology is sufficient to design and construct quasi-static fields in the neighborhood of 100 T. A subset of opportunities identified with steady-state operations at 75 T can be fulfilled with such an approach, along with transient experiments that profit from the time-dependent field profile. Examples of the former are de Haas-van Alphen experiments, which have longer relaxation time orbits, and cyclotron resonance experiments in dirty systems. Examples of the latter are studies in metallurgy and relaxation time measurements. Common to the technology for generation of quasi-static fields is the requirement of a large energy storage source (capacitor banks, rotating armatures, or flywheels). We call attention in this report to the cost advantages to be gained by taking advantage of such equipment when possible. The feasibility of construction of quasi-static field facilities has led to our second conclusion, that a program for the generation of quasi-static fields to and beyond 100 T is desirable. We wish to take note of the advantages of such an approach for the principal conclusion of this Panel. The diagnostic techniques developed for 100-T quasi-static fields will be of great value to the 75-T steady-state facility, once it becomes a reality. Indeed, the fabrication and operation of the former may strongly influence the design feature of the latter.

Finally, very high (1000 T to 2500 T) fields for very short time periods (less than a microsecond) can be generated relatively inexpensively. The science here is new and uncharted. Large energy sources are needed for these fields, but they can be chemical as well as electromagnetic. Experiments have already been performed near 300 T, and the diagnostics necessary at these fields could be used at higher fields. The experiments that are feasible in this field range cannot require high homogeneity. However, some (e.g., relaxation measurements) may even profit from the short rise and fall times involved. Magneto-quantum electrodynamics affords an example of a feasible class of experiments; so too does the study of intense temperature and pressure changes in materials of geophysical interest. Considerable preparatory work has already been accomplished, and we conclude that the time is ripe for exploitation of available methods that explore an unknown and potentially scientifically rich field regime.

CONCLUSIONS AND HIGHLIGHTS

In this section we summarize our principal scientific conclusions and give an indication of the excitement and richness of the research that could be accomplished with higher magnetic fields. Subsequent parts of this chapter describe these scientific opportunities in greater detail.

The Panel believes that the generation and use of high magnetic fields in the study of the properties of matter is of great importance to the national program for research and technology. Failure to mount and maintain a consistent, strong effort for the generation of higher fields will substantially impair the future research position of the United States and will result in missed opportunities for development and research.

We conclude that a strong effort to accelerate production of higher steady-state magnetic fields, including vigorous support for further research and development on all aspects of the technology of high-magnetic-field construction, is of central importance. The current limit of about 30 T for steady-state fields should be increased as technology advances. Present technology can be applied to the development of facilities with more than twice this field. The advantages of steady-state high fields are great, and every opportunity to achieve this mode of operation should be pursued vigorously. The production of quasi-static fields should also be pursued, but the important *long-term* effort toward the attainment of higher steady-state fields should have high priority. Research and development on the properties of high-field superconducting materials and magnets, as well as development of alternative forms of resistive magnets, are important components of this effort.

In summary, we conclude that significant new scientific opportunities exist in the utilization of steady-state, highly homogeneous magnetic fields up to 75 T and that a design program to attain such fields should be undertaken. The design and construction of facilities for the production of quasi-static magnetic fields approaching 100 T is a step toward this goal, and sufficient scientific opportunities exist to warrant construction of such facilities in their own right. As a dividend, the technology generated by such a program would be of inestimable value to a steady-state 75-T program. Further, important scientific opportunities require short-pulsed magnets with fields over 1000 T, which are feasible with current technology.

The development and construction of these facilities should not necessarily be carried out at a single center. Indeed, the complex diagnostic and experimental equipment needed to do forefront research would probably require a number of magnet installations, some at large-scale facilities such as synchrotron radiation, neutron scattering, or high-energy physics machine sites. The competition among laboratories and the possibility of exploring different approaches simultaneously would be healthy.

We emphasize that a consistent, sustained, orderly approach to the generation of higher magnetic fields and to their use in the study of the properties of matter is of great importance. Research on the properties of matter in high magnetic fields is at the forefront of biology, chemistry, metallurgy, and physics and should be aggressively pursued. A necessary concomitant to the development of new magnetic-field facilities is that sufficient research support be allocated to allow the exploitation of such high magnetic fields. In addition, large energy sources exist at facilities for fusion research, weapons technology, and high-energy physics; therefore, these major resources for high-field magnets and research should be considered in developing ultra-high-field facilities.

In what follows, we list some highlights of the scientific opportunities that the Panel considered. Amplified and detailed considerations comprise the remainder of this chapter.

Transition to Lower Dimensionality and Wigner Crystallization Magnetic fields reduce the dimensionality of motion of an electron gas. Confinement to orbits along the magnetic-field lines results in a lowering of the electronic kinetic energy, allowing the potential energy greater influence over electronic motion. For a sufficiently high field, the Coulomb interaction can dominate (equivalent to a low-density electron gas), with correlation causing crystallization for densities in the metallic regime. The effect should be most marked for two-dimensional metals (e.g., metal-oxide-silicon devices). Interesting model systems might be semiconductors, which under intense optical pumping form electron–hole droplets. These "metals" have low electron density but high conductivity. Intense magnetic fields are expected to localize the holes in a "string of pearls" along the field direction, with the electrons in a cylindrical sheath about the line of holes.

Electronic Structure of Exotic Metals Both one- and two-dimensional electronic structures exhibit metallic conductivity. Because of the extreme anisotropy of the Fermi surface, they tend to be more susceptible to lattice deformations than three-dimensional materials. A number of conflicting theories have been presented to describe their electronic properties. Unfortunately, all of these systems exhibit relatively short conduction electron scattering lengths, making conventional Fermi surface probes at conventional field strengths ineffective (e.g., de Haas-van Alphen, cyclotron resonance). Large magnetic fields would be required so that the product of the cyclotron frequency, ω_C, times the electron scattering lifetime, τ, could exceed unity. Under such conditions, use of Fermi surface probes could determine the origin of the complex phase transitions exhibited by these systems.

High-Field Superconductors The study of these materials is intertwined very closely with the advancement of high-field magnet technology. Aside from technological benefits, however, there are many basic scientific questions for high-field superconductors that can be at least partially answered by research at magnetic fields greater than those now available. The fundamental target here is a better understanding of the role of materials parameters such as composition, ordering, vacancy concentration, and dislocation density on critical temperature, critical field, and critical current density. High-field investigations are absolutely vital for the last two of these properties.

Metallurgical Phase Transitions At present, pulsed high magnetic fields are not used extensively in metallurgical research. When they become more readily available, they are expected to have a significant impact on metallurgical studies, in particular for the study of phase transformations. Examples are some of the martensitic transformations in which a nonmagnetic phase transforms into a magnetic phase. The transformation can be driven by an applied magnetic field. Application of a 100-T pulse with a duration of more than a few milliseconds (long enough not to cause eddy current heating) on an α-FeNi alloy changes the martensitic transformation temperature by more than a few hundred degrees. Therefore, the nucleation and growth of martensite can be controlled by the field, facilitating observation of the phase change during the process of transformation. Such a study should contribute significantly to the understanding of the nucleation mechanism, which is still an open and important question.

Chemical Reactions The detailed dynamics of chemical reactions in gases, in the condensed phase, and on surfaces are expected to be influenced uniquely by magnetic energies approaching kT at ambient temperatures. Sufficiently large magnetic fields will significantly modify the potential energy surfaces that dictate the approach and interaction between atoms or molecules. These same fields are sufficient to partially orient molecules in solutions through the diamagnetic interaction, thereby allowing an entirely new approach to the study of steric effects on chemical reactions. The orientation of molecules on surfaces can also be accomplished in such fields, and studies of surface reactions or states in high fields will expose hitherto unknown properties of those complex systems.

Structure of Biological Systems Increases in the static field employed in NMR spectroscopy from the current limit of 14 T to the range of 75 T will yield substantial increases in resolving power and will allow study of very-low-concentration nuclei. Lower-molecular-weight biological materials (up to 20,000), which now exhibit spectra of which only a small fraction is resolved, will generate spectra that can be interpreted in great detail. Among the important problems that would be opened to attack are antibody–antigen interaction, hemoglobin structure and function, transfer RNA structure in solution, protein–lipid interaction, enzyme–complex assembly, and receptor-binding site mapping. The determination of the time development of metabolite levels *in vivo* and the techniques of three-dimensional NMR imaging will be applicable to assemblies as small as individual cells.

Spectroscopy of Atoms and Molecules High magnetic fields alter the collision cross section for resonant collisions of atoms and molecules. For example, the long-range dipole-dipole contribution to excitation transfer can be nearly eliminated in the Na–Na* resonant collision for certain Zeeman-level transitions. This allows one, in principle, to study separately the higher-order nonresonant terms of the interaction potential that are masked in zero fields by the resonant dipole term. Study of collision dynamics under high magnetic fields involves the time of collision directly and promises new insights into the collision potential. On a strictly spectroscopic level, study of atomic and molecular spectra in very high magnetic fields and at high temperatures can be used to simulate conditions at the surface of white dwarf stars (which exhibit fields of the order of 100 to 1000 T). This would enable the unscrambling of astronomical spectra for which only theoretical models are now available.

DETAILED DISCUSSION OF SCIENTIFIC OPPORTUNITIES

In this section we treat the opportunities mentioned in Highlights in detail. Each subsection is classified in one of three categories so that the reader can better perceive the character of the scientific opportunities available. These categories are as follows:

CATEGORY 1. Experiments that are extensions of existing ones but that are incomplete in that the desired data cannot be obtained because existing magnetic fields are too low.
CATEGORY 2. Experiments that have been performed with existing fields and for which extension to higher fields would be useful.
CATEGORY 3. Experiments that might lead to new and interesting results if they were performed in high magnetic fields—it is not known what these results might be, but new fields of research might open as a consequence.

The field technology is also indicated. Steady-state fields are always useful, but the magnitude of field required will sometimes exceed even the 75 T that we have postulated. In these cases, pulse fields are required and will be explicitly noted.

Semiconductor Research

This important field of basic and applied research will be profoundly affected by the availability of high magnetic fields. Although much can be done with extensions of existing fields into the 30-T range, new developments could take place at 50–75 T. The topics we consider are not meant to be exhaustive; rather, they illustrate the excitement that high magnetic fields can generate in semiconductor research.

We shall cover six topics: (1) transition to lower dimensionality, (2) magnetic semiconductor electronic structure, (3) "sweeping" through the electron–phonon clothing of electronic motion, (4) testing the effective mass approximation, (5) shallow impurity studies, and (6) Zeeman splitting of deep impurity states. We note other interesting fields only by title: Hall angle saturation in noncompensated materials; electron–hole cylinder condensation (rather than droplets) leading to increased density, resembling behavior in neutron stars; heavy mass cyclotron resonance; the approach to the true quantum limit for degenerate Si and Ge (requiring fields near 100 T); two-dimensional magnetoplasmon and excitonic effects; and the study of negative hydrogen ions in semiconductors in high magnetic fields. All these studies will be possible with higher magnetic fields.

Transition to Lower Dimensionality.
Steady Fields. 50 T. CATEGORY 1.

Wigner showed in the late 1930's that at very low electron concentrations condensation into a lattice occurs as a consequence of the electron–electron correlation energy. This condensation has been sought under a variety of experimental conditions but has yet to be observed. Observation of the condensation, apart from its intrinsic interest, would also improve understanding of that elusive quantity, the correlation energy of an electron gas. Magnetic fields reduce the dimensionality of the electron gas. For a three-dimensional system, the electron orbits are cylindrical for sufficiently large fields ($\omega_c \tau \gg 1$), and translational motion takes place only along a single direction. For two-dimensional systems, as for example in a metal-vacuum-helium structure or a metal-oxide-silicon sandwich, a magnetic field of sufficient magnitude traps the electrons in their lowest Landau level. The Landau orbits restrict motion in the plane so that the translational kinetic energy is strongly reduced. Under such conditions, the system is quasi-zero dimensional, and Coulomb interactions at all densities are expected to have drastic effects on the low-temperature properties. Using the Hartree-Fock approximation, one can show, theoretically, that the system will develop a charge density wave instability as the temperature is lowered (Fukuyama, Platzman, and Anderson). For all fractional occupations of the lowest Landau level, except one half, the transition is first order. Similar behavior is expected for three-dimensional metals. Fukuyama has predicted a charge density wave state with wave vectors having components both parallel and perpendicular to the magnetic-field direction. The physics underlying the increased tendency toward localization involves the reduction of the kinetic energy of the electrons afforded by the presence of the magnetic field. Wigner crystallization is predicted for low electron densities (too low for these structures in the absence of magnetic fields at reasonable temperatures), because the electron kinetic energy decreases more rapidly than the correlation energy as the density is reduced. The use of a magnetic field makes observation of condensation practical at reasonable temperatures and concentrations by means of the "freezing out" of the kinetic energy inherent in low-Landau-level occupation. Typical magnetic fields predicted to lead to condensation are in the tens of tesla range. Magnetic fields near 50 T should provide sufficient reduction of the kinetic energy to make this electronic "solid" accessible at liquid helium temperatures.

Electron–hole droplets in semiconductors are also strongly perturbed by magnetic fields. Their low carrier density ($\sim 10^{17}/\mathrm{cm}^3$) and small effective mass means that magnetic fields can have huge impact on the correlation energy. For example, a field of 60 T applied along a [100] direction in Ge is sufficient to cause the electron–hole gas to occupy only a single Landau level. Predicted structures in the "crystallized" state are curious: the holes are expected to line up like a "string of pearls" along the field direction, with the electrons moving in cylindrical sheaths centered on the holes.

Observation of these examples of "electron freezing" would be the culmination of 40 years of study of the electron–electron correlation energy.

Magnetic Semiconductors.
Steady-State or Quasi-static Fields. 50 T. CATEGORY 1.

This class of solids exhibits another scientific opportunity afforded by the availability of high magnetic fields. The cyclotron resonance frequency can be observed in Landau-level resonance studies by optical absorption at high fields and frequencies, as demonstrated by Lax and his co-workers. However, to explore the electronic structure requires that $\omega_C\tau \geqslant 1$. For many materials, τ is so short that this condition is impossible to achieve at fields currently available in the laboratory. Striking examples are the europium chalcogenides (EuO, EuS, EuSe, and EuTe), which are both magnetic and semiconducting. Impurity scattering is large, however, thus τ is small at electron concentrations necessary for band conduction ($10^{18}/\mathrm{cm}^3$). (At lower electron concentrations, conduction is limited to hopping.) At 10 T,

$\omega_C\tau \approx 0.2$, which is too low for measurements of the de Haas-van Alphen effect or of anisotropy in the magnetoresistance to be useful for band-structure studies. The situation is so serious that one does not know even where the minimum of the conduction band is located. There are two competing models: the minimum is at the Γ point (center of the zone) or at the X point (the 100 face of the zone). The former implies s-like character for the conduction electrons; the latter d-like character. The former means spherical energy surfaces; the latter highly nonspherical ones. This important question can be settled by experiment if fields of the order of 50 T become available. This example is but one of a large number for which the material by its nature has a short scattering time and the only alternative is increasing the magnetic field.

Electron–Phonon Clothing.
Short Pulse. 100 T. CATEGORY 2.

Electrons are never "free" in solids. Their motion is affected by the presence of lattice vibrations. The coupling between these two systems affects the behavior of electronic motion, leading to an electronic effective mass different from that calculated by band theory for a rigid lattice. This dressing of the electron is excitation-frequency dependent. For motion of the electron faster than the lattice can follow, the electrons behave as free. Thus, an experiment that would take one from the "slow" to the "fast" regime should exhibit quite different electronic masses at the two limits. The most authoritative study of this behavior is the work of Holstein and is referred to as the polaron problem. Semiconductors are ideal candidates for study of this phenomenon. Cyclotron resonance frequencies $\omega_C = eH/m^*c$ can be made comparable with, or greater than, the longitudinal optical phonon frequency (LO phonon), the one most strongly coupled to the electron's motion. This allows one to make the transition from slow to fast electronic motion by merely increasing the cyclotron frequency, that is, by increasing the magnetic field. Some experiments that exhibit the beginning of this "undressing" of the electron have been performed by choosing systems for which m^*/m is very small. Consequently, the electron–phonon coupling is weak. However, of fundamental interest are the intermediate and strong coupling regimes that occur in polar materials when the effective mass is large. To sweep through the LO phonon frequency where resonant coupling will occur, fields of the order of 100 T are required (as well as infrared lasers to see the effect). The polaron problem represents one of the most interesting and difficult of the coupled system problems in condensed-matter science. A thorough study through the entire frequency regime where m^* is expected to vary would be of fundamental interest.

Effective Mass Approximation.
Steady State. 100 T. CATEGORY 3.

The use of a dielectric constant to describe the Coulomb potential in which the electron moves in a semiconductor depends crucially on the electron's orbit being large compared to the size of an atomic cell. When this ratio is not large, the electron experiences rapid changes in its potential, leading to a breakdown of the effective mass approximation. Large magnetic fields force the electrons into orbits whose radii are $\sim(\hbar c/eH)^{1/2}$. Fields of 10,000 T correspond to an orbit contained within one lattice cell. 100 T leads to orbits that enclose 10–20 sites, enough to begin to introduce additional structure in the cyclotron motion, and leads to the breakdown of the effective mass approximation. In the case of highly anisotropic layered compounds, these fields are reduced by an order of magnitude or more for motion in the direction perpendicular to the layers, amplifying the magnitude of the breakdown substantially.

Shallow Impurity Studies.
Steady State. 100 T. CATEGORY 3.

As noted in the preceding paragraph, as the orbit becomes comparable to the cell size, "central cell" corrections are required, and the effective mass approximation fails. Studies of the effect of the central-cell correction will enable the nature of chemical contaminants to be better understood in the case of technologically important materials such as GaAs, InP, and ternary and quaternary alloys based on the III–V compounds.

Zeeman Splitting of Deep Impurity States.
Short-Pulse Fields. 100–10,000 T. CATEGORY 3.

The Zeeman splitting of the rather broad, deep impurity levels in semiconductors is rarely detectable. Observation of the Zeeman splitting should be possible for fields of the order of 100 T. These measurements would assist in the assignment of the symmetry and origin of these levels. If the study could be extended to 10,000 T, the Zeeman splitting would be comparable to the band edge of the semiconductor host, enabling the nature of the impurity states to be strongly modified, as well as allowing observation of the excited states of the impurity potential.

Metals Research

A number of tools are available for the study of the Fermi surface of metals, including magnetoresistance and de Haas-van Alphen measurements and magnetic breakdown. The former two require that $\omega_c\tau > 1$ for the extraction of significant information. The latter requires fields such that $(\Delta E)^2 = \mu_B H E_F$, where ΔE is the bandgap, E_F is the Fermi energy, and μ_B is the Bohr magneton. These conditions have required metals of high purity or small bandgaps, given limitations on H of 15–20 T. The availability of high fields makes possible broad application of these tools to systems of great interest and importance. We discuss four examples, but clearly the list of possibilities is much longer. For example, one might even be able to saturate the magnetoresistance of simple metals in very high fields (potassium is a case in point) or to study the lattice conduction of heat by reducing electron transport perpendicular to the field in the extreme quantum limit.

The four areas in which unusual opportunities become available are (a) electronically driven-phase transitions, (b) charge density waves in potassium, (c) electronic structure of exotic metals, and (d) concentrated binary alloys (or disordered systems).

Electronically Driven Phase Transitions.
Steady State. 150 T. CATEGORY 1.

The relationship between structural instability and high-temperature superconductors is still not understood and is clearly of great importance. Recent experimental studies have shown that structural instabilities and anomalous defect behavior are characteristic of the high T_c A15 structure superconductors. This result is thought to originate either in a high density of states at E_F or Fermi surface nesting. In these materials, cyclotron resonance measurements require high magnetic fields for two reasons: (a) fields greater than the upper critical field $H_c{}^2$ are required so that the field penetrates the superconductor uniformly (fields of the order of 20–30 T are required for many A15 compounds, for example Nb_3Sn); (b) because τ is relatively short in these materials, very high fields are required to satisfy the condition $\omega_c\tau > 1$. Furthermore, interesting regions of the Fermi surface (which are flat and therefore of large mass) also require high fields for observation. With sufficiently large fields, one could examine the size and shape of the Fermi surface in both transforming and nontransforming samples, thus directly probing the interrelationship between electronic density of states, Fermi surface nesting, and structural stability. To think of actually "following" the Fermi surface change of shape through a structural instability in this manner is an interesting prospect. Preliminary studies with static-pulse fields by Lowndes and Arko, using the Amsterdam 40-T quasi-static fields, with 0.2-second decay ramp time, have shown that oscillatory effects can be observed in some A15 compounds. Fields of 150 T will be required to map fully the Fermi surface topology in these materials.

Charge Density Waves in Potassium.
Steady State. 30 T. CATEGORY 1.

The electronic properties of potassium continue to remain a mystery if one accepts the conventional nearly free electron spherical Fermi surface for this monovalent metal. Overhauser has argued persuasively that the (a) lack of saturation of the magnetoresistance at fields for which $\omega_c \tau = 300$, (b) anomalous high-field torque anisotropy, (c) intense optical absorption with a threshold of 0.6 eV of a bulk metal vacuum interface, (d) conduction electron spin resonance *g*-factor anisotropy, (e) residual resistivity anisotropy, (f) Hall coefficient discrepancy, and (g) remarkable lack of reproducibility of experiments on this supposedly "simple" metal all point to the existence of charge density waves in potassium. The waves are supposed to be oriented along the [110] directions, and a "general" crystal will contain domains in which the charge density wave vector **Q** is along a particular [110] direction for that domain. The existence of a unique **Q** value implies an anisotropy in the electrical resistivity parallel or perpendicular to **Q**. In a crystal containing many domains, the multidomain structure leads to a residual resistivity. However, each single **Q** domain possesses an anisotropic magnetic susceptibility (very small, of the order of 10^{-8} emu). Thus, in sufficiently large fields, one could line up the domains. Rotation of the domains must compete against local strain fields, and Overhauser estimates that fields in excess of 10 T are required. If high fields are applied to wires of potassium, one predicts that the residual resistivity will change by a factor of 5 back and forth as one rotates the field parallel and perpendicular to the wire axis. This unequivocal test of Overhauser's prediction is an important one that high magnetic fields can make of our understanding of the behavior of the so-called simple metals.

Electronic Structure of Exotic Metals.
Quasi-static. 100 T. CATEGORY 3.

Studies of exotic forms of solids, many with reduced dimensionality, have shown that metallic behavior is more general than previously thought. Superconducting polymers are known (e.g., $[\mathrm{SN}]_x$), as well as layered compounds (e.g., the transition metal chalcogenides), which have nearly one- and two-dimensional structure for their conductivities. They tend to be more susceptible to lattice deformations, and there are a number of conflicting theories regarding the character of their electronic structure and lattice coupling. The deviation of their Fermi surfaces from flatness (in the case of one-dimensional metals) or ridgelike (for two-dimensional metals) is essential for the understanding of their conductivity and stability. However, all of these systems have relatively short conduction electron scattering times. Use of conventional Fermi surface probing techniques (see section on Electronically Driven Phase Transitions) requires large magnetic fields so that $\omega_c\tau > 1$. High-field investigations would provide a basis for evaluating the many theories that attempt to describe structural phase transitions in these systems. In particular, one might be able to determine the extent to which electron–electron correlation affects the phase transition and associated changes in conductivity in these less than three-dimensional materials.

Concentrated Binary Alloys. Quasi-static for Exploration; Steady State for Details. 75–100 T. CATEGORY 3.

The availability of very high magnetic fields would allow measurements of electronic scattering rates and of dimensional changes in Fermi surfaces in binary alloys to be extended beyond the dilute limit. There are A_xB_{1-x} alloy systems for which it seems likely that these quantities could be measured over the entire concentration range ($x = 0$ to 1). This would be a significant experimental advance, for effects strongly nonlinear in x, nonrigid band behavior, and order–disorder effects could all be studied.

It is conceivable that strongly disordered systems, such as amorphous metals, could be studied in the quantum limit. Underlying short-range order may manifest itself in smeared quantum oscillations. Even changes in short-range order as a function of temperature and composition could be studied in principle.

At present precise quantum oscillation methods are limited to nearly pure metals. High magnetic fields will free the experimenter of this constraint and allow for precise measurements of changes in band structure as a consequence of alloying and structural changes.

Low-Temperature Physics Research

Two interesting prospects emerge in low-temperature physics with the advent of magnetic fields greater than 50 T. Both involve phase transitions that could not be observed otherwise. The first is the Bose condensation of spin-aligned hydrogen, and the second is the observation of a ferromagnetic moment for liquid ^{3}He-*A*.

Spin-Aligned Hydrogen. Steady State. 50 T. CATEGORY 1.

A number of experimenters are attempting to observe the predicted Bose condensation in spin-aligned hydrogen. The techniques all involve lowering the energy of the parallel-electronic-spin molecular configuration as compared with the usual antiparallel electronic singlet molecule. This might be done using an oven to generate atomic hydrogen, then allowing recombination to occur in the presence of a strong field. Unfortunately, conventional fields (15 T) are just on the borderline (or perhaps too small) for success. Condensation of spin-aligned hydrogen in the presence of a 50-T magnetic field should provide sufficient stability for the aligned state to remain for times long enough to look for the predicted phase transition.

This transition has unusual features that make the search for it of great scientific interest. By the very nature of the spin-aligned state, high magnetic fields are required, at least at the formative stage of the triplet molecules.

Ferromagnetic Moment in ^{3}He-A.
Steady State. 50 T. CATEGORY 1.

Paulson and Wheatley have shown that a ferromagnetic moment exists in ^{3}He–A using an ultrasonic method, but it was impossible to obtain a texture suitable for measurement in the low field limit. A field of 50 T should orient the moment, allowing for its direct measurement.

Liquid ^{3}He is one of the richest physical systems for study in condensed-matter science. It exhibits a complex phase diagram, with two quite distinct phases in the ordered state (the so-called A and B phases). The higher-temperature phase, A, is one where the ^{3}He atoms are paired with parallel spin. In the presence of a magnetic field, the A-phase transition line splits into two, with the parallel nuclear spins predominantly along the magnetic-field direction for the A_1 phase. Leggett has argued that a ferromagnetic moment exists in ^{3}He-A because of chemical and pairing effects. It is obscured by the internal dipolar coupling, which requires a field of 50 T to decouple the ferromagnetic moment from the dipolar field. Zero sound could detect the direction of the moment. As the external field is increased, the moment should swing from perpendicular to parallel to the field, allowing for the direct measurement of the moment. It is entirely possible that other orientation effects in ^{3}He could come into play as the external field overcomes the orientation-locking power of the dipolar field. These will develop as one gets “used to” working with this quantum liquid without the hindrance of the internal dipolar field.

Magnetic Properties

This field first comes to mind with the advent of high magnetic fields. A Zeeman splitting of 1.4 K results (for a $g = 2$ spin) in a field of 1 T. Availability of 75 T leads to Zeeman energies in the 100-K range, easily of the order of the exchange field for many ferromagnetic and antiferromagnetic materials. This leads to a wide variety of magnetic-field-induced phase changes in magnetic systems. It also suggests the possibility of trimerization of spin-Peierls systems for one-dimensional systems that have already undergone spontaneous dimerization from the uniform antiferromagnetic state. The energies are also comparable with the difference in valence energies in intermediate valence compounds. High fields could therefore be used to stabilize one limit of the intermediate valence state, allowing for the determination of the character of that limit, as well as a measure of the binding strength. We shall discuss three other aspects, all of which require high magnetic fields: (a) critical phenomena, (b) magnetic-field-induced transitions, and (c) singlet ground-state systems.

Critical Phenomena.
Steady State. 50 T. CATEGORY 1.

The multicritical points in magnetically ordered systems permit tests of modern theories of phase transitions and scaling. Great progress has been made in the past few years. Universality allows one to generalize the behavior of magnetic systems to general (nonmagnetic) phase transitions in matter. One of the most interesting regimes is the bicritical point in an antiferromagnet, where the spin-flop, antiferromagnetic, and paramagnetic phase boundaries meet. To study this region, fields of several times the critical field $H_c = (2H_E H_A)^{1/2}$ are required. (Here H_E and H_A are the exchange and anisotropy fields, respectively.) Typical values lie in the 15-30 T range. An example that promises interesting physics is the two-dimensional magnetic system K_2NiF_4 for which the spin-flop field is 27 T. A variety of lower-dimensional and crossover phenomena can be studied in the vicinity of this regime.

A second important field of research on critical phenomena concerns Ising systems in transverse magnetic fields. It has been shown for the one-dimensional case that the Ising model ground state in a transverse field can be mapped onto the Ising model in the absence of a field in two dimensions at arbitrary temperature. Series expansion results indicate that this is a general situation, with the Ising model in a transverse field in n dimensions mapping onto the Ising model without a field in $n + 1$ dimensions. Experiments on materials such as FeF_2 in 50-75 T fields offer the possibility of studying the properties of the four-dimensional Ising model!

Magnetic-Field-Induced Transitions.
Steady State. 75 T. CATEGORY 1.

The origin of ferromagnetism in metals is still an unsolved problem. For conductors that have large exchange enhancements, the effect of the applied field is magnified proportionally to the exchange enhancement; theories of itinerant ferromagnetism suggest that a ferromagnetic phase transition might be induced on application of a large applied field for appropriate band parameters. The magnetic response of the metal to the field involves the detailed structure of the density of states, which generally has not been calculated with sufficient precision to make predictions. Experiments using 20–35 T have been made on Pd and YCo_2. Although Pd is the most exchange-enhanced element of the periodic table and shows long-range polarization as a host for 3*d* elements (e.g., Fe, Co), no evidence for induced ferromagnetism has been observed in Pd. There is some evidence that YCo_2 might show this effect. Fields of 50–75 T would allow an increase in resolution of almost two orders of magnitude because the exchange-enhanced portion of the magnetic moment is expected to vary as $D^3 H^3$, where D is the exchange enhancement. Studies of the coupling between magnetic impurities in strongly enhanced hosts would also be rewarding. As the susceptibility of the host increases, the range of impurity–impurity coupling also increases, so that a high field might be used to vary the coupling in a controlled manner. These results would be important for understanding dilute alloys, spin-glass, and nondilute magnetic systems.

Singlet Ground-State Systems.
Steady State. 50 T. CATEGORY 1.

There are many magnetic systems in which the single-ion ground state is a singlet. Magnetism occurs through the Van Vleck off-diagonal moment, which can undergo a spontaneous transition if the mutually induced exchange coupling is sufficiently strong to overcome the crystal field single-ion splitting. The excitation spectrum of such systems remains an open theoretical question. High magnetic fields can compete with the crystal field splitting, in some cases allowing magnetic ordering where none existed before. It would be of great interest to follow the development of the induced moment as the applied field reduced the splitting of the ground and excited state. In particular, the theory can only treat the limit of small excited-state occupation. Experiments that move smoothly from the region where the theory is applicable to the region where it is not might well give a clue to the way to approximate the system (even to describe it!) in the regime of excited-state occupations comparable to the ground-state occupation.

Materials Research

The range of application of high magnetic fields to materials research is great. We shall concentrate on three subjects: (a) high-field superconductivity,

(b) metallurgical phase transitions, and (c) field-induced changes in pressure and temperature with geophysical applications. An interesting additional application is the nuclear magnetic resonance of ^{3}He in the embrittlement problem. Though the number of nuclei is small, at high fields (75 T) the resonance sensitivity is comparable to electron spin resonance (see the subsequent section on Research in Biology), allowing the use of magnetic resonance to study various nucleation phenomena related to mechanical strength of materials. Other applications are of comparable interest; however, the three we have chosen for discussion should serve as representative examples.

High-Field Superconductors.
Steady State or Quasi-static. 75 T. CATEGORY 1.

The present boundaries of the superconducting state are approximately 23 K (Nb_3Ge films) and 60 T ($PbMo_6S_8$). These boundaries are not well understood from either a theoretical or an experimental viewpoint. There is little doubt that the availability of research facilities for higher dc magnetic fields would be a boon for investigators. Work at high fields should yield a better understanding of the basic material parameters that control both the critical temperature, T_C, and the upper critical field H_{C^2}. Materials of interest include the Chevrelle phases, B1 and A15 structures, thin films, and finely divided superconductors produced by either rapid quenching or plasma deposition techniques.

Investigations of critical current densities and flux pinning at very high fields should throw new light on the electronic and magnetic interactions associated with small-scale defects in solids. Of special interest is a study at high fields of the empirical relationship $J_C \times B$ = constant, which holds approximately for most practical conductors. Further work is necessary on the fundamentals underlying this relationship, with the objective of discovering new methods of flux pinning to remove this serious limitation. Progress in this field would be of vital importance to future high-field magnet design.

Other basic aspects of superconductivity might be advanced by the availability of fields approaching 100 T. For example, one might search for the existence of triplet pairing of the electrons, which, if it occurred, should modify the magnetic-phase boundary curve at field energies approaching the condensation energy. Investigations of the temperature variation of H_{C^2} would also allow a test of a variety of theoretical predictions connected with the paramagnetic limit, effect of spin-orbit coupling, and other basic features of high-field superconductors.

Metallurgical Phase Transitions.
Quasi-static. 200 T. CATEGORY 3.

When there is a difference in the magnetic susceptibility or the magnetization between the phases involved, an applied magnetic field can induce or suppress the phase transformation. The use of magnetic fields to control the phase transformation is advantageous, for example, compared with driving the transformation with temperature changes, in that the change in the driving force can be achieved in a very short time, which is important when the transformation is very rapid. An example is the martensitic transformation in magnetic alloys, including steel. Martensite in steels is the α-Fe phase supersaturated with carbon and is obtained when the carbon steel is quickly quenched. Because of the presence of carbon in the interstitial lattice position, this phase is exceedingly hard. Even though the martensitic transformation has been known for almost 2000 years, its mechanism is not completely understood. Unlike many transformations in which atomic diffusion is a vehicle, the martensitic transformation proceeds via a collective motion of dislocations. Therefore, the mechanism of nucleation must be very different from the usual case. A high-magnetic-field pulse could induce the transformation during the length of the pulse, with the transformation ending when the pulse was over. Thus, one could stop the transformation at various stages, making it possible to observe the process (e.g., by electron microscopy) at intermediate stages of the transformation. At present, the lath martensite formation in $Fe_{68}Ni_{32}$ alloy, which occurs at around 100–200°C, would appear to be a good first candidate for study by this technique.

Field-Induced Changes in Temperature and Pressure with Geophysical Applications.
Short Pulse. 1000 T. CATEGORY 3.

A rapidly changing high magnetic field produces large changes in temperature and pressure, by either eddy-current effects or adiabatic heating and cooling. Surface (eddy) currents are generated within the penetration depth in the conductor that exclude the flux from the interior. The surface temperatures and pressures increase proportional to B^2. At 100 T, the surface melts and pressures of 400 atmospheres are reached. Much higher fields can be achieved and the states of matter under extreme conditions can be studied. Intense shock waves are generated into the bulk of the metal, with the formation of new structural phases, not feasible in conventional laboratory environments, expected. Should this possibility be realized, it would have an impact on research in geology and geophysics. The pressure at the center of the earth is estimated to be of the order of 3 million to 4 million atmospheres, which can be generated by a field of 10^3 T, whereas the highest static pressure achieved to date, is about 1.7 million atmospheres. The solubility of H, S, Si, and K under such high pressures in Fe–Ni alloys (which form the core of the earth) is one of the most important quantities controlling the nature of the core. The knowledge of the reactions of the Fe–Ni alloy with oxides or sulfides of Mn, Fe, Cu, and Ni under high pressure and temperature should help to improve understanding of the distribution of the mineral resources on the earth's surface.

In an insulating medium, a pulsed field will penetrate the entire volume. Thus, uniform changes in temperature can be produced rapidly for a short pulse in an adiabatic manner, even when the thermal conductivity of the solid is extremely low. This rapid change in temperature would quench metastable phases such as amorphous phases, which may not be obtainable by other methods.

Research in Chemistry

High-magnetic-field research will help to answer three outstanding problems in chemistry: (a) understanding complex reactions in condensed phases; (b) understanding the factors determining the dynamics of atoms in molecules and of atoms during the formation of molecules; and (c) understanding the electronic structures of highly excited states. The discussion that follows deals with ion-cyclotron resonance, spectroscopy and structure determination, chemical–biological reactivity, and chemical dynamics. Each of these research areas requires more than just a high magnectic field; adjunct facilities, such as state-of-the-art laser systems, spectrometers, and controlling computers are also needed.

Ion-Cyclotron Resonance.
Steady State. 100 T. CATEGORY 1.

For a given detection frequency, the mass resolution varies as B^2. The state of the art is a limit of 1000 mass units at 7.5 T. A 100-T steady field would allow a mass limit of 200,000, thus introducing the possibility of studying biological systems, polynuclear complexes, and large organometallics. It will be feasible to sequence a polypeptide by conducting successive chemical reactions in the spectrometer. The direction of activity in this field is toward higher magnetic fields, laser-induced chemistry of ions, and polynuclear systems. At 100 T, an ion-cyclotron resonance device can be used to study less than a picogram of material; therefore, this method would be useful for trace species in biological systems and for isotope separation.

Spectroscopy and Structure Determination.
Short Pulse. 100 T. CATEGORY 3.

There are a vast number of useful spectroscopic experiments that become feasible when 100-T fields are available. It will be possible to study nonlinear magnetooptics in considerably more detail than was previously possible. The Faraday effect, Cotton-Mouton effect, and higher-order magnetooptic effects have not been explored as have electrooptic phenomena. Nonlinear magnetooptics is a fresh research field for experiment and theory. This is especially true for dilute gases in which the lower-order effects are already often difficult to detect. The measurements that could be made at higher fields would bear directly on the higher-order magnetic susceptibilities of molecules, hence providing the basis for a more nearly complete description of the energies of molecular systems in magnetic fields.

Fields of 100 T can decouple the electron spin from the molecular axis in many molecules such as hydroxyl or nitric oxide. It would be possible to study the effects of this decoupling. First- and higher-order Zeeman effects will be possible for many molecular excited states. The more complex Zeeman effects of high-Rydberg states will be accessible. Rotational *g*-factors can be measured, and nuclear hyperfine structure in excited states can be observed without the difficulties of the radiative width or Doppler width that currently obscure many phenomena. The quartet and quintet states of molecules, previously unknown, might be explored; level crossing (and anticrossing) and optical double-resonance experiments can be contemplated in a new regime of separations between zero-order states. Second-order magnetic energy shifts could be measured even with complex molecules and other systems displaying wide linewidths.

Chemical and Biological Reactivity.
Steady State. 100 T. CATEGORY 3.

Magnetically related research avenues that will lead to improved understanding of chemical reactivity are studies of reaction mechanisms by variations of relative reaction rates in complex systems; studies of new chemical properties brought about by changing molecular wavefunctions in the magnetic field; studies of the effects of magnetically induced anisotropy on otherwise isotropic chemically reacting systems; and studies of photochemical reaction pathways involving magnetically sensitive singlet and triplet states of molecules in high fields. Because 1 T produces an energy splitting of 1.4 K for a free electron, high fields can generate Zeeman splittings of hundreds of degrees so that chemical activation processes can be modified substantially.

Optically induced chemical reactions often involve electron spin triplet states of molecules or biradicals. Because of the anisotropy of the spin-spin and spin-orbit interaction, the three spin sublevels are not degenerate even in zero field and there is an intrinsic chemical spin anisotropy. Different spin sublevels will have quite different chemical reactivities. At normal temperatures the observed reaction rate is an average over the contributions from the three states. In fields of 100 T, directed along particular molecular directions, the rates of these photochemical reactions may be affected by factors of 10^3 as a result of the spin-orbit anisotropy. Studies of this type can lead to a substantial improvement in the understanding of the nature of chemical reactions, cage effects, and radiationless processes. The magnetic field in this case causes both orientation and spin selectivity.

The rates of chemical reactions in solutions are described in terms of rate constants that are ensemble and orientation averages of microscopic rates. The relative orientation of the chemical reactants influences the course of a reaction, and for large asymmetric molecules, many encounters may be needed before reaction occurs. Because of these effects, we can expect reaction rates to be sensitive to 100-T external fields. The opportunity to study in a direct fashion the steric factors influencing chemical reactions is thus provided. The magnitude of effects such as this depends on a number of as yet unknown molecular topological parameters and on the degree of orientation of β: $\beta = (\chi_{||} - \chi_{\perp}) H^2/kT$, where $\chi_{||}$ and $\chi_{\perp}$ are the susceptibilities parallel and perpendicular to the plane of the molecule, respectively. A molecule such as benzene has $(\chi_{||} - \chi_{\perp}) = 6 \times 10^7$ emu/mol, so at 300 K, $\beta \sim 10^{-3}$ for $H = 75$ T. The degree of orientation in the sample can be studied by means of the magnetically induced birefringence (Cotton-Mouton effect) even at relatively low magnetic fields. Larger anisotropic molecules and biopolymeric systems are even more readily oriented since the diamagnetic susceptibility is an additive property. Studies of rotational relaxation in liquids and biological systems will be possible with pulsed fields of 100 T, with initial orientations that are different from those achieved with electric fields.

Chemical reactions that involve ion transport, as well as anisotropic molecular motion, such as those occurring in biological membranes, are expected to be magnetically sensitive at sufficiently high fields. Research of this type will provide a new dimension in understanding properties of membranes.

Chemical Dynamics.
Steady State. 100 T. CATEGORY 3.

Fundamental processes in chemical dynamics are receiving intense experimental and theoretical study. There is need for tools that can be used systematically to perturb the potential surfaces. Surface crossing points are particularly vulnerable to external magnetic fields. Because these are the regions of nuclear configuration space in which much of the dynamical action occurs, their study is important. Using fields of 100 T, it will be possible to explore magnetic effects on collisions and on the breakdown of the Born-Oppenheimer approximation. Laser-induced chemical reactions occurring subsequent to the excitation of single rotational–vibrational levels will be affected by the field-induced mixing of discrete rovibronic levels with continuum states. Other important applications in dynamics are the study of magnetic effects on collisions at high fields, on the effects of energy excess on energy transfer, and on orientational selection rules in moderately large molecules. The nonradiative relaxation and autoionization of molecules will also be influenced by 50–100 T magnetic fields that will couple Rydberg levels significantly to the ionization continuum.

The collision of two hydrogen atoms provides a prototype situation for understanding magnetic effects on dynamics. During the approach of two H atoms at zero field, the potential energy may be lowered when the spins are opposed corresponding to the formation of the ground singlet state. In the event of a collision with a third body, the H_2 molecule would then be formed in some vibrational–rotational level of the ${}^1\Sigma g^+$ electronic state. In the presence of a 500-T field, the situation is changed if the atoms are at thermal equilibrium for normal temperatures, for now the pair of atoms will most often see a repulsive potential comparable with kT so that they will slow down on approaching one another. The formation of H_2 is prohibited, and the atoms will fly apart after the collision. Whereas in the zero-field case the bound singlet and repulsive triplet state of H_2 are degenerate only at large separations of the atoms, the situation is changed in a magnetic field, for then the potential wells for the $|0>$ and $|-1>$ spin states should "cross" at some relatively small internuclear separation and there is a threshold kinetic energy for bond formation. Transitions in the crossing region can occur by means of third-body effects or by the spin-orbit interaction, which for the case of $H_2\,\Sigma^1 g+$ and ${}^3\Sigma\mu^-$ is vanishingly small. With nonhydrogenic doublet atoms or molecules, the spin-orbit coupling is much larger and the rate of transitions between the singlet and triplet potential curves could be studied in high-field experiments. In complex molecules there are bound energetically accessible states of both singlet and triplet multiplicity, and it is the state-to-state details of the combination processes that are magnetic-field sensitive. New features of spin-relaxation dynamics leading to the thermal equilibrium can be observed from such experiments.

Calculations for the potential curves of H_2 and $H_2{}^+$ in strong magnetic fields have already been attempted. These calculations could be extended to molecules having three or more nuclei and to the new sets of potential surfaces used in studies of molecular reaction dynamics in the presence of strong fields. The symmetry properties of the states and the selection rules will be altered. In particular, there is no longer rotational invariance and the field introduces new quantization axes where space goes from spherical to cylindrical symmetry. This is expected to influence the motion of charged particles so that in ionization processes the states of emitted electrons are not continuous. These effects influence the angular distribution of the photoelectron spectrum.

Photochemical reaction paths and rates can be modified because sufficiently high magnetic fields will influence nonradiative relaxation processes in molecules. Here the effects could be quite large for fields of 100-500 T, and the experiments will contribute to the understanding of radiationless processes in molecules and to the development of chemical separation methods. Pulsed fields could be used for studies of many of these optically induced processes. Molecular recombination pathways may also be studied using high fields ($\mu_B H \sim kT$). If photolysis of B in the presence of A produces two molecular ions, say by electron transfer: $A + B^* \Rightarrow A^- + B^-$, the recombination of the ions will lead to A and B in a distribution of electronic and vibrational states that will be changed by an external field. One process that might be enhanced by the field is $^2A^- + {}^2B^- \Rightarrow {}^3A + {}^1B$ producing metastable triplet states of A. Reactions of this general type might possibly occur in photosynthetic systems.

Research in Biology

Uses of Nuclear Magnetic Resonance (NMR).
Steady State. 75 T. CATEGORY 1.

In the past ten years the application of NMR spectroscopy to the study of structures of biological molecules and solutions such as proteins, nucleic acids, lipids, and carbohydrates has contributed important understanding of structure and function basic to biomedical sciences. To obtain greater resolution and observe individual resonances from nuclei in all parts of the molecule, considerable effort has been devoted to increasing the strength of the static field. Superconducting magnets of 5.0 T were used in 1962, commercial spectrometers are now available with fields up to 9.4 T, and development of a spectrometer operating at 14.1 T is well under way. These advances were valuable for small molecules, but the resolution for large molecules remains frustratingly small. Because the molecular motion in solution is faster than mechanically obtainable spinning speeds or electronically attainable forced spin-flip rates, the new techniques of magic angle spinning and dipolar decoupling do not help appreciably in increasing the resolution. Present experience also does not encourage one to predict the attainment of high resolution in spectra of solid proteins of high molecular weight.

TABLE 1 Statistical Prediction of Number of Separate α-Proton Resonances Observable in Representative Proteins at Several Field Strengths

Field (Tesla)	Ribonuclease $W_m = 13{,}690$ 124 Residues	Subtilisn $W_m = 27{,}288$ 274 Residues	Dehydrogenase $W_m = 39{,}805$ 374 Residues	Hemoglobin $W_m \sim 60{,}000$ 600 Residues	Immunoglobulin $W_m \sim 150{,}000$ 1500 Residues
5	12	5	0	0	0
10	24	14	8	0	0
20	56	27	20	12	0
40	74	55	40	24	0
80	93	109	80	48	20

Resolution: Whether the resolution will increase with increasing fields depends on whether the individual resonance lines narrow or broaden as the field increases. For cases in which magnetic dipolar relaxation is expected to dominate, as, for example, for the α-protons of proteins, resolution should increase as field is increased. Taking into account the predicted line widths, the number of resonances, and the spectral range in which the resonances occur, one can make a statistical prediction of the number that should be separately resolved at various applied fields. The number for a variety of proteins is given in Table 1. At currently available field strengths, we can resolve a small fraction of the resonances in proteins of low molecular weight, such as ribonuclease, while those of higher molecular weight are not yet open to study. Improvement in field strength, however, greatly increases the power of the method for lower-molecular-weight proteins and brings new classes of proteins into range. For ^{13}C, chemical-shift anisotropy is important for trigonally bound carbon, so that resolution of carbonyl groups in proteins, for example, would worsen at sufficiently high fields, but for tetrahedral carbon (as in α-carbons) the situation would continue to improve in the range of 5–80 T.

Currently there is great interest in studying the solution structure of the transfer RNA's for which crystal structures have been established by x-ray diffraction. At available fields, the low-field-shifted NHN resonances are not completely resolved, and their number (and assignments) is a subject of some controversy. Increased field strength to 20–30 T will result in sufficient resolution to allow complete assignments, studies of thermal folding and unfolding, and determination of the conformational energies. Other research areas opened to study at higher fields include antigen–antibody interaction, protein and lipid interaction in cell membranes, interaction of histones with nucleic acids, enzyme complex assembly, and identification and mapping of receptor binding sites.

Studies of phosphorus metabolites in intact cells using ^{31}P resonance is currently a very important development. These studies, pursued at higher fields, would benefit by increased sensitivity and spectral spread.

Sensitivity: Sensitivity is expected to continue to improve in the 5–80 T range, though not so rapidly as at lower fields, because $(T_2/T_1)^{1/2}$ decreases as $1/H_0$ in the high field limit. Increases in sensitivity are important because they allow studies of smaller samples of substances that are difficult to obtain and studies at lower concentrations where aggregating or insoluble species are concerned.

New Phenomena-Orientation Effects, Observation of J, Coupling to Quadrupolar Nuclei: At fields used to date, orientation of single diamagnetic molecules has had no detectable influence on NMR spectra. Orientation has been achieved using liquid crystals, where domains, rather than individual molecules, are oriented. Further, small orientations of small molecules have been detected by the Cotton-Mouton effect. Recently such effects have been used to study rigid helix lengths in DNA, orientation in phospholipid membranes, and local order in liquid polymers.

If a molecule has an anisotropic diamagnetic susceptibility (such as benzene $\Delta\chi \sim 60 \times 10^{-6}$ cm^3/mole), orientation will be of the order $H_0{}^2 \Delta\chi/RT$. Orientation at 10 T and 100 T will be 2.4×10^{-5} and 2.4×10^{-3}, respectively. If the dipolar structure of completely oriented benzene covered a spectral width of 10 kHz, structure would not be visible in the spectrum at 10 T but might be visible at 100 T. By choosing molecules with larger anisotropic susceptibilities (condensed-ring system, paramagnetic complexes) and spectra more sensitive to orientation (larger dipolar splitting or quadrupole splittings), such features might become visible at fields as low as 10 T. This would provide a method for the determination of precise interatomic distances within complex molecules in solution, a determination for which no other satisfactory methods are available.

In regard to observation of *J* coupling to quadrupolar nuclei, the formula for $1/T_{1q}$ due to relaxation by a quadrupole moment suggests that $1/T_1$ will become long in the high-field limit ($\omega\tau_C \gg 1$). Under these circumstances, the splitting of signals from adjacent nuclei by the quadrupolar nucleus will become visible; for example, peptide proton resonances will show splitting by the ^{14}N nuclei to which they are attached. This extra parameter should be useful in characterizing the bonding state of the peptide NH (whether it is H-bonded, nonplanar, solvent exposed, etc.).

In the same way ^{14}N broadening and eventual splitting in transfer RNA's will be detectable at modestly higher fields and could lead to unambiguous assignment of bridging NHN signals and characterization of the hydrogen-bonding scheme in these molecules.

NMR Imaging: The use of higher applied fields for NMR imaging will result in greater sensitivity, which means that smaller volumes of tissue will give detectable signals and smaller biological structures can be imaged. For typical experimental conditions, the volume of tissue giving rise to an image element at 10 T and 80 T is 3×10^{-8} cm^3 and 1×10^{-9} cm^3, respectively. Time-averaging techniques will improve these volumes somewhat, so that three-dimensional imaging of the internal structure of isolated individual cells will be possible. This enlarges the prospect for studying and understanding chemical processes and material transport in the cell.

Ultra-High-Field NMR
Quasi-static and Shorter Pulses. Up to 300–400 T. CATEGORY 2.

For conventional-pulse NMR spectroscopy it is necessary to have very steady high dc fields with great uniformity (10^{-9} over cubic millimeters) over extended periods of time, preferably from a few hours to continuous operation. The availability of such fields allows maximum information to be extracted from the spectrum and permits such aids to assignment in the various forms of double irradiation and cross relaxation to be applied. At the same time, it should be pointed out that somewhat limited but nevertheless quite useful experiments can be carried out under less stringent conditions—long pulsed fields on the order of 100 T for seconds, up to 300–400 T for milliseconds. Rapid-passage techniques would provide high-field information on T_1 and T_2 relaxation times, J-modulated echoes, and even high-resolution spectra, provided that the time evolution of the magnetic field is known and reproducible.

Magneto-Quantum Electrodynamics (MQED)
Short Pulse. Greater than 250 T. CATEGORY 3.

The availability of high magnetic fields and high-energy electrons will make possible more precise tests of quantum electrodynamics without requiring the calculation of many other, nonelectrodynamic effects such as those due to strong interactions that result from the presence of protons in the experiments. Small pulses of high-energy electrons ($E \sim 900$ GeV) will be available in the next five years when Fermilab's "Tevatron," a 1000-GeV proton accelerator, is operational. The electrons will be produced by decays of muons and bremsstrahlung. Combining these beams of electrons with pulsed 250-T magnetic fields will make possible two types of experiments that are of fundamental interest. Each of these measurements would be done on a "pure" electrodynamic system—electrons in an external magnetic field.

The first of these experiments would involve tests of radiative corrections to quantum electrodynamics in strong fields. Measurements of the anomalous *g*-factor of the electron in a high field and of the production of electron–positron pairs in a field will provide tests of quantum electrodynamic theory and will indicate the importance of "strong interaction" effects in electrodynamic phenomena.

The second involves the measurement of the spectrum of synchrotron radiation at high energies and high fields. These measurements are of considerable interest in calculating quantum corrections to the classical synchrotron radiation formulas. For $E = 900$ GeV and $B = 250$ T, the parameter $\Sigma = 3/2\,(E/mc^2)\,B/B_C$, where $B_C = 4.4 \times 10^9$ T, is equal to 0.15. When $\Sigma \sim 1$, quantum effects are important, so that measurement of the spectrum at 250 T might exhibit these corrections. In addition, at these energies and fields, the radiative damping will be extremely large, for the elctron would radiate away all of its energy in less than 1 cm. This strong damping regime will provide further tests of the theory, as well as potential copious sources of high-energy photons.

Spectroscopic Research

The availability of high magnetic fields will expand greatly the opportunities for spectroscopic studies of atoms and molecules. Experiments have been performed in fields of the order of 15 T (maximum). Extension to 30 T would probably double the number of new experiments, with from 60 to 75 T doubling the number again. One can anticipate steady progress in this field, increasing linearly with increases in available fields.

Apart from the intrinsic interest that these new experiments would generate scientifically, they would also be relevant to astronomical investigations. The magnetic fields at the surfaces of white dwarfs are of the order of 100–1000 T. Current observations are fitted to theoretical spectra of atoms appropriate to this field range, which may not be a sound procedure. Not only are the theoretical treatments limited in their accuracy, but the combination of high temperatures and high fields results in peculiarities in lineshape that can complicate observation substantially. This "motional Stark effect" lineshape can, however, overcome the Doppler broadening and allow studies of radiative and collisional broadening. Laboratory simulation of astronomical spectra might become a valuable tool in the study of white dwarfs and other objects with magnetic fields in the 100–1000 T range.

We shall discuss four categories of spectroscopic experiments that would be possible with high magnetic fields: (a) high Rydberg states in which the Zeeman energy and the Coulomb energy are comparable, (b) motional Stark effect lineshape, (c) anticrossing observations, and (d) collision dynamics.

High Rydberg States.

Steady State, 75 T; to Short Pulse, 1000 T. CATEGORY 1.

The magnetic energy becomes comparable with the Coulomb energy for electrons in a principal quantum number state n when $B = 10^5/n^3$ T. This requires that one work at very high quantum numbers for laboratory fields (CaI has been studied to $n = 90$). Fields of 1000 T would enable one to study much lower-energy states and to extend the number of systems that could be studied. The behavior of complex atoms in these field ranges is not well charted. In addition to the intrinsic interest of states in the regime where the magnetic and Coulomb energies are comparable, magnetic white dwarf stars exhibit fields at their surface between 100 and 1000 T. Determination of the spectra of atoms and ions in the laboratory under similar fields would aid substantially in the identification of spectral lines from these sources.

Motional Stark Effect Lineshaper.

Steady State. 75 T. CATEGORY 2.

When an atom is subjected to a large magnetic field, its emission lineshape will be dominated by the motional Stark effect if its velocity (temperature) is sufficiently great. This effect arises from the velocity-dependent terms in the absorption line energy: $\delta E(v) = (v_y/c)E_0 + (\alpha'/c^2)(v_x{}^2 + v_y{}^2)H^2$. Here E_0 is the absorption energy in the rest of the frame of the atom, v_y is the speed of the atom in the y direction, the field H is along the z direction, the light that is absorbed propagates along the y direction, α is one half the difference in atomic polarizability in the ground and excited state, and c is the velocity of light. The first term is simply the Doppler shift; the second results from the atom experiencing an electric field $\mathbf{E} = (\mathbf{v} \times \mathbf{H})/c$ in its own rest frame and is quadratic as a consequence of the second-order Stark shift of the atomic energy levels. The remarkable aspect of the combination of both terms is that for sufficiently large fields and velocity, the absorption lineshape becomes highly asymmetric. On one side it is characterized by an abrupt cutoff, on the other by a relatively long exponential tail.

This shape, together with the velocity profile, greatly complicates the absorption spectrum of an atom at high temperatures in high magnetic fields. It may well dominate the emission lineshape for sources including white dwarfs and (under some circumstances) even plasma fusion machines. The study of atoms under these conditions could, therefore, be important for analytic purposes. Further, the cutoff occurs over a width comparable with the homogeneous linewidth not the Doppler width of the transition. This finding suggests that a careful lineshape analysis can result in sub-Doppler information in high-temperature gases.

Anticrossing Investigations.
Steady State. 75 T. CATEGORY 2.

The magnetic-field energy can be made sufficiently great that atomatic or molecular energy levels possessing large zero-field separations can be made to cross. In general, matrix elements exist between levels, so that a repulsion occurs in the crossing region and the levels "anticross." This means that if we monitor the emission of one of the levels preferentially, the intensity of emission will "switch" from one line to another as the field increases through the anticrossing region.

The beauty of such measurements is twofold. They enable one to determine the zero-field splitting accurately (assuming that the Zeeman energies of the two levels are known separately or can be determined from the spectrum). By this technique, therefore, one can determine excited triplet-state energies precisely, though direct absorption from a ground or lower-lying singlet may be forbidden. Because the zero-field splittings can be substantial, this form of spectroscopy requires larger fields as the zero-field splitting becomes larger. The second aspect of this measurement is the width of the crossover regime. For sufficiently long-lived states, the transition width is given directly by the matrix element that couples the energy levels. This can be an interesting quantity, representing a highly forbidden term in the Hamiltonian (e.g., between states of different multiplicity) that could not otherwise be obtained. This form of spectroscopy will undoubtedly be used extensively for studies of excited levels and their couplings in the future. An example is the study of the quartet states of CN by T. A. Miller, who determined the rotational constant and bond length of these states, as well as the fine-structure constants and a rough value of the vibrational frequency. Before these experiments, nothing was known of the quartet states in CN. The availability of higher fields will considerably enhance the chances of finding similar anticrossings in molecules like N_2^+ and C_2.

Collision Dynamics.
Steady State. 75 T. CATEGORY 2.

The presence of an intense magnetic field generates a precession of the ground and excited moments of atoms or molecules that can change the collision cross section in a gas. This relatively young field began with the thesis of J. C. Gay and promises to yield information concerning the collision potential for like and unlike atoms and molecules. An example is Gay's study of the Na–Na* resonant transfer process. He studied the transfer of excitation from one Zeeman component (M=–3/2 sublevel of the $3^2P_{3/2}$ state of Na) to another (M= 3/2 of the same sublevel) using a narrow-line laser to excite only the former Zeeman component. Application of an 8-T field effectively quenched the resonant transfer.

The future potential of such studies lies in the ability to alter a particular zero-field excitation transfer process by application of a field (in the Na–Na* resonant transfer case, shutting off the role of the long-range dipole–dipole interaction) and allowing other terms to be studied separately (in the Na–Na* case, higher-order nonresonant terms of the collision potential could be studied). The larger the field, the shorter the collision time can be and still have the excitation transfer dynamics altered. This line of research promises to become important once fields of sufficient strength are available.

4

Applications

INTRODUCTION

Other chapters of this report deal with the opportunities for new scientific research at high magnetic fields and the techniques and facilities necessary for the prosecution of such research. This chapter is concerned with a different aspect—the technological payoff already achieved or expected from the availability of higher fields.

Scientific research does not always give birth to new technology; quite often there is considerable delay between the emergence of new knowledge and its exploitation. No such delay occurred in high-magnetic-field research; indeed, the techniques necessary to advance this science are also capable of rapid exploitation in new technology vitally important to future U.S. economic progress. To illustrate this point, we will mention several national problems for which the technological solution depends to varying degrees, sometimes crucially, on high magnetic fields.

That new energy sources are crucial for the future economic health of the United States hardly needs to be noted; almost equally important is the more efficient distribution and use of energy. High magnetic fields can contribute to both of these goals. For example, the most promising long-range solution to the energy supply problem is the achievement of thermonuclear fusion. At present, high magnetic fields provide an attractive method of containing the high-temperature, high-density plasma that is necessary to achieve a fusion reaction. Similarly, the efficiency of electric power generation should be radically improved. One possible way is to use a magnetohydrodynamic (MHD) power generator in which a hot ionized plasma is passed through a magnetic field, generating power directly. The overall efficiency of such an MHD generator increases as the magnetic-field strength is raised. It is also possible to increase the efficiency of electric generators by increasing the strength of the magnetic field in the excitor coils. Later in this chapter we will discuss these and other promising high-field, energy-related technologies in greater detail.

National defense technologies are also strongly affected by the availability of higher magnetic fields. The key concept here is that higher field strengths will enable engineers to reduce the size and weight of rotating electrical machines without any loss of power throughput. Essentially, the machine power density is greatly increased, which will almost certainly have a far-reaching influence on the design of propulsion systems for ships. Further, energy-intensive weapons systems will attain lighter, more compact power supplies. What is useful for defense will also apply to many aspects of civilian transportation; radically new systems of propulsion and lift for vehicles will emerge when higher magnetic fields are available.

One of the key technological advances that opened some of the possibilities we have mentioned was the discovery of high-field superconductors, which occurred during the past 20 years. Because of the relative youth of this technology and its central role in high-field applications, we will discuss briefly how it works and how it fits into the general framework of electrical technology. The rest of the chapter will be devoted to various technologies for which high magnetic fields play an essential part. We have not attempted to catalogue every possible application but have focused on those that seem to us most important and farthest advanced. The following conclusions and recommendations are based on what we believe is required in high-field research and development to promote the advance of various technologies and to lead to new technologies at very high fields.

CONCLUSIONS

We conclude that there are many important, currently developing technologies for which high magnetic fields, in excess of 2 T, are vital to success. In many of these applications, the range from 2 to 10 T has not yet been fully exploited; indeed, in several instances, the achievement of a large working volume is more of a problem at present than higher field strength *per se*. For this reason, technologists are not pressing strongly for fields above 10 T. Stated another way, the relatively recent access to fields from 2 to 10 T has created so many exciting opportunities for engineers that fields beyond 10 T have not yet been seriously considered by most technologists.

Exploitation of still higher fields, beyond 10 T, is likely to yield new technological opportunities. For example, successful mirror machines for fusion would probably require fields above 10 T. Increases in the power density of motors and generators could be achieved with higher fields. If fields in the 100-T region were available, new chemical processes would be possible, such as the separation of oxygen from nitrogen in the gaseous state.

Although we cannot point out specific needs for higher fields than are extant, aside from the chemical application mentioned above, the existence of a facility providing such a higher field, whether it be 30 T, 45 T, 60 T, or higher, would be valuable insofar as it would stimulate invention on the part of the applications technologists. It would give them a goal to strive for. In addition, such a facility would afford critical field and current density measurements to people working in high-field superconductivity and magnet development. This would inevitably advance the state of the art and thus add to science and technology. Ideally, one would prefer a steady-state facility, even though quasi-static fields can supply a poor second choice for reliable measurements when steady-state fields are unavailable.

Our considered opinion is that the health of high-field superconducting magnet technology in the United States would be greatly improved by a research facility providing steady fields up to 45 T. The experience gained in building such a facility, together with the research data that it would yield, would benefit magnet technology across the board, thus having an impact on the many technologies that we will describe in this section. Therefore, increased research is required to search for new superconducting materials with upper critical fields in the 45–100 T range, if possible with critical temperatures above 20 K.

In addition, funds are required specifically to establish the process technology necessary to produce long lengths of practical magnet conductors suitable for superconducting coils in the 20–45 T range.

HIGH-MAGNETIC-FIELD TECHNOLOGY

The basic building block of a high-field magnet is a multiturn coil of conducting material through which an electric current passes. The invention of this device in the nineteenth century led, through the work of Faraday and Maxwell, to the modern electrical industry. Magnet coils are used in generators, motors, transformers, and many other electrical devices. As electric power technology developed, it was found that the electric current used to excite the magnet coils could not be increased indefinitely because of resistive heating in the conductor. However, the magnetic field in the coil could be enhanced by inserting a strong magnetic material such as iron. An optimum mix of copper, iron, and ventilation resulted in machines designed for magnetic fields up to about 2 T. It is not economic to operate copper–iron systems much above this flux level, which is essentially the saturation field of iron.

Of course, steady magnetic fields above 2 T can be readily achieved in the scientific laboratory by forced cooling of copper coils, as Bitter did in his pioneering work. Modern high-field magnets of this type can attain 20 T or more, but they are not of great use to the electrical engineer because of the enormous power required for operation and the severe cooling problems.

In 1911, Kamerlingh Onnes discovered that many metals lose their electrical resistance entirely at very low temperatures. For some time it was thought that such superconductors would be used as windings for high-field electromagnets. Unfortunately, these pure metal superconductors became resistive in quite modest magnetic fields in the vicinity of 0.1 T. In 1961, Kunzler and his associates found a new class of superconductor, now called Type II, which could remain superconducting in extremely high fields exceeding 20 T. By this discovery, the way was opened to a new era of electrotechnology based on high-field superconducting coils.

The progress in developing superconducting magnets was quite rapid after 1961. Today, 10-T magnets are quite commonplace, and the technology is pushing toward 20 T. As might be expected, these early high-field coils were used primarily in research. Technological applications generally require large working volumes, as well as high fields. It should be noted that problems of developing coils with larger volumes are at least as formidable as those connected with increasing field strength.

Most current development work on superconducting magnets is funded as part of major technology programs such as fusion and MHD. The availability of suitable high-field magnets is a crucial element in the overall plan for these new technologies. Support of magnet development in this fashion is highly appropriate, but it can be argued that there is also a tendency in these programs to neglect some of the fundamental research that ought to be pursued in parallel—a point to which we will return.

ENERGY TECHNOLOGY

The applications of high magnetic fields to improvements in energy technology are diverse and cover a broad range from the national requirement for new energy sources to the technologies of more efficient energy conversion (between heat and electricity, for example), distribution, and utilization. High fields also offer hope of coping more effectively with two serious difficulties associated with energy plants, that is, their pollution behavior and reliability.

Fusion Reactors

One of the most important future energy source options for the United States is the controlled thermonuclear reactor using hydrogen isotopes as a fuel. The basic and unsolved problems of this reactor are achievement of both a sufficiently high temperature and adequate density in the fuel plasma to enable a self-sustaining reaction to take place. The plasma cannot be contained in any material container. Possible methods of containment include either a high-magnetic-field "bottle" or the inertia of the plasma itself. Of these two options, magnetic confinement is currently the more advanced in development.

Practical fusion reactors with magnetic plasma containment are virtually inconceivable without large superconducting magnets. The Department of Energy is allocating major funds to the toroidal-field Tokamak experiments, with less support to the "magnetic-mirror" experiments. The development of large D-shaped toroidal-field magnets to be used in Tokamak machines has begun; large NbTi solenoidal magnets, baseball magnets, and yin–yang magnets are being built for mirror reactors. These magnets are generally in the range of 6–8 T. Also under development for both concepts are Nb_3Sn magnets intended for fields ranging from 10 to 16 T.

Tokamaks are fusion devices in which a solenoidal field, containing a high-temperature plasma, is bent into a torus to eliminate end losses. The toroidal field is provided by D-shaped superconducting magnets with minor diameters typically one fourth of the major diameter. These machines are potentially capable of providing power plants of several gigawatts at a competitive capital cost of about $1000/kW. The smallest economic plant would thus represent a several billion dollar investment.

The concept of magnetic mirror containment has recently benefited from two major innovations, each leading to a new range of potential configurations and applications. The first of these is the tandem mirror concept, in which a solenoidal field of perhaps 6–8 T contains a cylindrical plasma that is "end plugged" by two pairs of high-field (12–18 T) yin–yang magnets. The relative simplicity of this geometry, particularly when used in a hybrid fission–fusion variant, could offer genuine economic competition to the toroidal Tokamak in the multigigawatt range.

The second innovation, the recent field-reversed mirror concept, is unique among its competitors, for its ideal individual cell size is of the order of 20 MW, and its geometry, materials, required magnetic fields, and neutral-beam injector would all appear to be of modest cost and to require only modest technology. The achievement of a stable plasma in this configuration is problematical, but experiments within the next two years should provide an answer.

The release of kinetically stored flywheel energy into the poloidal fields of Tokamak experiments for ohmic plasma heating is a potential application of advanced rotating-machine technology. Current plans are to use conventional alternators for this purpose; superconductive homopolar machines with high-field excitation offer an attractive alternative.

MHD Power

Magnetohydrodynamics (MHD) is a technique to generate electrical power by means of an interaction between a conducting fluid and a magnetic field. The fuel is essentially hot gas derived from coal, oil, or a nuclear reactor. The motivation for the development of MHD generators for use in central station power generation is the potential for a significant improvement in plant thermal efficiency as a result of the much higher temperatures that are used in MHD generators.

The power density that can be attained in an MHD generator is proportional to the electrical conductivity of the fluid and to the square of the flux density of the magnetic field. Because the conductivities of the fluids that are available for use in practical MHD generators are quite low, seeding chemicals are injected into the fluid flow to increase these conductivities. However, even with the use of seed, the conductivities of these fluids remain several orders of magnitude below that of copper. As a consequence, high magnetic fields are required to maintain the physical dimensions of these generators within practical limits. When coal is burned to provide combustion gas as the fluid, the seeding materials have the added feature of removing virtually all the sulfur oxides from this gas, thus substantially reducing effluent pollutants.

The power required to generate magnetic fields in excess of 2 T over large volumes becomes prohibitively high if these fields are generated by making use of conventional conductors for their windings. Consequently, making use of conventional magnets would reduce the efficiency of MHD generators to a level that would render them unattractive for use in central station power generation. On the other hand, electromagnets making use of superconductors for their windings can readily generate magnetic fields in the range of 5–7 T and require hardly any electrical power to maintain these fields. High magnetic fields generated by means of superconducting windings are, therefore, essential to the successful development of efficient MHD generators for central station use.

Because 40 percent or more of the U.S. power plants are expected to be coal-fired by the year 2000, the MHD program emphasizes the use of coal as a fuel. The United States currently hopes to have an operational pilot plant making use of MHD by 1985 and a base-load commercial demonstration plant by 1995.

To date, the largest superconducting magnet built for use in an MHD generator weighs 40 tons and develops a magnetic flux density of 5 T. This magnet was constructed by the Argonne National Laboratory for test purposes in a joint U.S./U.S.S.R. (U-25) experimental program to develop MHD power generators. Design studies have been completed on the superconducting magnets required for full-scale (600-MW) central-station-type MHD generators. These studies reveal that such magnets will weigh approximately 2200 metric tons and cost about $60 million. Plans are to work at about 6 T in these systems, but higher fields would be desirable for higher efficiency if they could be attained reliably and economically.

The MHD combustion studies have indicated that the plant and process would be simplified if one could work with a combustion airstream enriched with oxygen. A possible approach to achieving such enrichment is to use the strong paramagnetism of the oxygen molecule, which enables it to be separated from nitrogen by a high magnetic field (perhaps the main MHD magnet field). This process is under study in several laboratories; preliminary work suggests that reasonable efficiencies may require fields in excess of 100 T. It appears possible that if fields of this magnitude were readily available in the engineering sense, a variety of new chemical separation processes of this type would become economically feasible.

Electrical Machines

As we have noted, modern electric machine technology is founded on copper–iron electromagnets operating up to about 2 T. Most machines are air cooled or, in the case of central station generators, cooled by hydrogen gas or water. Because of the convenience of voltage transformation, the bulk of the present power systems are based on ac machines, with dc confined to special applications such as railroad traction.

With the advent of high-field supermagnets in the 1960's, a search began for the optimum areas of machine technology in which superconductors could replace copper systems. The pattern that has emerged so far is that the supermagnets are not suitable at present for direct substitution in ac windings because of excessive losses in the superconductors that are currently available. However, there are specific devices such as dc homopolar machines or ac synchronous generators in which use of a high field in part of the machine would be highly advantageous.

The dc homopolar machine was invented by Faraday. Its principal feature is a disk or drum rotating in a magnetic field applied normal to the plane of the disk, causing current to flow from the axis to the periphery of the disk. Several high-field superconducting experimental models of this machine were constructed in the past decade, but despite savings in size and weight, it has not been adopted for widespread industrial use. The most promising application at present seems to be ship propulsion, which we discuss subsequently.

A different situation exists for the central-power-station, turbine-driven ac synchronous generator, in which a large rotating dc field winding generates ac power in a stationary external armature. The power dissipation in the rotor is almost half the power loss of the entire machine and can be essentially eliminated by substituting a high-field superconducting winding for the present system of copper coils mounted in a slotted ferromagnetic steel rotor. Several medium-size experimental prototype superconducting machines were constructed in the early 1970's, specifically at MIT (3 MVA) and Westinghouse (5 MVA). The Electric Power Research Institute (EPRI) has recently supported design studies for a 300-MW machine and will probably contract for the development of such a machine in the near future. The magnet will probably be wound from a niobium–titanium superconductor and will operate at about 5-T maximum field.

The economic benefits of using superconductive high magnetic fields in central station generators are quite impressive. Not only are the generator losses reduced by 50 percent, but the higher magnetic field allows the frame size to be reduced, lowering the overall cost of the machine appreciably. A further possible benefit is the addition of a high-voltage stator, which will enable direct generation of transmission line voltage, thus eliminating a large step-up transformer. Benefits could exceed $25 per kilowatt for a large power plant. If such machines capture a major fraction of the U.S. market in the next two decades, utility revenue needs through the year 2000 should be reduced by about $2 billion.

The design philosophy of these early machines is heavily influenced by the extreme need for reliability in power station generators. The superconducting magnet design tends, therefore, to follow a well-tried engineering path, with a field strength (5 T) well short of what is known to be achievable using more advanced superconductors.

Wider use of high fields in machines and transformers might develop if the ac losses of high-field superconductors could be reduced or eliminated. This research has not received a great deal of attention and would seem to be a fruitful direction for future effort.

Energy Storage

A major problem of electric utility systems is that a good fraction of their generating plant is idle much of the day. This underused equipment is called on for only short periods to supply peak loads. Electricity costs could be reduced if electrical energy could be stored in low load periods and released at peak times, so that the generating plant could be run continuously. Electrical energy can be stored in batteries, capacitors, and high-field superconducting magnets. Recently, at Los Alamos and the University of Wisconsin, serious studies of major energy-storage systems using superconductivity have taken place.

These energy-storage projects are at too early a stage of development to allow firm statements about their economic feasibility. Preliminary conclusions suggest that the load-leveling requirements of the United States, which are principally diurnal, could be satisfied by Inductor Converter units covering about 10 percent of the peak electrical load. These magnets would probably be extremely large-volume units constructed from cryostable Nb–Ti conductors, with operating fields below 5 T. The future needs in this instance are for higher-current-density, lower-cost superconductors, as opposed to higher-field systems.

Energy Utilization

The application of high magnetic fields to energy utilization has received less attention, probably because most end-use devices are small and widely distributed. An exception is public transportation systems. Some radically new concepts have emerged in the past two decades based on the use of high magnetic fields to suspend vehicles magnetically in place of conventional spring and wheel systems.

Magnetic suspension for vehicles is an old idea, dating from Bachelet's work early in the 1900's. The basic principle is that a repulsive force is produced between a magnet (on the vehicle) and eddy currents generated in a conducting track over which the vehicle moves. The concept does not seem to be practical for low-field magnets, below 2 T; however, it becomes economically more attractive when high-field superconducting magnets are employed, as Powell and Danby pointed out in 1966.

Magnetic suspension has several advantages over more conventional tracked vehicles. With conventional tracked vehicles, major problems arise at speeds over 300 km/h. Track alignment becomes critical and hard to maintain; excessive wear occurs between rail and wheels and also at sliding electrical contacts for electric propulsion. Separation between train and guide rails is achievable with magnetic levitation, and magnetic propulsion can be obtained by a linear-induction or linear-synchronous-motor arrangement in the guide rail. Small-scale models of magnetically levitated vehicles have been tested in the United States, Germany, and Japan. Larger systems are under development, particularly by the Japanese National Railways, which is now the world leader in this technology.

The National Aeronautics and Space Administration (NASA) has recently been exploring an interesting application of high magnetic fields to heat pumps, another field of energy use. This application is based on the principle of adiabatic demagnetization of paramagnetic materials, which has long been known to low-temperature physicists. The same principle can be applied at room temperature using gadolinium, which has a Curie temperature of 20°C. By use of a recuperator and counterflow heat exchangers in conjunction with a high, varying magnetic field, a Stirling cycle heat pump ensues; in the high-field limit this concept has Carnot efficiency.

The basic principles of this device were demonstrated at NASA; current funding is provided by EPRI. The NASA demonstration showed that a recuperator could develop a temperature differential exceeding 80 K in a 7-T field; the EPRI experiment will demonstrate a prototype heat pump using this principle. The efficiency should be several times higher than that of conventional heat pumps and refrigerators.

MAGNETIC SEPARATION

Low-field electromagnets have been used for many years as a general tool for iron scrap separation and ore beneficiation. The promise of higher fields has recently stimulated great interest in this subject, which is focused on magnetic separation of much more sophisticated mixtures than ever before. A promising energy application is the removal of pollutants from the cooling system of power plants and also from fossil fuels prior to combustion.

The technology involved is High Gradient Magnetic Separation (HGMS). The principle of HGMS is the interposition into the working field volume of a porous matrix of magnetizable material so that many high-gradient interfaces are present. Stacked iron balls and ferromagnetic steel wool are examples. The imposed field should be sufficient to magnetically saturate the matrix; for most separations the efficiency continues to increase with increasing field by raising the magnetization of the paramagnetic particles being collected.

The use of magnetic filters is growing most rapidly in nuclear-power-station technology. The corrosion products are fine-magnetic-particle oxides and hydroxides of construction metal elements such as iron, manganese, and nickel. Radioactive species of various origins also appear in these products. Filtration takes place at ~300°C, and flow rates range from 10 tons/h in test units up to projected rates of 3600 tons/h.

Development of this application started in 1970, with matrices of steel balls, which provided mediocre magnetic gradients. Recently, there have been tests with the superior steel wool matrices. Current field levels are modest, 0.5 T, but over a large volume of 2-m diameter by about 0.5 m high. Heitmann forecasts that further development will use superconductive coils for higher fields and ultimate separation of weaker paramagnetic materials. In contrast, Oberteuffer believes that industry would be slow to adopt superconductive technology and that the cheap power available at power stations reduces the economic stimulus for conversion to superconductivity.

Another possible application of HGMS is to the desulfurization of coal. Between one third and two thirds of the sulfur in eastern and central U.S. coals is bound as discrete particles of inorganic compounds of sulfur and iron, principally iron pyrites, which are liberated when coal is pulverized before combustion. The HGMS approach to coal cleanup is one of a number currently under consideration that have varying costs, efficiencies, and problems. Its low add-on cost, estimated at roughly $1 to $3/ton of coal, makes it attractive. By contrast, the well-known flue gas desulfurization adds about $10 to $15/ton to coal costs. A variety of chemical coal cleanup methods are also under consideration, with estimated costs of from $3 to $10/ton.

A promising and related example of HGMS is the removal of inorganic mineral particulates from liquified coal. Although such coal conversion processes appear to be expensive, that is, $10 to $30/ton, they are receiving much attention and major funding from the Department of Energy, EPRI, and oil and utility companies because of the useful form of the product, for example, as liquid or easily transported solid. As with the magnetic desulfurization of raw coal mentioned in the preceding paragraph, the particulate cleanup of liquified coal is attractive from an economic viewpoint. Oder has estimated a cost of about $1 or $2/ton of coal, a factor of 4 cheaper than the current methods of high-temperature filtration. In addition, the chemical process of hydrogenative liquefaction renders the iron–sulfur compound more strongly magnetic, that is, conversion of pyrite to pyrrhotite.

Other applications for HGMS include mineral processing and ore beneficiation, which has a long history if one includes poorer-quality separators (Edison and others before him). The improvements brought about by HGMS permit beneficiation of more weakly magnetic ores such as oxidized taconite iron ore and the separation of paramagnetic tourmaline from the tin mineral cassiterite, SnO_2. Waste-water cleanup is also feasible either by the direct removal of suspended magnetic solids, as from steel mills (see also power station water discussed previously) or by the coagulation of contaminants onto magnetic "seed" particles. This process has been demonstrated for oils, phenols, coliform, PCB's, and other water impurities. There are also studies of cleanup of magnetic particulates from stack gas streams, for example, from steel-making furnaces. Another novel and interesting technique, with an open but lower gradient coupled with a long-interaction path, has been developed in the United Kingdom. It uses a superconductive quadrupole coil arrangement ($H \gtrsim 6$ T) with a spiral flow channel. This approach is especially attractive when the relative fraction of magnetic material is no longer small.

All of these applications can be classified as magnetic separation of the first kind, relying on the inherent magnetic susceptibility of the material to be separated. Magnetic separation of the second kind occurs when the medium of separation rather than the separated particles is made magnetizable, for example, a colloidal solution of a ferromagnetic or ferrimagnetic substance, or an aqueous solution (or melt) of a strongly paramagnetic salt. The apparent density, hence the effective buoyancy force, can be adjusted by the applied magnetic-field gradient. Such techniques are under study and development with iron electromagnet systems for reclaiming various nonferrous metals from scrap and for ore beneficiation. Another variation, eddy-current separation, has been developed using permanent magnet arrays. It is finding practical application in removal of nonferrous metals from solid waste.

DEFENSE TECHNOLOGY

Ship Propulsion

The British Navy substantially advanced superconducting machine technology by providing funds for the development of a 50-HP superconducting solid-brush-switched homopolar dc motor that operated successfully in 1965. The design was expanded to a 3250-HP pump motor that was demonstrated in 1971, and to a 1-MW land-based model of a ship power transmission system in the mid-1970's. These machines contained no iron and emphasized low weight; small machine diameter, high efficiency, and low helium consumption were of lower priority.

The U.S. Navy superconductive electric propulsion program started in the late 1960's and emphasized high efficiency, which implied low-helium-consumption, small-diameter motors to permit fitting them in low-drag nacelles, and adaptability to driving high-efficiency, contrarotating propellers. The resulting homopolar acyclic dc machines have liquid-metal current collectors and are compact, rugged, and simple, with liquid helium consumption of the order of 5 liters/h and efficiencies of 98–99 percent. A 400-HP motor of this type has served as an experimental facility for five years; several 3000-HP propulsion systems are under construction and will probably be operated in the laboratory and at sea during the next two years. Systems of 40,000 HP are planned for the early 1980's.

The synergistic benefits resulting from the flexibility of arrangement and operation permitted by these efficient, compact systems could reduce fuel consumption of naval monohull combatants by as much as one half for the same payload, performance, and range. (The cost of fueling U.S. surface ships is $2 billion per year.) Equally important, the lightness and compactness of superconducting systems could be essential to the economic feasibility of long-range, high-performance ships. The development of practical advanced superconductors such as Nb_3Sn or V_3Ga could further benefit naval machinery by providing the ultimate propulsion system for high-performance ships. A subtler, less-quantifiable advantage is the greater operating margin (equivalent to a "factor of safety" in other fields), which would be highly regarded by any ship's commanding officer.

Part of the superconductive machinery program is the development of compact, shock-resistant helium refrigerators and compressors of 10 liters/h capacity. High-power-density oil-cooled rectified alternators are also being built as alternatives to acyclic generators. The development of other advanced normal-temperature, liquid-cooled machines has been stimulated by this program.

Airborne Electric Power

Future combat aircraft may require electrical power levels of tens of megawatts for periods of several seconds. To produce such power, chemical energy stored in propellants may be converted into electrical power by either turboalternators or MHD devices. Obviously there is a premium on the achievement of compact, light systems for this application.

The U.S. Air Force has funded programs on high-speed (6000–12,000 rpm) superconductive alternators since the early 1970's. Severe conditions are imposed: very rapid speed changes (several thousand rpm per second), high radial accelerations of liquid helium in the rotor (above 10,000 g), and high coil-charging rates (several T per second). Under these severe conditions, NbTi superconductors are marginal; the development of multifilamentary Nb_3Sn wire with high-temperature capability thus received its first major impetus from a U.S. Air Force development program.

Permanent-magnet alternators are strong potential competitors in this field, as are plasma MHD systems using superconducting magnets. These two systems are under development by the Air Force.

High-Frequency Radiation

The ability to generate appreciable power levels of high-frequency radiation in the broad region between radio frequencies and the optical band has opened radically new defense technologies, of which radar is probably the most prominent. One of the key devices that made microwave radar possible is the cavity magnetron, in which electrons are caused to move in circular orbits by an applied magnetic field, usually provided by a large permanent magnet.

The possibility of creating other novel electron-radiation devices by using much stronger magnetic fields has intrigued inventors for many years. One

TABLE 2 Emission Wavelength versus Magnetic Field and Cyclotron Harmonic Number

Emission Wavelength	Magnetic Field				
	10 T	30 T	75 T	120 T	1000 T
$\omega = \omega_C$, λ =	1072 μm	357 μm	143 μm	89 μm	10.72 μm
$\omega = 2\omega_C$, λ =	536 μm	179 μm	71 μm	45 μm	5.36 μm
$\omega = 3\omega_C$, λ =	357 μm	119 μm	48 μm	30 μm	3.57 μm
$\omega = 4\omega_C$, λ =	268 μm	89 μm	36 μm	22 μm	2.68 μm

such device is an electron resonance maser; this is an electron-beam tube operating in a uniform magnetic field and emitting coherent radiation at the electron cyclotron frequency, ω_C or eB/m_ec, and its harmonics. The electron mass, m_e, must be treated relativistically for an accurate frequency calculation.

In practice, most electron cyclotron masers have operated in the weakly relativistic regime, with energies of 20–80 keV. A particularly efficient high-power version of the electron cyclotron resonance maser, called the gyrotron, has recently been invented in the Soviet Union and operated at wavelengths as short as 2 mm in the fundamental (ω_C) operation and 0.92 mm in the first harmonic ($2\omega_C$) operation. Because the emission frequency depends linearly on B, it is obvious that high emission frequencies (that is, short wavelengths) can be achieved at high magnetic fields. Typical numbers appear in Table 2.

Short wavelengths might be achieved by either increasing B or harmonic number n or both. However, efficiency drops off rapidly with n, so that if efficiency greater than 10 percent is required, operation at ω_C ($n = 1$) will probably be necessary; therefore, high magnetic fields will be required for high frequencies.

The gyrotron is the most promising device for extending high-power microwave capabilities to higher frequencies. Aside from the defense and communication uses, another potential application includes heating magnetically confined plasmas to very high temperatures to initiate thermonuclear reactions. A fusion power plant might require 100 MW or more of microwave heating power at a frequency of the order of 200 GHz, which might be supplied by a bank of 100-kW gyrotrons.

OTHER APPLICATIONS

There are several applications of high magnetic fields other than for energy or defense. These include the use of fields in certain specialized materials technologies and the development of new particle accelerators, which, although they are primarily research devices, could yield exciting future technological payoffs.

Materials Technology

High-field magnets were important in the recent discovery of a new class of permanent magnet materials based on intermetallic compounds of rare earths and cobalt. In 1966, the magnetocrystalline anisotropy of a single crystal of YCo_5 was investigated using a 5-T superconducting solenoid. The conclusions of this work pointed to prospects for new permanent magnet materials and stimulated a major effort in materials research and metallurgical processing. The high coercivities, up to 3 T, of various members of the rare-earth cobalt family require high fields for the initial magnetic alignment process, as well as in characterization studies.

The figure of merit of this permanent magnet system is roughly double that of its predecessors. This increase permits great changes in magnetic circuit design, together with considerable savings in power, weight, and space. An example of these savings is the development of a new 8-inch-diameter battery-powered torpedo motor of 140 HP to replace a previous version of at least 12-inch diameter.

The detection of magnetic impurities in solids can be done with increasing sensitivity as the applied magnetic field is increased. So far, this technique has been of value chiefly as a means of studying weak magnetic materials in the laboratory; however, for the first time, the General Electric Company recently applied it in a manufacturing plant. A 7.5-T superconducting magnet system is employed as part of a system to monitor planned variations of magnetic properties in nuclear fuel rods. This type of quality-control function using high magnetic fields will probably become more widespread in the future.

The superconductors that are used in the construction of high-field magnets must themselves be evaluated in the high-field environment. Lest this be regarded as merely a "bootstrap" operation, it should be noted that the development of these materials over the past 20 years depended heavily on the availability of water-cooled copper solenoids and pulsed-field magnets. Measurements up to 60 T are necessary, and these can only be made with pulsed fields at present.

High-Energy Particle Accelerators

The application of high magnetic fields to beam bending in high-energy particle accelerators might seem to be of primary interest for research in particle physics. Although this is true, there has also been synergism between the development of high-field devices for nuclear research and the general development of large high-field magnets; indeed, in the past two decades progress in magnet engineering has come about more from nuclear interest than from any other source.

Most of the accelerators have been based on copper–iron technology and limited to working fields of around 2 T. The advantages of higher fields are obvious; that is, the total size of machine can be reduced while maintaining the desired energy level. Alternatively, larger particle energies can be achieved with a given size of machine. A further advantage for large machines is that operating power costs can be reduced by using superconducting magnet windings.

Accelerator engineers have been reluctant to convert to major superconducting systems until these were shown to be reliable and predictable from an engineering viewpoint. Therefore, they have taken tentative steps in the new direction by building auxiliary devices such as bubble-chamber magnets and individual sections of accelerators. This stage now seems to have passed, with designers moving ahead to full-size machines. For example, a new energy doubler or Tevatron is being constructed at Batavia, Illinois, in the same tunnel used for the present machine. By doubling the deflecting field to about 4 T, the bending radius is maintained for the increased energy. Using Nb–Ti magnets, the energy can be doubled for approximately $30 million, which is about one tenth of the original accelerator cost. The next large-scale application of this new high-field technology is Isabelle at Brookhaven National Laboratory. This high-energy accelerator will operate at 5 T and will generate colliding beams at 400 GeV each. The cost of $275 million is again small when compared with that required by conventional high-field technology.

Future applications of accelerator development offer a number of interesting technological possibilities for the future, particularly if the size and operating cost can be greatly reduced by such methods as those mentioned in the preceding paragraph. Accelerators (and storage rings) are already used as sources of continuously tunable high-frequency (ultraviolet and x-ray) synchrotron radiation for basic and applied research. The insertion into the electron beam of high-magnetic-field superconducting "wiggler" magnets (so-called because the fields wiggle the electron beam, causing it to emit further radiation) enables users to tailor the spectrum of radiation to specific requirements. Much work on the development of these magnets at the highest possible fields is required.

High-energy heavy ions have also been proposed as a trigger for controlled thermonuclear fusion. The ions would deposit their energy into pellets of thermonuclear fuel, heating them to fusion ignition temperature. The high energies (~ 200 GeV) and high currents required would lead to an enormous accelerator unless high fields were used to bend the beams to within a manageable radius at a manageable cost.

Finally, high-energy, high-current proton accelerators are being considered as a means of burning used fuel from nuclear reactors, breeding new fissile materials, and producing energy by inducing nuclear reactions on impact of the protons on the radioactive material.

5
Magnet Design and Materials

INTRODUCTION

The goals identified in Chapter 3 on Scientific Opportunities to ensure the continued progress of research using high magnetic fields were

1. Continuous operation up to approximately 75 T;
2. Quasi-static pulse operation up to approximately 100-200 T, with fields roughly constant for 10–100 msec;
3. Pulse operation up to 1000 T (nondestructive) for times in the microsecond range; and
4. Very short (destructive) pulse operation in the nanosecond range up to 10,000 T (100 megagauss).

Our task in magnet design and materials was to determine the resources necessary to attain these far-reaching goals, as well as to consider ways that currently available resources might be used in the near term to extend capabilities to intermediate or more modest goals. The Panel examined three categories of field generation: (a) continuous high fields with superconducting and resistive systems, (b) quasi-static pulse systems of intermediate-field range, and (c) very-short-duration ultrahigh field systems. We then offered several recommendations for a national program to advance toward new field levels and toward maximum utilization of those fields.

For much of this century scientists and engineers have worked to extend magnetic-field levels beyond those readily available at any given time. Continuous-field generation, for example, progressed from the large iron magnets of the 1920's to 10 T in the 1930's, to 20 T in the early 1960's, and to 30 T in the late 1970's. Each new major increase required significant time and effort to develop technologies, test concepts, and marshal the major new commitment of resources that was needed. This is a time of new scientific opportunity for high-field research. The availability of hybrid-magnet steady fields approaching 30 T and the relatively widespread use of superconducting magnets to 15 T, some with extraordinary resolution and stability, have generated a broad scientific base for high-field research.

An important development that is occurring, and which must be taken into account, is the growing sophistication and scale of large power supplies and large superconducting magnets, both of which have received substantial support from fusion research activities. Thus a scale of resources previously unavailable to the high-field research community is developing. To capitalize on the scientific and technological opportunities, we offer the following conclusions.

CONCLUSIONS

After examining the field-magnitude goals set forth in Chapter 3 on Scientific Opportunities, we have assessed the resources required to extend the current state of the art toward these goals. We find that it is technically feasible to reach a continuous field of 75 T and quasi-static fields in the 100-T range. We find that pulse operation in the microsecond domain is feasible to 1000 T (and beyond), but that the limit of nondestructive techniques is approximately 200 T.

We find also that fields appreciably beyond 1000 T will be very difficult to achieve. Nonrepeatable, high nonuniform field environments to 5000 T are not impossible to imagine, however; nor is it impossible that nonrepeatable local fields in intense plasma discharges might reach 10,000 T.

On the basis of the preceding considerations, we conclude that a vigorous program should begin that will ultimately lead to 75-T continuous fields. As a major first step, an in-depth feasibility and cost analysis should be undertaken to determine the status of appropriate methods for producing steady-state, highly homogeneous fields of 75 T. This effort should include a study of high-field superconducting magnets, resistive magnets, and hybrid systems, which combine superconducting outer coils and water-cooled inserts, and which represent the approach most likely to result in the highest steady-state fields, and as such should receive priority attention. Intermediate goals between the available 30 T and the desired 75 T should be pursued; goals of 45 T and 60 T would divide the interval in thirds.

We further conclude that an important goal is the extension of the upper-field limit for superconducting materials and coils, which will ultimately contribute to the production of 75 T through the hybrid approach; in the shorter term, such coils will contribute to special applications such as high-resolution nuclear magnetic resonance (NMR), for which water-cooled or hybrid magnets are less well suited.

Given the current status of technology (for example, high-field large-volume superconductors and existing power supplies) a 75-T project would be beyond the resources available to the magnet user community. However, developments in superconducting materials, technology, and the size of power supplies are all being pushed by other research areas such as fusion; therefore, a combination of technologies that would lead to an economical solution may be available in the not unreasonably distant future. The technical and economic considerations of generating 75-T steady-state fields should be continuously re-examined to guide research and re-evaluate opportunities for substantial progress.

We further conclude that quasi-static fields up to 75–100 T are feasible and can be economically attained using existing technology and large pulse supplies similar to those in the fusion program. These fields, of approximately nominal 1-sec duration, can allow preliminary experiments in preparation for the steady field, which would become available in the longer-range future. The coil technology has much in common with the necessary steady-field technology; thus it would stimulate progress toward that goal.

Additionally we conclude that increased support for one or more centers, where there is experience with ultrahigh fields (1000 T and above) is required to stimulate experimental work and the development of facilities in this currently underused area. The technology is largely in place, and a program should therefore be initiated as soon as possible. Experimental techniques should be perfected and key experiments undertaken to demonstrate the applicability of the short-duration fields to the very significant experiments that have been proposed. Existing major investments in high-power pulse equipment should be utilized to the maximum extent. However, in choosing a facility to support, one must take into account the quality and the breadth of the scientific support group necessary to do the work. Hence existing facilities need not necessarily dictate the natural location of such expanded support.

CONTINUOUS-FIELD GENERATION

Superconducting Magnets—Present Status

These magnets have come of age since the early 1960's when the first small-volume, nominal 10-T magnet appeared. The magnets listed by the Subpanel on High Magnetic Field Facilities and Users represent the current state of the art. The advent of these reasonable-volume fields above 14 T has made possible the extension of high-field research to a number of centers. Prior to these developments, continuous fields of this level were available only in those central facilities that had large power supplies.

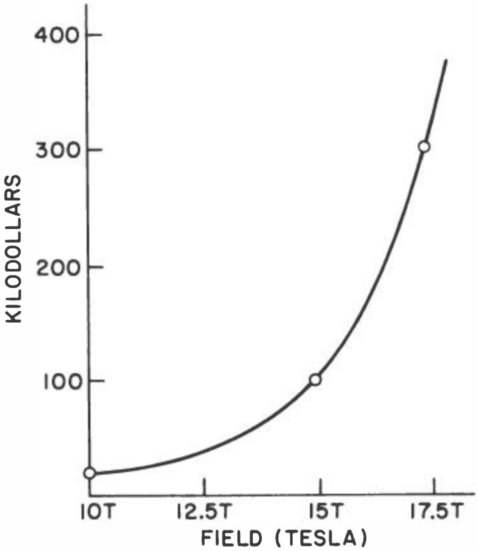

FIGURE 1 Approximate cost of 5-cm bore superconducting coils in the field range from 10 to 17.5 T.

Although fields of 10 T are easily attained with superconducting magnets, the cost of producing fields substantially above 10 T rises rapidly. Figure 1 gives an approximate cost curve for 5-cm bore coils. There is a factor of 5 increase between 10 T and 15 T, and an additional factor of 3 rise when one goes to 17.5 T, the highest field generated to date by a superconducting magnet.

As the capital investment in a superconducting magnet increases, so does the investment in support equipment and in the necessary operating cost to fully utilize it, as described in Chapter 6. Failure to provide such operating expenses in the past has limited the full utilization of many superconducting installations.

Superconducting magnets have advantages beyond their independence from large central power supplies. In principle, they can be placed in a persistent mode, thus being free from time variations. This plus the ability to carefully control the winding process can lead to extremely high-homogeneity fields for NMR. Many NMR grade systems in the 6–8 T range are in use, but work is just beginning in the higher field ranges.

An NMR system recently installed at Carnegie-Mellon University produces 14 T in a 9.5-cm bore with an uncompensated homogeneity of 2×10^{-5} G over the central centimeter. This has been compensated to allow resolution of

0.4 Hz at 600 MHz. The magnet system, exclusive of spectrometer, costs approximately $250,000. Further improvements of NMR will undoubtedly result when multifilamentary Nb^3 Sn is available and persistent current joints can be developed.

Superconducting Magnets–Future Possibilities

In the near term, multifilamentary Nb_3Sn materials will be sufficiently well developed to provide an alternative for the Nb_3Sn or V_3Ga tapes now used in coils. This advance should lead to faster sweep times (now limited by helium loss rates to many minutes for a full up–down sweep), potentially higher homogeneity, and persistent mode coils.

Also in the near term, one can expect some extension of the maximum field generated by superconductors. If the best V_3Ga tapes are used, a field of 20 T can be generated in a 3.2-cm bore for a magnet cost of approximately a factor of 2.5 times higher than at 17.5 T. The cost of such a magnet would be about $700,000.

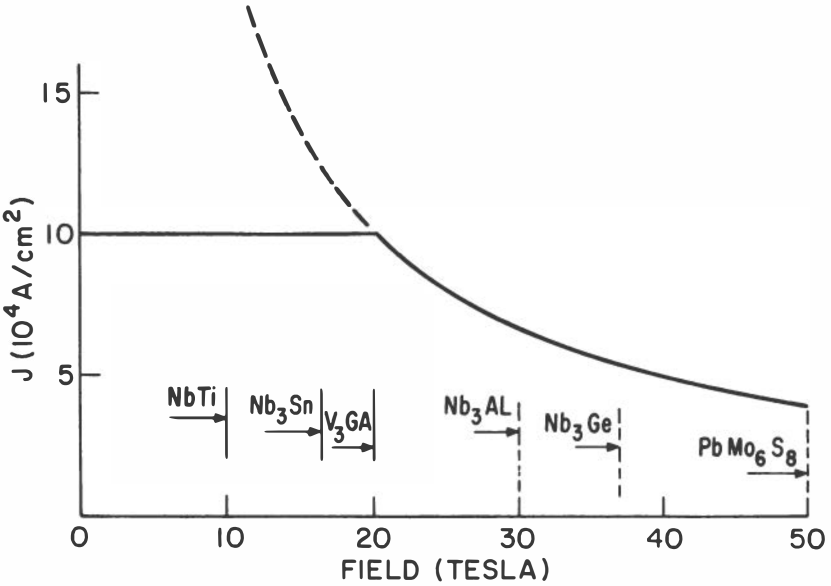

FIGURE 2 Limiting winding current density assumed for advanced superconducting coils. The limiting useful field for various developed and speculative materials are indicated.

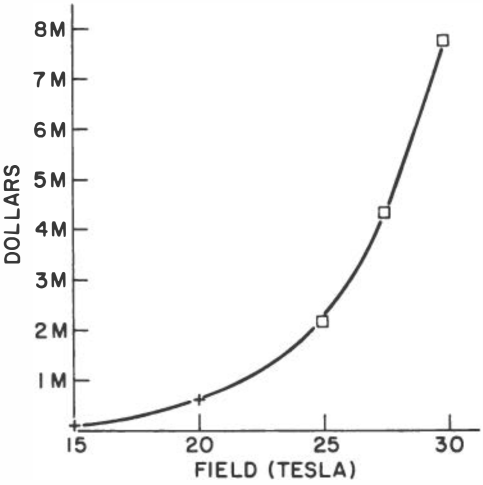

FIGURE 3 **Estimated cost of 3-cm bore superconducting coils for very high fields using the current density limitations of Figure 2. Material costs are based on current NB_3Sn conductors scaled by the field to which they are exposed.**

Looking farther ahead, one can speculate on the impact of applying higher-critical-field materials. There are, of course, materials with critical fields in the 50-T range. Experience with all materials developed to date suggests, however, that although the higher-critical-field materials obviously extend the maximum possible fields, they tend to have the same constant product of field times critical current as the lower-field materials. Thus any given wire will carry half the current at 20 T as it did at 10 T, independent of what superconductor is used in the wire.

If we make some reasonable assumptions about the cost and properties of future materials, we can project the cost of magnets above 20 T. We assume that (a) consideration of coil protection limits overall coil current density to 10×10^3 A/cm^2; (b) this limiting current density can be used up to 20 T only and must be degraded at a constant $B \times j$ above that point as increasing fractions of the conductor must be occupied by the superconductor; (c) any portion of the winding at diameters greater than 40 cm must drop the limiting current density to 7.5×10^3 A/cm^2, again for considerations of protection; and (d) any new materials will have the same cost per ampere-meter as Nb_3Sn, and like Nb_3Sn will require greater thickness of material, thus greater cost, as the field goes up and the current-carrying capacity drops. These limiting assumptions are illustrated in Figure 2, together with the appropriate field ranges for the developed and anticipated materials.

The cost curve up to 30 T resulting from these assumptions appears in Figure 3. The cost of a 30-T magnet is clearly very high; in fact, it compares unfavorably with the cost of alternative generation techniques such as hybrid systems (discussed in the section that follows). Figure 3, for fields above 20 T, further assumes the commercial development of materials that exist now only as small samples. Unfortunately, there is reason to expect that this commercialization will not happen, because there is no market of sufficient scale to warrant the expensive development. Niobium–titanium and niobium–tin have been developed in response to markets in the fields of high energy, fusion, and rotating machines. Research magnets, no matter how ambitious, would not compare with the scale of these applications.

If we accept the basic assumptions that went into Figure 2, it appears that continuous-field generation beyond 20 T would turn to other than superconducting systems, for example, resistive or resistive–superconducting hybrid systems. If fields must have special characteristics, such as high resolution or extraordinary spatial homogeneity, the superconducting approach might be carried further in spite of the unfavorable cost comparison.

It is vital to consider also what might happen if the assumption underlying Figure 2 does not hold. The most far-reaching effect would be a future violation of the constant $B \times j$ principle. This constancy is based on defect-type flux-pinning, hence more on experimental than fundamental arguments. Considerable effort has gone into maximizing current-carrying capacity in NbTi, Nb_3Sn, and V_3Ga. The prospect that fundamentally different pinning mechanisms will be discovered that will apply to the higher-field materials cannot be ruled out, but the probability does not seem high. We also note that the allowable overall current density in the magnets would not be altered by such a new mechanism. Overall current density is determined more by stability and protection considerations; however, the amount of superconductor required per unit coil cross section would diminish, and that would be expected to have an impact on the wire cost.

Resistive and Hybrid Magnets—Present Status

Until the economic arguments in the previous section change, continuous fields much above 20 T will continue to be generated by resistive water-cooled magnets or resistive inserts boosted by external superconducting coils. These boosted, or hybrid, systems are a good combination, because they place the resistive elements on the inside where the field is high and the power requirements lowest, and the superconductor on the outside where the field is low enough but the power requirements highest. The current state of the art for resistive and hybrid systems is given in Table 3.

TABLE 3 State of the Art of Resistive and Hybrid Magnets

Field (T)	Bore (cm)	Power (MW)	Type
30	3.2	10	Hybrid
25	3.2	5	Hybrid
20	3.2	2.5	Hybrid
23.5	3.2	10	Resistive
19.5	5.4	10	Resistive
18.5	3.2	5	Resistive
16	5.4	5	Resistive

Table 3 indicates that resistive magnets with power supplies of at least 5.0-MW capacity and hybrid magnets of at least 2.5-MW capacity can produce field magnitudes higher than the 20-T level that is available relatively economically from superconducting magnets. However, there are certain advantages to resistive magnets, even below 20 T, largely as a result of sweep speed.

In central facilities where there are power supplies, the hybrid can be readily applied to boost any field level limited by the available power. It can also be used to allow multiple experiments by reducing the power necessary for a given field, thus releasing power for parallel operations. A hybrid magnet to generate 30 T with 10-MW power requires an investment of approximately $300,000 for a 7.5-T boost superconducting coil and another $200,000 for installation and suitable closed-cycle refrigeration system.

If 30 T were desired and no facilities existed, one would have to examine the total capital cost, which would depend on the field generated by the superconductor and the amount generated by the power supply. If 8 T were chosen for the superconductor, representing a modest technological undertaking, 10 MW of power would be required, which would call for an investment of approximately $5 million for power supplies and $0.5 million for the superconducting system. If one chose 12 T for the superconductor, a reasonable step forward, the superconducting system cost would increase to approximately $1.7 million, but the power requirement would drop to $3.3 million. The total cost for the latter systems would thus be about 10 percent lower.

A central power supply can be time-shared with a number of magnets in a cost-effective way. Water-cooled magnets are inexpensive; a 5-MW, 18.5-T repeat magnet costs about $20,000 to construct. A larger central facility such as the National Magnet Laboratory has 24 high-field magnets time-sharing a central 10-MW power supply that can be subdivided into four 2.5 units. Two hybrid systems will extend the maximum field to 30 T and allow two 25-T magnets to run simultaneously.

Resistive and Hybrid Magnets—Future Possibilities

An ambitious near-term goal for hybrid systems might be to extend an NMR environment beyond what can be reached with superconductors. For example, a field of 25 T in a 10-cm-bore hybrid magnet could be generated with 4.0 MW of power and a 15-T superconducting boost coil. The field could be stabilized by series regulation and field feedback stabilizer coils, with a final stage of passive stabilization by means of a thin superconducting shield made from a high-critical-field material.

A longer-term quite ambitious goal would be a 75-T hybrid magnet. The equivalent magnetic pressure at 75 T is 22,000 atm. We must remember, however, that magnetic stress is not a fundamental limit for solenoids. If a magnet is divided into independent nested solenoidal elements, the stress can be limited to an arbitrary level by controlling the field generated by each subelement. The inner elements are more efficient, of course, and the less field they can generate, the more must be generated in elements further out. Nevertheless, fields of arbitrary level could be generated. The limit then is not fundamental but practical. Does the magnet grow too power-consuming, or does it become impossibly large and expensive?

The present highest continuous field, of 30 T, could be extended to much higher fields if the necessary, very large power supplies were available. Using heat-transfer rates and copper alloys reinforced with interleafed steel sheets, both of which are used in the 30-T hybrid magnet, one can extrapolate power requirements to a field level of 75 T. Figure 4 shows such an extrapolation, with the amount of reinforcing progressively increased as the field increases. Were such a coil, having an outer diameter of 1 m, operated without an external superconducting booster section, it would require 165 MW continuously to generate 75 T. Even with an ambitious 20-T superconducting booster coil, 89 MW would still be required.

Higher-field outer superconducting sections will further reduce the power supply required but will also be very expensive. As with the pure superconducting coils discussed in the previous section, a fundamental change in the empirical rule that $B \times j =$ constant must occur to allow substantial cost reduction.

Although such a 75-T system is technically feasible, its cost clearly would be high. A 100-MW supply of adequate stability would cost about $50 million. A 20-T booster coil of 1-m inner diameter is estimated at an additional $25 million at a minimum. Power costs for a 100-MW supply would be $5000/h at $0.05/kWh.

The largest continuous dc supply suitable for research magnets now in existence is 50 MW (Princeton Plasma Physics Laboratory) and is used for nuclear fusion machines. The National Magnet Laboratory (NML) and Gre-

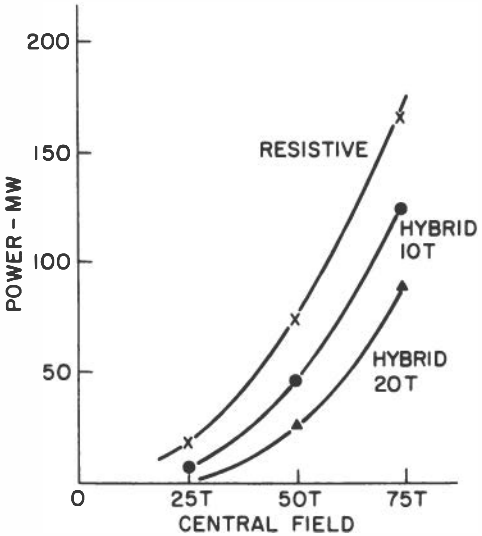

FIGURE 4 **Power-supply requirements for 3-cm bore resistive and hybrid magnets. The two hybrid curves are for 10-T and 20-T booster fields, respectively.**

noble each have 10-MW supplies, the largest devoted to high-field research applications.

We can expect progress in the intermediate range between the 30 T now possible and 75 T, which is feasible but certainly a long-range goal. Moving from 30 to 35 T is feasible by simply increasing the present 30-T hybrid booster field from 7.5 to 12.5 T. An investment of approximately $1.5 million would be required. If one were able to use the Princeton 50-MW supply for a research magnet, it is possible that a field of 50 T could be achieved for an investment of approximately $5 million in a 10-T booster superconducting coil to surround a 40-T, 50-MW water-cooled insert.

QUASI-STATIC PULSE SYSTEMS

Present Status

Although continuous fields are necessary for many experiments and always desirable, certain experiments can be conducted in shorter times. Pulse times on the order of 1 sec could represent an approach for experiments that benefit from continuous fields. These long pulses can be powered by various techniques. In the University of Amsterdam facility, a 6-MW controlled rectifier supply switches directly onto the mains. A field of 40 T can be produced for 0.1 sec in a 2-cm bore. Similar parameters have been obtained at the NML by silicon-controlled-rectifier switching of the fully excited rotating dc generator output. At Toulouse, a third approach uses a 1.25-MJ capacitor bank and a crowbar circuit to produce a 0.1-sec rise and a 1-sec fall to a peak of 40 T in a 2.5-cm bore.

These coils operate adiabatically and generally use precooling with liquid nitrogen or, in Amsterdam, with liquid neon, to limit the temperature rise. Recool times of present devices are on the order of 1 h, but increased attention to obtaining high repetition rates could reduce this to the 5-min range. Because the pulse rate is limited, particular attention must be given to multiple-channel data collection and sophisticated diagnostics, which are an important part of any limited-time-scale facility and can dominate the cost of experimental equipment. To achieve repeatable pulses will be vitally important if such pulse fields are to be used for NMR and other high-resolution experiments.

Future Possibilities

Quasi-static pulse facilities could represent the best chance to extend present experiments well above 30 T during the next decade. This possibility is greatly enhanced because of the increasing use of large pulse supplies for fusion experiments. The NML, for example, is installing a 200-MW, 200-MJ pulse supply for the Alcator fusion experiment. It is of interest to examine what such a supply can offer for quasi-static pulse experiments in small volumes.

Precooled magnets that depend on thermal inertia are limited by the product of magnet current density squared times the pulse time ($j^2\tau$). The larger the scale of the magnet for a given field, the lower the resultant current density; hence, the longer the pulse can be without overheating. The larger the scale, the larger the energy source must be, but the longer the pulse can be held. This relationship is illustrated in Figure 5, which shows two scales, magnet weights of 500 and 4000 kg, and gives the field achievable at various pulse times, subject to a given temperature limit. The scale curves also represent constant-energy requirements. We note that 50 T can be generated for 1 sec if a coil has a mass of 4000 kg and if a 200-MJ energy source is available. A peak power of 200 MW would be required. The curve also indicates that 75 T could be held for 0.5 sec with the same temperature rise, but a 400-MW peak power supply would be required.

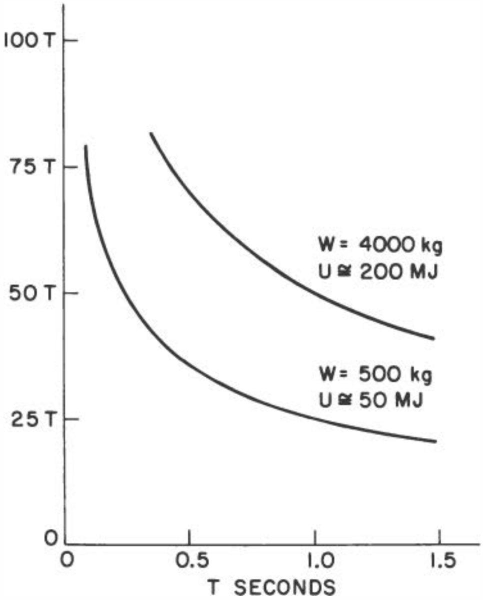

FIGURE 5 Field versus pulse time for 5-cm bore LN_2-cooled long-pulse coils. The two curves are for constant magnet weights and stored energies. The peak resistive powers required can be estimated by dividing the stored energy by the pulse time.

We note also that the resistive continuous-field coils in Figure 3 could be driven on a pulse basis. The magnets are more complex than the LN_2 precooled coils and require large coolant pumps, but fields can be held for times determined by the energy storage of the supply rather than by the heat capacity of the coils.

The cost of the long-pulse magnets is relatively low. A 50-T, 1-sec magnet would cost about $100,000. A large pulse supply involving a rotating alternator capable of delivering 200 MJ at a 200-MW peak power level would cost approximately $10 million.

The long-pulse magnets, particularly using present fusion program power supplies, represent the least expensive entry into the field range between 30 and 75 T. Realization of these ambitious pulse coils will represent a major magnet design challenge for the next few years. This program could speed the attainment of continuous fields in this range by stimulating technological exploration and providing significant new opportunities for physics research.

SHORT-PULSE SYSTEMS: FIELD GREATER THAN 100 T

Nondestructive Coil Approaches–State of the Art

For the foreseeable future, fields greater than 100 T must be produced on a pulsed basis. Thus, in addition to the usual specifications such as volume and field homogeneity, other factors must be considered, for example, the time variation of the field, the number of times the magnet can be used before destruction, and the survival of test samples and diagnostic equipment. All of these factors usually worsen as the field magnitudes increase.

Pulse fields obtained from capacitor discharges have been the principal method of generating fields beyond those available from continuous fields. A small bank of 10 kJ can generate fields of the order of 75 T for a 50-μsec half period in a 5-mm bore and have been used since the early 1950's. A more ambitious bank of 100 kJ can typically be used to generate 65 T in a 2-cm bore for a 650-μsec half period.

These systems are seldom operated as facilities but are usually considered part of a particular experiment. This need not be the case if personnel and dedicated instrumentation are made available to operate as a facility.

Nondestructive Coil Approaches–Future Possibilities

The future goal of nondestructive short-pulse coils appears to be 100–200 T.

M. Date, of Osaka University, obtained several shots with peak fields greater than 100 T (pulse width 175 μsec) before destroying a specially designed, force-reduced coil at 107 T. Based on these encouraging results, he has received funds from the Japanese Ministry of Education to build a 1.5-MJ, 30-kV capacitor bank that should be capable of generating magnetic fields of 150-T peak (1-msec pulse width) over a 6-mm id × 10-mm long volume. If one assumes a sinusoidal waveform, the magnetic fields should exceed 90 percent of the peak for nearly 300 μsec. Experimental samples and diagnostic equipment normally would not be destroyed in such an arrangement.

Although it is not likely that coils of this type could have an indefinite lifetime, they probably can be designed ultimately to withstand many shots, particularly at the somewhat lower field of 120 T. We note that Date's proposed capacitor bank is roughly equivalent to half the Los Alamos Scyllac bank fired at half voltage. It is possible that with continued coil development, use of the full Scyllac bank would generate long pulsed fields appreciably above 150 T over larger volumes.

In principle, one can extend the nondestructive concept to arbitrarily high fields by following the multiple-section-coil approach. The principle is simply to generate only as much field with a given section as the strength of that section can support, and to generate the balance of the field with successive

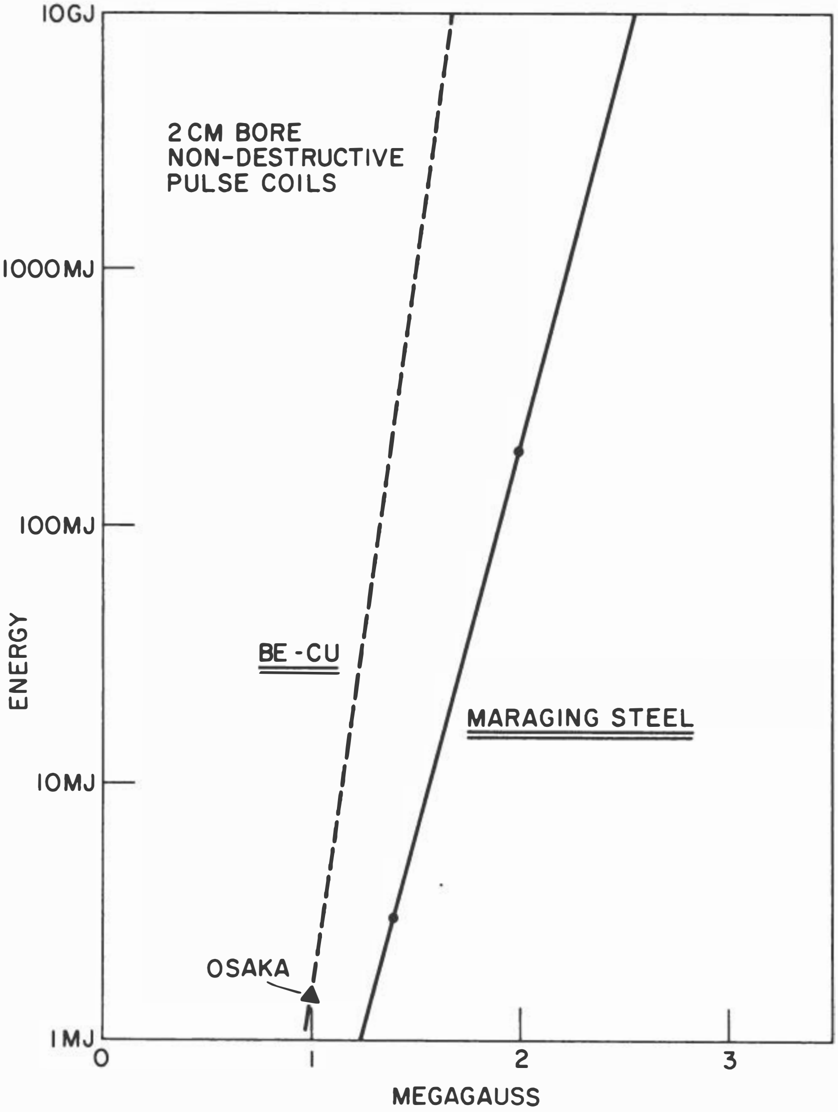

FIGURE 6 Energy requirements for multishell nondestructive pulse coils. The Osaka magnet project is indicated.

shells. The higher the field, the less can be generated by the inner elements where the field is high, and the more must be generated in shells farther out, but at the cost of rapidly increased energy demands. Figure 6 extends the three-shell approach used in Osaka to more shells. Using the strongest ductile material available, we note that more than 100 MJ are required to exceed 200 T.

Fast capacitor banks cost some $500,000 to $1 million per MJ. The largest high-speed capacitor bank ever built is the 10-MJ 60-kV bank at Los Alamos, for the Scyllac fusion experiment. The banks for the large laser experiments are comparable.

Destructive Coil Approaches—State of the Art

Currently there are several ways to produce 120–300 T fields over short times, all of which result in coil destruction. The simplest systems involve capacitive discharge either directly into a single turn coil, an imploding wire or shell, or a transformer coupled to a liner that implodes, compressing flux into a smaller volume. Calculations suggest that single-turn coils should be capable of fields approaching 800 T, but to date fields have been limited to 300 T. Typical pulse times near the peak field are about 1 μsec. The imploding transformer coupled foils (Cnare effect) have also been used to produce fields in the 300-T region.

To date, with the exception of explosive systems whose volumes can be 10–30 cm^3, the volumes are small, ranging from about 1 cm^3 to a few hundredths of a cm^3 at the higher fields. The duration times of the fields, more than 90 percent of peak, are usually short, ranging from a few tenths of a microsecond for some fields produced by electromagnetic implosion to a microsecond or so for fields produced by direct capacitor bank discharge into a coil. Again, these times are at present much larger for explosively produced fields.

Some of these observations, however, can be misleading, because the time duration of the fields is usually larger when the coil radii are larger, and in implosions, when the liners are thicker. As larger capacitor banks become available, both final field radii and liner thicknesses can be increased, thus increases in volumes and pulse duration times can be expected.

Generally speaking, samples and diagnostic equipment have a good chance of surviving in direct-driven-coil arrangements; samples and some equipment are normally lost in explosive or electromagnetic implosion-produced fields.

Research should be encouraged with all systems, for each has specific advantages and the possibility of improvement. Many people believe that it will be difficult to greatly exceed 300 T without using flux compression techniques, at least in reasonable volumes and useful time scales. It is perhaps not unreasonable to anticipate useful laboratory-produced fields of more than 500 T with electromagnetic implosion techniques.

Imploding foils or wires can be used to produce direct pressure by collapsing on the sample. Foils have produced pressures of about 150 kbar, and imploding wires, 300 kbar. The wire experiments represent the least energy, and, although the samples packed into the interior of the wire clearly are fragmented by the implosion, such experiments can safely be carried out in a small laboratory. They rely upon the well-known Z-pinch effect for compression, with corresponding azimuthal magnetic fields. Examples will be mentioned later where much higher azimuthal fields might be generated.

Axial fields greater than about 300 T have only been produced so far by explosively driven cylindrical flux compression systems. The highest fields reported (and confirmed by other investigations) are in the range of 1000-1500 T, diameters of 5-6 mm, and lengths 20-50 mm (estimated). For a fixed explosive-liner system, a lower initial magnetic field (seed field) generally results in a higher final field but at a smaller radius. The fields are limited to levels that develop sufficient pressures to stop the incoming liners (modified somewhat by diffusion processes). The duration times for fields greater than 90 percent of peak are usually less than a microsecond, depending on the system geometry and the peak field developed.

The maximum pressure available from chemical explosives, together with explosion symmetry available, has so far limited fields produced by this method to about 1500 T. Use of nuclear explosives allows higher fields, and 4000 T may have been achieved in the Soviet Union. Experiments with conventional explosives are often carried out in remote sites, but modest-scale experiments can be performed, as they often are in the Soviet Union, in laboratory confinement vessels. Small experiments generally involve less than 50 MJ of explosive energy.

Some exploratory work has been done on localized azimuthal megagauss field generation by other techniques. It should be remarked here, however, that the magnetic fields are not uniform but instead vary inversely with distance from the current source. Use of these fields for high-field experimentation will therefore be very difficult but perhaps feasible for some situations. In one case a very fast capacitor bank of the type used with high-power pulse generators was used to explode a fine wire. From the known current and current channel x-ray measurements, calculations indicate that fields in the 500-T range were generated for periods of 50 nsec.

In related experiments, current has been passed through a thin (5000 Å) aluminum shell, causing it to vaporize and implode and the resultant plasma to constrict. Calculations indicate that fields of 1000 to 2000 T should be achievable by this technique.

Highly localized high fields are apparently found in certain intense plasma discharges. Laser-driven pellet implosions are accompanied by a filamentary current structure that produces local 100-T fields. The same filamentary structure in plasma-focus experiments gives rise to intense local fields, with speculation suggesting fields in the 10,000-T range.

Destructive Coil Approaches—Future Possibilities

Established high-field researchers believe that fields considerably above the 1000-T level are possible with experiments of sufficient scale. Some combinations of explosive-driven, transformer-coupled foils and compressing fields produced by large superconducting coils outside the blast shield might produce fields in the 5000-T region.

High-field flux compression calculations are uncertain, as they involve not only sophisticated MHD plasma stability considerations but also require equations of state and conductivity information that is poorly known at the extreme conditions encountered.

Some preliminary calculations have been made recently with the same computer simulation that predicted earlier 1000–1500 T shot results. Peak field values near 4000 T, diameters of 4–5 mm, and duration time for fields greater than 90 percent of peak of 0.2–0.25 μsec were calculated. Further calculations can probably project even more favorable results. These results must be treated with great caution, however, in view of the uncertainties mentioned previously. The importance of producing such fields merits further calculations, complemented by a number of actual experiments.

The typical scale of a few millimeters can be increased if there is sufficient justification. Calculations for a 50-cm-diameter liner driven by hundreds of kilograms of TNT lead to fields in the 2000- to 3000-T range in final diameters of 20 mm. Single experiments would cost many thousands of dollars at this scale.

Electromagnetically driven experiments, such as the axial current flow in a thin foil, driven by the large pulse generators built for E-M simulation, could be a promising direction. These very large units are found in several laboratories.

Certain types of spectroscopy might possibly be carried out in the intense plasma discharges: although the environment is highly localized and virtually uncontrolled and nonrepeatable, it might be used if one could develop a local trustworthy spectroscopic probe.

Experiments using the ultrahigh fields universally list experimental techniques as being as difficult as the generation of the fields. Field changes of 10^9 T/sec induce voltages of 10 kV in a probe of only 10 mm^2, and ablation of surfaces from strong heating creates a damaging plasma environment. Experiments with spectroscopy, or perhaps chemical reactions, are undoubtedly better suited for ultrahigh fields than more traditional solid-state experiments. Such experiments do not involve expensive carefully prepared samples, nor are they troubled by sample thermal problems.

6

High-Magnetic-Field Facilities and Users

INTRODUCTION

To provide perspective on the current status and possible future developments of high-magnetic-field facilities in the United States, it is useful to recall briefly some history.

Because the saturation field of iron is 2 T, the first proposals for and achievement of fields above 3 T, as early as 1914, made use of iron-free high-power solenoids. Major advances occurred in the 1930's in the United States, with Giauque's work on kerosene-cooled solenoids at the University of California at Berkeley and Bitter's work on water-cooled solenoids at MIT. Bitter's basic design for high-field solenoid magnets has survived, and modifications of this design are used in most high-magnetic-field facilities today.

Magnets of this and related designs are relatively inexpensive (≃ $20,000 for a typical magnet); thus, the main capital cost of a facility is the power supply and cooling system. These features are responsible for the typical configuration of most of the high-field facilities in the world; namely, a number of solenoid magnet stations that can be connected on a time-shared basis to a single (or multiple) large power supply (supplies), providing a considerable flexibility in bore sizes, configurations, and the like.

Recent rapid advances in high-field superconducting magnet technology have led to a substantial number of superconducting magnet systems producing fields greater than 12 T distributed throughout the world. These systems have provided certain additional capabilities not available with resistive magnets; however, very few of them are actually operated as true facilities.

The highest steady fields (25–30 T) are being, or soon will be, produced by hybrid resistive–superconducting magnet systems, located necessarily at facilities with large power supplies for running the resistive magnets. For fields above 30 T, some type of transient operation, quasi-static or short-pulse, is required at present. There are very few such systems in the world, particularly those producing fields of the order of 100 T or more, that are currently used for research.

CONCLUSIONS

The United States still leads the world in the number of large resistive magnet facilities, maximum field capability, number of magnet stations, and use of these facilities; but the development of facilities and their use in Europe have been increasing rapidly in the past few years. Recently, the increased demand for magnet time in both the United States and Europe has been for the highest available fields. A vigorous effort and substantial additional investment in capital equipment will be required if the United States is to meet the needs in this field. Therefore, we conclude that additional capital equipment funds are required to accelerate the development of facility hybrid magnets and to extend the highest steady-state fields. Additional facilities should also be upgraded and expanded, as suggested in the section on Auxiliary Equipment and Facilities.

The related questions of geographic distribution of present facilities and users and of establishment of small regional facilities have been considered. Currently, most large steady-field facilities are located in the northeast corner of the United States. Because of travel costs and experimental logistics, most users come also from the region where these facilities are found. A wider geographical distribution of users might be achieved through special travel funds allocated to facilities specifically for long-distance, shorter-term research projects. A complete resolution of these problems is outside the scope of this study, which is based on the view of only a small part of the concerned scientific community; however, the fact that the scientific opportunities, discussed in Chapter 3, appear to be greatest in fields above 15 T, coupled with the capitalization and operational costs, argues against the establishment of small regional facilities at present. Therefore, we conclude that small regional magnet facilities, with fields up to 15 T, should not be established at this time. No new individual high-field superconducting magnets should continue to receive support where the capital expense cannot be justified scientifically; such magnets are not facilities and cannot be justified on that basis.

Although several installations in the United States produce peak pulse fields in excess of 100 T, there are currently *no facilities* in the United States dedicated to the use of such fields for general research purposes. The technology and expertise for producing short fields in excess of 300 T and quasistatic fields up to about 100 T are available now. Transient fields are the cheapest and quickest way to achieve very high magnetic fields and the *only* way to achieve the highest fields of interest to researchers (~ 2500 T). In spite of the more limited range of experiments amenable to the transient-field approach and the difficulties in obtaining data, a number of workers have shown that practical experiments can be carried out. Therefore, we conclude that the establishment of a transient magnetic-field facility, or facilities, is required to meet the needs of research and technology for magnet fields in excess of 100 T.

In determining the creation of the above-mentioned facilities, three factors, in addition to capital cost, should receive consideration:

1. The quality and breadth of the scientific staff of the institution;
2. The geographic location, taking into account the current geographic imbalance in distribution of facilities and users;
3. The degree to which additional funding can be used to build on present technology.

Further, any such facility should receive strong additional support for the development of sophisticated measurement techniques and additional equipment and facilities. The possibility of associating a small steady-field facility with the transient-field facility to concentrate effort and make the entire operation more cost effective should be considered. Therefore, we further conclude that facilities should be funded sufficiently that necessary support measurement equipment (e.g., optical spectrometers, ESR and NMR spectrometers) be in place.

CURRENT STATUS OF HIGH-MAGNETIC-FIELD FACILITIES

Steady-State Field Facilities—Resistive Magnet Systems

As we have mentioned, most of the high-magnetic-field facilities currently in operation in the world employ resistive magnets, and most of these are of the Bitter type and are water cooled. (The characteristics of the known resistive magnet facilities are summarized in Tables 4 and 5.) Other designs are employed only in isolated instances; for example, the University of California at Berkeley in the United States and Oxford and Grenoble in Europe.

Of the U.S. facilities described in Table 4, the Francis Bitter National Magnet Laboratory (NML) is the only one that serves the general scientific community. During the past two years, more than 120 different visitors made use of the high fields at NML for a variety of experiments. At the Naval Research Laboratory (NRL) facility, approximately 30 percent of the users

TABLE 4 U.S. High-Magnetic-Field Facilities—Resistive Magnets

Installation	Commissioning Date	Type	Number of Stations	Max. Field/Bore	Power Supply	Cost/Exp. Run
FBNML	1960	Bitter, hybrid[a]	22 (4 simultaneous)	23.5 T/1$\frac{1}{4}$ in.	10-MW 4–2.5 MW Motor Gen.	$1200/short shift (3$\frac{1}{4}$ h)
NRL	1948	Bitter S.C., hybrid[a]	6	18 T/1$\frac{1}{4}$ in.	6-MW rectifier 2-MW Motor Gen.[b]	$1500/5-h period
University of Pennsylvania	1968	Bitter	2	14 T/1 in.	4-MW Motor Gen.	$600/day[c]
University of California at Berkeley	1960	Giauque (kerosene coolant)	2	12.8 T/5 in.	8-MW Motor Gen.	—

[a] Under construction.
[b] Being phased out.
[c] Exclusive of personnel, maintenance, and supervisory costs.

TABLE 5 Foreign High-Magnetic-Field Facilities—Resistive Magnets

Country	Installation	Magnet Type	Power Supply	Max. Field/Bore
France	High Magnetic Field Laboratory Grenoble (German participation)	Bitter, polyhelix hybrid[a]	Motor Gen. 10 MW	20 T/5 cm
	C.E.A., Saclay	Bitter	4 MW	15 T/4.2 cm
United Kingdom	Clarendon Lab., Oxford	Tsai, polyhelix, S.C., hybrid	Motor Gen. 2 MW	16 T (Hybrid)/ 5.7 cm
Federal Republic of Germany	Hochfeld Lab. der Technishen Universität Braunschweig	Bitter	Rectifier 5.5 MW	15 T/5 cm (18 T/3 cm)[b]
Holland	High Magnetic Field Laboratory Nijmegen	Hybrid, Bitter	Rectifier 2.3 MW	25.4 T/5 cm
Poland	International Laboratory for Magnetic Fields and Low Temperature, Wroclaw	Bitter, hybrid[a]	5.5 MW	17 T/3 cm
Soviet Union	Lebedev Institute of the USSR Academy of Sciences, Moscow	Bitter	9 MW	18 T/5 cm
	Kurchatov Atomic Energy Institute, Moscow	Bitter, hybrid	6 MW	18 T/4 cm, 25 T/4 cm
Japan	High Magnetic Field Laboratory, Tokohu University, Sendai	Bitter	3.5 MW	12 T/5 cm

[a] Under construction.
[b] Planned.

are external to the laboratory but use considerably less than 30 percent of the magnet time. The University of Pennsylvania and University of California at Berkeley facilities are used only by their respective university faculty and students, except for occasional outside scientific collaborators.

Because the characteristics of the magnets and the necessary supporting equipment and staff are much the same, the general operation of most of these facilities is quite similar. Magnet "shifts" (typically 3¼ hours to 8 hours) are scheduled in advance; thus, users must set up experiments in advance and be prepared to run them during their shift. The estimated cost of a shift appears in Table 4. These numbers are rough approximations, but the estimates agree reasonably well (note that the University of Pennsylvania figure does not include personnel, maintenance, and supervisory costs, which receive separate support). The cost of electrical power constitutes a relatively small fraction of the total cost at present, with salaries and overhead of support personnel making up the largest fraction.

A wide range of experimental studies are conducted at these facilities, including investigations of solids, liquids, gases, and plasmas, making use of optical spectroscopy, electrical and thermal transport, magnetic, ultrasonic, and Mössbauer resonance techniques, magnetostriction, and numerous other procedures and techniques. Most experimental investigations can be classified as solid-state physics or materials science. Table 6 gives a detailed breakdown of the types of experiments carried out during the past two years at NML and NRL.

TABLE 6 Percentage of Magnet Use by Type of Experiment[a]

Type of Experiment	FBNML[b]	NRL[c]
Superconductivity	32	22
Optics and spectroscopy	25	20
Magnetism	14	18
Transport (electronic and thermal)	11	20
Plasma physics	10	5
Miscellaneous (include resonance, Mössbauer, liquid crystals, ultrasonics, biology)	8	15
TOTAL	100	100

[a] Percentage of generator hours.
[b] Past 6 quarters.
[c] Past 2 years.

Each of these installations provides additional facilities and equipment support to users. These generally include cryogenic fluids (at cost to the user), magnet monitor voltages, magnetic-field modulation, vacuum pumping, general-purpose electronic equipment (recorders, lock-ins, simple data-acquisition systems, etc.), and simple Dewars suitable for the different magnet bores. Particularly at NML, and somewhat less at NRL, a substantial amount of specialized experimental equipment, such as spectrometers, lasers, and magnetometers, is also available, generally through arrangements with the scientific staff. This finding points to the essential role of the in-house scientific and engineering staff at the large facilities in developing specialized instrumentation and state-of-the-art research capabilities for high magnetic fields.

The use of these facilities varies considerably. At the NML, use has been increasing recently; at present, the demand for magnet time consistently exceeds the available time, even with short shifts. The major increase has been in the highest-field (four-generator) magnets. At NRL, use has remained relatively constant for the past several years, averaging about 75 percent of the available experimental shifts. Use is less at the University of Pennsylvania facility, averaging about 40 percent.

It is useful to compare the current situation in the United States with that in the rest of the world. Table 5 summarizes the characteristics of foreign magnet facilities. Recent developments in Europe are particularly interesting. Although the Clarendon Laboratory has had a resistive magnet facility for more than 30 years, the rest of the facilities are recent; for example, the joint French–German facility in Grenoble, the Braunschweig facility, and the Nijmegen facility have all been commissioned since 1971. (The Nijmegen hybrid magnet was built and tested at the NML.) In contrast, all U.S. facilities were commissioned prior to 1968.

The joint French–German high-magnetic-field laboratory in Grenoble is the largest of the foreign facilities. We will describe it in some detail, for it provides a basis for comparison with the U.S. situation and illustrates the European commitment to high-field research. The Grenoble High Magnetic Field Laboratory was commissioned in 1972 and currently operates at a maximum power of 10 MW (two 5-MW generators), with six separate magnet stations. Two of these stations are capable of maximum fields of 20 T in a 5-cm bore, with two concentric Bitter magnets. The use of this facility has increased dramatically since its opening, from total magnet hours of 403 in 1972 to 4972 in 1977. Recent increases have been greatest in the 20-T magnets (each of which requires full power), placing even heavier demands on the facility. Forty to fifty outside visitors have used the magnets during the past year, in addition to the substantial German and French in-house scientific and technical staff. A wide variety of research programs has been carried out at Grenoble; again the majority of these studies have been solid-state physics or materials science. Substantial additional facilities similar to those at the large U.S. installations but including high pressures and very low temperatures (dilution refrigerators under construction) are (or will be) provided to visitors.

Steady-Field Facilities—Superconducting Magnet Systems

Compared with that of resistive magnets, high-field superconducting magnet technology is relatively immature and has improved markedly in the past ten years. Many of the discussions concerning the relative merits of resistive versus superconducting magnets are based on older versions of the latter; however, magnets produced in the past several years offer greatly improved operating characteristics. Problems such as nonlinear behavior, degradation of field homogeneity with time, the need for retraining after thermal cycling, severe limitations on maximum sweep rates, and inability to modulate have been alleviated and, in some cases, completely eliminated. In view of this progress, we restrict our consideration to those facilities employing *modern* superconducting magnets and those capable of fields greater than 12 T (Nb_3Sn or Nb_3Sn plus V_3Ga conductors). Magnetic fields only slightly lower than this can be achieved reliably and inexpensively with Nb–Ti multifilament wire magnets, and facility-type operation is not an economic necessity for most workers.

Table 7 shows the characteristics of the known modern superconducting magnet systems capable of fields of 14 T that are currently in operation throughout the world. [These magnets were all constructed by Intermagnetics General Corporation (IGC).] There are a considerably larger number of magnets with maximum fields in the range 12–14 T; but we will concentrate on the highest field solenoids (Table 7) to facilitate the direct comparison with resistive magnet facilities. The acquisition cost of these systems varied from less than $50,000 to well over $500,000 (the Japanese NRIM magnet system).

A letter of inquiry was sent to all U.S. locations, and many of the foreign installations were also contacted requesting information about the operation of these magnets. Much of the discussion presented below is based on the responses to these inquiries.

The magnets that seemed best (and most) utilized were those that were either (a) designed for a rather specific purpose, for example, split coil for optical experiments, and used fairly extensively by one or two groups for that type of experiment or (b) purchased as a general-purpose magnet that was part of a larger facility consisting of *several* lower-field superconducting magnets. Examples of the latter type are the Oxford magnet, which is a mobile

TABLE 7 Worldwide High-Field Superconducting Magnet Systems (> 14 T)

Country	Location	Max. Field/Bore	Special Features
United States	Indiana University	14.5 T/5.5 cm	–
	Sandia Laboratory, Albuquerque	14.3 T/3.2 cm	–
	University of Colorado	13.7 (4.2K) 15.2 (1.7K)/3.2 cm	Split coil
	Purdue University	14.3 T/5.5 cm	Split coil
	University of California at Santa Barbara	14.6 T/3.2 cm	–
	NASA–Lewis, Cleveland	14.6 T/6.4 cm	High homogeneity
	Oak Ridge National Laboratory	14.6 T/6.4 cm	–
	NRL	15.1 T/6.4 cm (room temperature bore)	High homogeneity; room-temperature access
	Carnegie-Mellon University, Pittsburgh	14.0 T/9.5 cm	Very high homogeneity; NMR

Japan	Tokyo University Vac. Metallurgical Co., Ltd., Tokyo	15.4 T/3.2 cm 14.4 T/2.6 cm	
	Japanese National Research Institute for Metal, Tsukuba	17.5 T/3 cm	Duplex magnet; Nb_3Sn outer; V_3Ga inner. Current world's record holder
	Kyushu University	14.4 T/3.2 cm	–
Soviet Union	Lebedev Physical Institute, Moscow	16.5 T/4 cm	High homogeneity
	Electronics Institute, Moscow	15.5 T/5.5 cm	–
Federal Republic of Germany	University of Würzburg	14.6 T/3.2 cm	Fast sweep reversible
United Kingdom	Clarendon Laboratory, Oxford	15.8 T (4.2K) 16.5 T (3.0K)/2.6 cm	Fast sweep
Brazil	University of São Paulo	15.1 T/5.5 cm	–
Poland	International Laboratory of High Magnetic Fields and Low Temperature, Wroclaw	15.5 T/3.2 cm	–

facility, literally "on wheels"; the Würzburg magnet, where there are seven other lower-field magnets devoted to specific experiments; and the São Paulo magnet, which is also one of several superconducting magnets.

The highest field superconducting magnet in the world (the Japanese NRIM magnet) has not been extensively used because of the general inconvenience (~ 2-h sweep to full field) and high cost of operation. During the past year only about ten shifts were utilized.

The only U.S. magnet system that seems to have been purchased with the intent of making it a true facility magnet is at NRL. This system employed a "foot-type" room-temperature access Dewar; it is intended to keep this system cold for several months at a time, initially with batch filling but soon with a closed-cycle refrigerator to reduce operating costs. All other respondents to the inquiry from the United States indicated that only batch filling was being used. The NRL magnet system is not yet fully operational; therefore, this type of facility operation cannot yet be assessed.

From the survey, we conclude that:

1. Few of these magnets are actually operated as facilities; typically only one or two groups use the magnet, and use is generally rather low.
2. In several cases, operating costs (generally cryogenic fluids) have dissuaded extensive use of the systems. Evaporation rate and cryogenic design are of concern to many.
3. Geographic location and resulting travel costs and specialized requirements (stability, high homogeneity, sensitive experimental equipment, etc.) were the principal reasons for purchasing the superconducting magnet rather than using a central facility.
4. Single superconducting magnets cannot do all things for all people. A single superconducting magnet is *not* a facility and is not cost effective in this context. However, individual high-field superconducting magnets can be exceedingly effective and useful when dedicated to specific experiments if the capital and operating costs can be justified.

Steady-State Facilities—Comparison of Resistive and Superconducting Magnet Facilities

The advantages and disadvantages of resistive and superconducting magnets are discussed in Chapter 5 of this report. Here we provide an *economic* comparison of the two types of *facilities* (a hypothetical facility in the case of the superconducting magnets, for a true facility does not exist at present), considering first the acquisition cost, then the operating cost of each type irrespective of their inherent advantages and disadvantages.

It is not valid simply to compare the acquisition and operating cost of a single high-field superconducting magnet with acquisition and operating costs of a large resistive magnet facility, or for that matter, to compare costs of running single comparable resistive (electricity costs) and superconducting (liquid helium and nitrogen costs) magnets. A more meaningful comparison would be total costs of similar *facilities* that could provide a comparable range of fields, bore sizes, and the like.

For the resistive magnets, we choose a modest facility similar to that at NRL, that is, a 6-MW rectifier power supply, six stations, and a mix of three bore sizes (1¼, 2½, and 4⅛ in.) with a maximum field of about 18 T. There are three full-time technicians and one full-time professional associated with the facility.

To provide a comparable (hypothetical) superconducting magnet facility, we take three separate magnet systems, one 1¼-in.-bore 17-T magnet and two larger-bore 15-T magnets, perhaps with special configurations for optical access, high homogeneity, room-temperature access, and the like. Additionally, we consider 1.5 full-time technicians and a half-time professional to be associated with cryogenic aspects, measurement technique development, scheduling, maintenance, and administration of the facility. The acquisition cost of the resistive magnet facility is estimated as follows: power supply, $600,000; cooling system, $500,000; magnet design and construction (six magnets plus three spares), $300,000; miscellaneous equipment, $200,000; total, $1.6 million.

For the "comparable" superconducting magnet facility, we estimate the following costs: magnets, one 16.5 T at $350,000 and two 15 T at $175,000, that is, $350,000; miscellaneous equipment (refrigerators, measurement equipment, etc.), $150,000; total, $850,000. Thus the capital costs of the resistive magnet facility are about a factor of 2 greater than for the superconducting facility.

Operating costs are estimated for the resistive magnet facility from the actual total costs of the NRL facility, including salaries and overhead, maintenance, and the like, for 75 percent use of the total number of available 5-h experimental periods of $1500/period.

The costs of the superconducting magnet facility are estimated as follows:

1. The total salary and overhead for two man-years, $130,000.
2. Batch filling, two experimental periods per day per magnet, typically two magnets running simultaneously, 12 cool-downs per year per magnet, helium and nitrogen costs of $3.25 per liter of liquid helium, and an average evaporation rate of 1.5 liters per hour; total cryogenic fluids cost, $91,000 per year.

Thus, with 780 experimental periods (of 5 h each) used, the cost is about $300 per period, significantly less expensive than the resistive facility.

In projecting this economic comparison into the future, one must take into account that both liquid helium costs and the cost of electrical power are expected to increase substantially during the next several years.

Steady-State Field Facilities–Hybrid Systems

The design of and rationale for hybrid magnets in extending the capabilities of resistive magnet facilities are discussed in Chapter 5.

There are at present operating hybrid magnets at the Kurchatov Institute (25 T), Nijmegen (25 T) (designed, built, and first operated at the NML), and the Clarendon Laboratory (16 T). Hybrids are under construction at the NML (30 T) (30 T has already been achieved with 10 MW and the Nijmegen magnet superconducting solenoid) and NRL (24 T), and one is planned at Grenoble (30 T).

The estimated cost of the 30-T magnet at NML is $500,000; the projected cost for the planned Grenoble magnet is 10 million French francs ($2.25 million at the current exchange rate). The large disparity in cost appears to result from the inclusion in the Grenoble estimated magnet costs, of personnel costs for the extensive design and development for *both* the superconducting outer solenoid and the polyhelix design resistive inner coil over about a 5-year period. At the NML, on the other hand, the development costs for both the resistive and superconducting solenoids have been largely written off in producing the Nijmegen hybrid, thus the costs represent only actual construction costs. In addition, the Grenoble system is to have a 5-cm bore, necessitating a 13-T, 50-cm-bore superconducting magnet; while the NML hybrid has a 3.2-cm bore and requires a correspondingly smaller superconducting magnet section (7.5 T, 40-cm bore).

Transient-Field Installations–Introduction

Well-developed, conventional high-field instrumentation can be used for field measurement, temperature measurement, and various types of experimental data acquisition in steady magnetic fields. In transient fields, on the other hand, particularly for the shorter time scales, measurement techniques are not so well developed; signal to noise is a much greater problem, and equilibrium conditions are not generally established. In addition, steady fields are easily used by inexperienced researchers, whereas the problems just cited for transient fields require a much more detailed knowledge of the technology and measurement techniques.

Transient Field Installations–Quasi-static Systems

Certain types of magnets are designed to be capable of functioning continuously at high power but receive their power from a limited energy source.

One magnet system of this type is installed at the Australian National University in Canberra; it is powered by a homopolar generator that stores 580 MJ. This system has provided fields of almost 30 T in the 5-cm bore of a polyhelix magnet for several seconds but is inactive at present. This field is not pulsed in the usual sense, for the heat capacity of the magnet cannot absorb the Joule heat, and cooling similar to that of steady-field resistive magnets is required.

Advances have been made in recent years in other types of quasi-static field generation. Fields up to about 40 T have been generated and maintained for large fractions of a second. At the University of Amsterdam, a liquid-neon-cooled solenoid produces constant 40-T fields (within 0.1 percent) for 80 msec, with a 6-MW rectifier supply. The coil starts at 30 K and heats to about 150 K after each pulse. Approximately 2 h are required for the magnet to cool again, leading to a duty cycle of about 10^{-5}.

In Toulouse, France, a different approach has been used to generate quasi-static fields. This system is described in Chapter 5. It has been used successfully as a facility, and a number of different visitors have used the field for experiments in solid-state physics, usually on a collaborative basis.

Quasi-static fields have been generated in the United States only at NML.

Transient-Field Installations–Short-Pulse Systems

Nondestructive pulsed fields obtained by capacitor discharge have long been used to produce fields between 30 T and 100 T for periods of milliseconds to microseconds in small volumes. These are generally rather inexpensive systems that require modest capacitor banks; therefore, they have not come into widespread use as facilities. The range of experiments in this region is even more restricted. Relaxation times must be short, and signal to noise must be inherently good, because integration times are necessarily very short.

For useful fields above 300 T, some type of flux compression scheme is necessary, either electromagnetic or explosive. Destruction of the coil and/or sample is a serious drawback to these approaches. However, in the past there has been significant effort devoted to production of ultrahigh magnetic fields by these techniques, and recently there has been renewed interest because of possible applications in controlled fusion research and compact, electrical power-source development. A "fallout" from these efforts is the development of techniques for field measurement, as well as signal-processing techniques; the latter have also benefited from short-pulse work in other fields, for example, short-pulse laser technology.

Ultrahigh magnetic fields are produced at a number of installations in the world. In the United States these efforts are concentrated around magnetic-field confinement in fusion research, and fields are not usually produced for general research purposes (see Table 8).

TABLE 8 Worldwide Transient Field Installations

Country	Installation	Present Status	Characteristics 1,d (mm) (Energy Source)	Peak Field/Duration
United States	Lawrence Livermore Lab.	Inactive	10 × 1 (1-MJ capacitor bank)	300 T/1–2 μsec
	Sandia	Inactive	10 × 5 (0.25-MJ capacitor bank)	200 T/< 1μsec
	Los Alamos	Active	100 × (25 to 10)	100–150 T/4–6 μsec
		Active	100 × (25 to 10)	175–250 T/3–4 μsec
		Inactive	20 × (5 to 7) (0.3-MJ capacitor and explosives)	1000–1500 T/<0.5 μsec
	FBNML	Active	20-mm bore (100-kJ capacitor bank)	50 T/10 msec or 60–70 T/0.7 msec
		Under development	20-mm bore (5-MW motor generator)	>30 T/<0.3 sec
	NRL	Inactive	∼70 mm × 10 mm (540-kJ capacitor bank)	140 T/6 μsec
		Under development	∼10-mm diameter (high-explosive high-pressure gas)	<50 T/(nondestructive)
Holland	Amsterdam	Active	2-cm bore (6-MW dc rectifier supply)	40 T/80 msec (flat)
Australia	Australian National University, Canberra	Inactive	5-cm bore (580-MJ homopolar generator)	30 T/several
Japan	Institute for Solid State Physics, University of Tokyo	Active	2.5-mm bore × 10 mm (2-MJ capacitor bank)	280 T/1 μsec
		Under development	0.8-mm bore (5-MJ capacitor bank)	70 T/10–100 msec 1000 T
France	Toulouse	Active	25-mm bore (1.25-MJ capacitor bank)	40 T/∼1 sec fall time

Destructive ultrahigh fields up to 280 T have been produced at the Institute for Solid State Physics, University of Tokyo, and used for research in semiconductors and magnetic materials, as well as for development of measurement techniques for very high (and destructive) magnetic fields.

Operations at facilities at Frascati (Italy), Grenoble (France), Tohoku University (Japan), and Illinois Institute of Technology have been suspended.

FACILITY PLANS AND POSSIBILITIES

Current Plans—Steady-State Fields

As far as we can determine, no plans exist at present for extending the maximum fields produced by resistive magnets beyond those now obtainable at NML. However, construction of hybrid systems is planned or already in progress at all of the large resistive magnet facilities in the world that do not have such systems. In one case, NML, operation at 30 T has already been demonstrated. Thus steady fields of 30 T should soon be available for users of NML in the United States and in several years at the High Magnetic Field Laboratory in Grenoble for European users.

A 20-T superconducting magnet is planned jointly by IGC and the University of Tokyo, but several years will be required to develop, construct, and test it before it can become operational. It will also probably be quite costly (see Chapter 5).

Current Plans—Transient Fields

A quasi-static field facility that will be capable of over 30 T for times up to 1 sec is being developed at NML. This system utilizes the present dc generators (2) with a bank of 20-kA SCR switches. A prototype has been demonstrated.

Currently, we know of no plans to develop short-pulsed field facilities for general research purposes in the United States.

In Japan at the Institute for Solid State Physics, University of Tokyo, there are plans to develop a quasi-static system (10 to 100 msec) capable of up to 70 T for metals studies. Additional plans include the development of a short-pulse system using a 5-MJ condenser bank in an effort to produce a maximum field of approximately 1000 T in a 0.8-mm-diameter space.

In Louvain, Belgium, the establishment of a short-pulse facility for fields in excess of 100 T for general research purposes has been planned for several years. Implementation has been hampered by lack of funds.

Future Possibilities—Steady-State Fields

It is clear (from Chapter 5) that the most efficient and cost-effective means of providing steady fields higher than those currently available on a facility basis will be through the use of hybrid magnets. These facilities can be developed most cost effectively at locations where resistive magnets and their power supplies already exist. In the near term, that is, from 2 to 5 years, 30 T will be available at the NML and, with a modest additional investment in a higher-field superconducting booster coil, this capability could be extended to 35 T with the present power supplies. In the longer term, from 10 to 20 years, a substantially larger investment could allow facility operation of a hybrid magnet up to 50 T (see Chapter 5); perhaps, with further technological development, the 75 T envisioned in Chapter 3 could be attained.

Future Possibilities—Transient Fields—Quasi-static Systems

The cheapest and quickest way to achieve fields in the range 50–100 T that could be provided to users on a facility basis is through the use of quasi-static systems. With present power supplies for fusion experiments, peak fields in the 50–75 T region, with durations of several tenths of a second, can be generated. One such power supply is being installed at the NML. Application of the principles determined from the development of the current quasi-static system should permit extension of the maximum fields to approximately 70 T with this generator.

Although there are a number of drawbacks of transient fields (even of this relatively long duration), they appear to be the most cost-effective means of providing high fields in this range for the majority of users, for the cost of the magnets is relatively low ($100,000 for a 50-T magnet) and somewhat smaller power supplies are required than for steady fields.

Future Possibilities—Transient Fields—Short-Pulse Systems

Future possibilities for extending the maximum field, duration, and volume of the various types of short-pulse magnets were discussed in detail in Chapter 5. The magnets are inexpensive, but they must be replaced frequently (after each shot for destructive operation). High-voltage, fast-capacitor banks can be constructed with an investment of about $1/Joule, or one of the large capacitor banks at, for example, Los Alamos or Lawrence Livermore Laboratory could be used. With the latter approach, further research and development could be undertaken with a relatively small additional investment. On the other hand, facility operation of magnets of this type presents a challenge. A somewhat restricted range of experiments can be performed; optical measurements or particle beam probes appear to be best suited for this type of field, for the probe (source) and spectrometer/detector can be completely external to the magnet. Thus, this type of facility should provide a wide range of intense EM radiation sources (particularly lasers) to span the spectrum between the microwave and ultraviolet, as well as fast detectors and spectrometers (rotating-mirror spectrometer cameras with image intensifiers). Other techniques that have proved successful are dynamical susceptibility and magnetoresistance; equipment of this type, as well as the sophisticated fast electronics, timing circuitry, and reliable field measurement techniques, would also be necessary. Therefore, a substantial investment ($1 million to $2 million) would be required for these necessary auxiliary facilities and techniques.

FACILITY UTILIZATION AND USER CONSIDERATIONS

Utilization

Many factors contribute to effectiveness and use of a high-magnetic-field facility. To a large degree this problem is circular, and this fact should be recognized. The utilization of facilities depends on physical location, maximum fields and configurations, additional facilities provided, dissemination of information about the facility, and the like. Yet, development of new facilities and increased capability for present ones depend on demand from the scientific community and/or recognized payoff in new scientific and technological opportunities.

Any sort of realistic projection of use is difficult because of the factors that we have just mentioned and could, in fact, become self-fulfilling. With this in mind, we do not attempt to offer a detailed projection of future use of high-magnetic-field facilities but only reiterate that use of the NML has shown dramatic increases recently (at present 100 percent) and that the large European facilities, such as Grenoble, also show a steady increase in demand for magnet time over the past few years.

Full utilization of the NML facility, as well as of the Grenoble facility, results in part from increased demand for the highest-field magnets that use the entire facility power, thus precluding simultaneous runs. Most of the increased scientific interest is in the *highest* available magnetic fields.

The discussion that follows is based largely on information about and experience with the large resistive magnet facilities (most of which relates to NML), with some input from superconducting magnet "facilities"; at present no similar data base for transient-field installations exists. However, some of the discussion is sufficiently general that it could apply to any type of high-field facility.

Geographic Location and Travel

Physical location and resulting necessary travel for many investigators are factors affecting use of high-magnetic-field facilities. The two major resistive magnet facilities (and three of the four such facilities) are located in the northeast part of the United States. It is useful to examine the geographic distribution of the outside visitors to the NML (including long-term visitors and some from abroad, though a small number of these visitors do not use the resistive magnets). Figure 7 shows graphically for a two-year period the percentage of outside visitors versus the distance of their home institutions from the NML. More than 37 percent of the visitors are located within 100 miles of the NML (mostly in the Boston area). It appears that travel is a limiting factor not only because of its cost but also because of the extra time and logistics required for an experiment. Travel cost and living expenses for a group including a senior investigator and several graduate students and coming from an institution located more than 100–200 miles away can be a significant limitation. Equipment of groups coming from greater distances generally is not transported back and forth but left at the installation on a semipermanent basis. For most standard research grants, the cost of one or two such trips can represent a fair fraction of the total travel budget if the high-

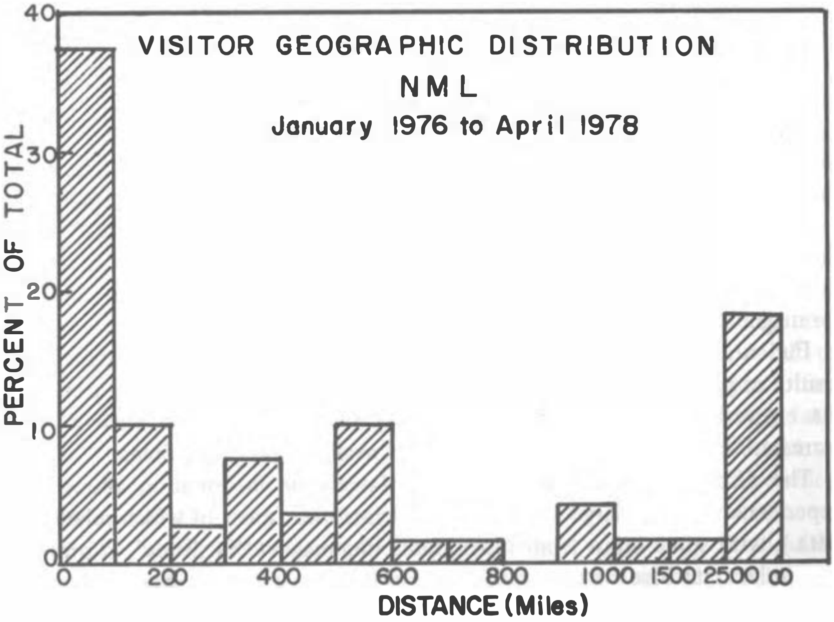

FIGURE 7 Visitor geographic distribution, January 1976 to April 1978.

magnetic-field experiments are only a part of a larger research program that is conducted predominantly at the investigator's home institution. If the experiments are planned far in advance, specific funding can be requested, but for shorter-term efforts, costs can be a real problem. Many investigators cannot afford to travel great distances, and, even if travel funds are available, the logistical problems are a strong deterrent. A few additional magnet facilities could not substantially alleviate the problems except for a small number of potential users who would be located from 100 to 200 miles from such a facility.

Application and Screening Procedures

Scientists who might be interested should be informed of the existence of high-magnetic-field facilities and of the details of fields provided and additional available facilities.

Potential users can learn about high-field facilities in several ways: from journals that publish work conducted at an institution or that feature news stories (for example, *Physics Today*); by informal interaction with those who have visited the facility; through personal contacts with members of the staff of the facility; and through descriptive brochures (both the NML and the NRL have recently sent a large number of brochures to members of the scientific community).

Screening of potential users of the NML is carried out in several steps. After an initial verbal screening comes a mandatory written application; the written application form is sent to about 75–80 percent of those who apply. The large majority of written applications are approved, with the result that about half of all those who have applied (verbally or in writing) to NML eventually carry out experiments with the high-field magnets. No attempt is made to assign priorities to the applications according to scientific merit. The feeling is that even if the scientific value of an experiment is doubtful, or the competence of the experimenter, or the need for the high fields, approval should still be granted as long as only a small amount of magnet time is involved. When a large amount of time has been requested, the application is approved for a modest number of shifts, with the work then being re-evaluated on the basis of the initial results. The feasibility of an experiment frequently is not in question, for many potential users have lower-field magnets at their own institutions and have already conducted the proposed experiments in those lower fields. A Users Committee has been established to resolve conflicts, oversee allocation of facility time, and consider facility improvements for users.

At the NRL, as the number of outside users is relatively small and magnet time is not fully used, no formal application and screening procedure has been established. Requests are generally made through staff members, and no additional screening is done.

Scheduling

Scheduling magnet time at a large facility can present problems, especially when time is oversubscribed as it is currently at the NML. Short shifts and careful scheduling (every two weeks) have provided a partial solution; however, a substantial queue still exists. In addition, although the time pressure and need for detailed planning might contribute to more efficient experiments in a given time period, there is less time to think and to assess intermediate results; this situation can result in some wasted effort and inefficient use of magnet time. Further, large blocks of time are quite difficult to obtain. Because part of the scheduling problem has been caused by increased demand for the highest fields, considerable relief would be provided by installation of hybrid magnets as part of the facility. For example, the same 10-MW power supply could be used to run one 30–35 T magnet, two (or perhaps three) 25-T magnets, or three (or four) 20-T magnets, provided the suitable superconducting outer sections were available.

The NRL uses a simple weekly scheduling procedure; requests for magnet time the following week are made at a weekly meeting. As the available time has not been fully utilized, there are generally few scheduling problems, and with sufficient notice, large contiguous blocks of time (up to a full week's run) can usually be obtained. Again, no assignment of scientific priorities to experiments is carried out.

The possibility of establishing scientific priorities for the use of magnet time to alleviate problems in the demand for available magnet time has been considered; the general feeling is that because of the broad range of research projects and the usually short time scale of the experiments, such a procedure would be difficult to implement and, except in rare cases, would cause more problems than it solved.

Auxiliary Equipment and Facilities

All the large resistive magnet facilities provide additional technical support, instrumentation, experimental equipment, and, in some cases, additional extensive facilities. We are concerned here with possible improvements in such facilities and the need for specific additional equipment and facilities.

A problem often encountered in the use of high-field facilities is the necessity for repeatedly assembling and disassembling highly complex and sensitive experimental instrumentation at the magnet stations. When the facilities are not fully utilized, apparatus can remain at a magnet station for relatively long periods with only minimal difficulties; however, when there is a queue of users, the assembling and dismantling of equipment can lead to substantial inconvenience for a large number of users. The addition of more "popular" magnets and magnet stations could partially alleviate this problem.

In addition to the routine equipment and consumable materials (cryogenic fluids, for example) that are generally provided by high-field facilities, the availability of certain specialized equipment that is either too sensitive or too large to be transported easily would make high-field facilities more generally useful and might attract scientists who, for reasons of logistics and equipment problems, have had to limit their use to the lower fields provided by superconducting magnets. Some examples of such specialized equipment are general support facilities for chemistry, ultrahigh vacuum chambers and heat pumps for chemistry experiments, a complete range (submillimeter to ultraviolet) of lasers (including dye lasers), spectrometers and detectors (with appropriate optical components and hardware), pulsed lasers with associated detectors and signal-processing electronics (particularly useful for short-pulse magnet systems), signal averagers, and digital acquisition and data-processing equipment.

On a somewhat larger scale, facilities such as ESR and NMR spectrometers and very-low-temperature cryogenic facilities (dilution refrigerators) would be very useful in relation to some of the scientific opportunities discussed in Chapter 3.

Much of this equipment is commercially available, but some of the very specialized equipment, such as NMR facilities and dilution refrigerators, will only be available to and truly usable by visitors through the efforts of an active, innovative scientific staff associated with the facility.

APPENDIX A:
Letter to the Scientific Community

Dear –

I have been asked to chair a committee of a panel reporting to the National Research Council investigating opportunities for research given some major new facilities to generate high magnetic fields. The impetus behind the study is the suspicion that a large portion of the scientific community in the United States would be very interested in doing research, given the availability (and accessibility) of a facility (or facilities) capable of producing

1) 750 kilogauss (c.w.)
2) "Static" pulse operation to approximately 1.5 megagauss, with constant fields for 10–100 milliseconds.
3) Pulse operation to 10 megagauss (non-destructive) for times in the microsecond range.
4) Very short (probably destructive) pulse operation to 100 megagauss (for nanoseconds?).

using high magnetic fields. Clearly, a substantial national investment would be involved. In order to determine whether such an investment makes sense, our committee is investigating the scientific prospects should such facilities exist.

I am writing you to ask if you could help us. If you had at your disposal fields of the sort described above, what experiments important to your field of research could you do? We would be interested in every category, but if a new area of opportunity would open up we'd like to know about it. Could you take some time and think of what you might be able to do, or what others should do, given the availability of fields in the above range? I would appreciate hearing from you. It will be of great help to us.

Thanks very much.

Sincerely,

Raymond Orbach

APPENDIX B:

Contributors to the Study of High-Magnetic-Field Research and Facilities

The Panel is deeply grateful to the following persons who responded to its requests for information, prepared material for its consideration, and in other ways assisted with this study. Without their cooperation and interest, the study would not have been possible.

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