



Federal Laboratory Consortium

SUPERCONDUCTIVITY RESEARCH AND TECHNOLOGY IN THE FEDERAL GOVERNMENT

The interest in superconductivity and its applications is equally shared by our Federal laboratories, US domestic industry and universities. The opportunity for cooperative efforts is obvious. To help improve communication between Federal laboratories, industry, and universities, the FLC has initiated an effort to catalog laboratory activities in superconductivity research, development and applications.

The following material represents a preliminary listing of activities and contacts. The FLC will update the document as appropriate, however individual agency or laboratory contacts will have more details and comprehensive information on their respective activities. The material is divided into two sections:

- A) Department of Energy activities;
- B) Department of Defense activities; and
- C) National Science Foundation activities.

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The Federal Laboratory Consortium:

- Comprises over 600 Federal laboratories and centers, and their parent agencies, with annual in-house R&D budgets of approximately \$20 billion
- These organizations employ approximately one sixth of the Nation's science and engineering professionals

Chartered by an Act of Congress to strengthen the cooperative transfer of Federally developed technology to industry, State and local governments and universities.

CONTENTS

A) Department of Energy.....	1
Ames Laboratory.....	3
Argonne National Laboratory.....	4
Brookhaven National Laboratory.....	6
Lawrence Berkeley Laboratory.....	7
Los Alamos National Laboratory.....	8
Oak Ridge National Laboratory.....	9
Pacific Northwest Laboratories.....	10
SANDIA National Laboratories.....	11
Energy Technology Engineering Center.....	13
Lawrence Livermore National Laboratory.....	14
Idaho National Engineering Laboratory.....	15
Fermi National Accelerator Laboratory.....	15
B) Department of Defense.....	17
Naval Research Laboratory.....	17
Benet Laboratory.....	19
David Taylor Naval Ship R&D Center.....	21
Rome Air Development Center.....	23
Naval Underwater Systems Center.....	25
Air Force Wright Aeronautical Laboratories.....	26
Materials Technology Laboratory.....	28
C) National Science Foundation.....	30

Please note that "ORTA", as used in listing points of contact, refers to the Offices of Research & Technology Applications at the laboratories.

A) DEPARTMENT OF ENERGY

The Division of Material Sciences, Office of Basic Energy Sciences, DOE has provided the following summary of High Temperature Superconductivity Research at DOE:

The emphasis of research in high temperature superconductors at each laboratory is as follows:

Ames Laboratory - physical properties, current density measurements, effects of magnetic fields, theoretical studies, and synthesis

Argonne National Laboratory - powder preparation and processing of wires, tapes, etc., structure determination using pulsed neutrons, microscopy, transport (e.g., electrical, heat, etc.) in wires and tapes.

Brookhaven National Laboratory - mechanical properties, structure determination using synchrotron light and neutrons, fabrication of multifilamentary conductors, relationship between microstructure and superconducting properties.

Lawrence Berkeley Laboratory - synthesis, especially chemical substitutions leading to new compounds, growth of single crystals electrochemically or hydrothermally, high resolution electron microscopy, thin films and electronic devices (SQUIDS).

Los Alamos National Laboratory - synthesis to develop preparation techniques, growth of single crystals from solution or via grain growth, effects of high magnetic fields on both critical currents and critical temperatures.

Oak Ridge National Laboratory - powder preparation, sintering of powders to dense materials, sol-gel processing, neutron scattering to study phonons and magnetic structure, electronic structure via optical and electron spectroscopies, theoretical models of thermodynamic, magnetic, and transport properties.

Pacific Northwest Laboratory - processes to enhance superconducting fraction via separations techniques.

Sandia National Laboratory/Albuquerque - thin films and electronic circuits, physical properties of thin films and polycrystalline superconductors.

In addition, two joint programs have been started recently which add to the efforts already underway. These are described briefly below:

A collaborative program between Ames Laboratory, Argonne National Laboratory, and Brookhaven National Laboratory to develop a conductor from the new high-transition-temperature (92K) oxide superconductors based on the Y-Ba-Cu-O system was started in April of 1987 by the Division of Materials Sciences, Office of Basic Energy Sciences, Department of

Energy. The goal is a conductor that can carry a current of 100 A at a current density of 10^4 A/cm^2 at 77 K in a field of at least 2 Tesla. The material must be able to maintain this performance under a strain of 0.2 percent. The approach will be to develop processing techniques based on (a) green-state ceramic tape casting and extrusion, (b) near-hydrostatic extrusion of reacted or pre-reacted powder in a tube, and (c) thick-film techniques such as co-evaporation, reactive sputtering, and plasma or flame spraying. Fundamental issues affecting the limits on critical current density due to intergrain resistance and pinning will be addressed.

A collaborative program between LANL, LBL and ORNL was started in May of 1987 by the Division of Materials Sciences, Office of Basic Energy Sciences, Department of Energy. The efforts in this new program are focused in four major areas: I. Synthesis, II. Characterization and Analysis, III. Thin Films and Devices, and IV. High Current Conductors. The three laboratories have expertise and special equipment that will be used in this research. Coordination between the laboratories will include scientific information exchanges, exchanges of research samples, collaborative research tasks, use of special research facilities, and regular information meetings to assess progress and establish R&D priorities.

The Division of Materials Sciences' laboratory effort is coordinated through meetings, three of which have been held so far. The first was in January at Argonne National Laboratory, the second in February at DOE, Germantown, and the third was held on May 14 and 15 in DOE, Germantown. The fourth meeting is scheduled for September 21 and 22 at Argonne National Laboratory.

To coordinate the R&D in the Department of Energy a subcommittee of the Energy Materials Coordinating Committee on superconductivity has been established. Its first meeting was May 20. Iran Thomas, Director of the Division of Materials Sciences is the Chairman. Coordination among agencies is provided by a subcommittee established by COMAT. Lou Ianniello, Deputy Associate Director for Basic Energy Sciences is the Chairman of this subcommittee.

The Office of Basic Energy Sciences also sponsors the High- T_c Update which is published by the Ames Laboratory, Iowa State University.

High- T_c Update is intended to serve as an information exchange on superconductivity research. Items solicited include: 1) brief descriptions of on-going work; 2) particular research problems, pitfalls, and/or solutions; 3) summaries and announcements of meetings; 4) preprints, reprints, and other information sources.

Contributions and inquires on the High- T_c Update should be directed to:

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1) Information Exchange Project:

The High- T_c Superconductivity Information Exchange, located at the Ames Laboratory and funded by the Division of Materials Sciences, BES, DOE*, provides a centralized site for communicating superconductivity information to researchers working in the rapidly evolving field of high-temperature superconductivity. It is extremely important that U.S. researchers be kept abreast of what other researchers here and abroad are doing, and the Information Exchange is able to respond quickly to meet this need. The Information Exchange has two parts: the High- T_c Update, which is published twice a month, and an individualized information exchange.

The field of high- T_c superconductivity is evolving rapidly. As it changes, so will the Information Exchange. Various government agencies are already using the Exchange as a means of reaching the high-temperature superconductivity research community. In the future, the High- T_c Update could include "state-of-the-moment" research summaries, additional international news, descriptions of ongoing research projects, and reports on problems and successes in materials fabrication and applications.

2) Research Activity:

The Ames Laboratory is well known for its work in rare-earth separation and purification and in metals development and fabrication. Pure rare earths are the cornerstone of superconductivity research, and Ames Lab has been a center for superconductivity research for a number of years. In 1980, an interdisciplinary team of Ames Lab researchers developed the

in-situ process for making flexible wires out of a superconducting cooper-niobium composite. In 1985, Ames was the site of an international conference on superconductivity.

Since December, 1986, when high- T_c superconductors first made headlines, an interdisciplinary team of Ames Lab researchers has been exploring new materials. While the theorists determine theory, the synthesists are making new ceramic materials, the experimentalists investigate the properties of these materials, and the metallurgists develop ways to fabricate wires out of these brittle materials. In addition, the Ames Lab is engaged in a collaborative effort with Argonne and Brookhaven National Laboratories to conduct research on high- T_c superconductivity.

The Ames Lab is not only the center of a national--and international--information exchange on superconductivity; it is also the center of exciting research in this important field.

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Elements of the ANL High Temperature Superconductor program include: The largest DOE Basic Energy Sciences program for superconductivity and magnetism, ultrahigh-field superconductors, superconducting superlattices, and organic superconductors; major facilities include intense pulsed neutron source electron microscopy center beamlines at NSLS; related programs include BES studies of perovskite transformations and ceramic processing for solid oxide fuel cells.

- 1) Linking industry with Illinois superconductivity research. On June 23, Argonne National Laboratory was the site of a conference, cosponsored with the State of Illinois, to bring together industry, academia, and federal laboratories in Illinois for an update on

high-temperature superconductivity. More than 200 attended the meeting to learn the latest research developments, and how industry can interact with the Illinois institutions who are at the frontier of this new technology.

Conference topics included worldwide developments, and recent advances in superconducting materials, including the thin flexible ceramic wire that Argonne was the first to form, and potential applications of high temperature superconductors and their economic impact. In addition to Argonne, three other institutions--Fermilab, Northwestern University, and the University of Illinois at Urbana--provided an overview of their programs in high-temperature superconductivity and mechanisms for industrial interaction. Also on hand were officials from the State of Illinois Governor's Commission on Science and technology, co-sponsor of the conference with Argonne, to explain the state's role in Illinois superconductivity research.

2) Materials Research on High T_c Perovskite Superconductors:

GOALS: Using Argonne's strengths in synthesis, structure, properties, and theory of complex superconductors, ANL established a focused program on the physics of high T_c Perovskite superconductors.

With the additional Argonne strengths in basic properties of perovskite and related ceramics (defect properties, phase transformations, electronic properties) and the ceramic processing capabilities demonstrated in the solid oxide fuel cell program, develop a focused program on conductor development. The aim would be to demonstrate a composite (stabilized) conductor capable of carrying 100A at a current density of $10^4 \text{A}/\text{CM}^2$ at 77K in magnetic fields of at least 2 Tesla.

Results to date:

- Approximately 15 research papers submitted since 1/1/87.
- Approximately 6 patent disclosures made.
- Invited talks given at March 1987 APS Meeting, April 1987 MRS Meeting (also planned for Japanese low temperature conferences in August-September 1987).
- Organized first DOE-BES workshop on 1/20/87.
- Lead role in BES Conductor Development Proposal (O'Hare Meeting 3/4/87; draft submitted to BES 3/24/87).
- Proposal presentation to DOE-Conservation 3/87.

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The Superconductivity Program at Brookhaven

The superconductivity program at Brookhaven National Laboratory has a history of almost 25 years, and the Applied Superconductivity Conferences which are now held every other year were conceived and first held at Brookhaven. The effort formally called the Cooperative Superconductivity Program, has always been a broad based program that combined basic research with technology. Initially, magnets for high energy physics were the basis of the applied work and this was then expanded into a major program for construction of a power transmission line test facility. The magnet group is still involved in superconducting magnet design and construction for the magnets that will be used at the giant new accelerator, the SSC. The power transmission test facility is still in place and funding is being sought to study the impact of the new high T_c superconductors.

The basic research program emphasizes the unique Brookhaven tools such as the High Flux Beam Reactor, for neutron scattering, and the National Synchrotron Light Source to do experiments at the forefront of the new science of high T_c superconductors. Significant discoveries at these facilities, and in other work at the laboratory, have yielded information about the magnetic structure and the electronic nature of these materials and are leading the way to understanding the basic mechanism for the high T_c . Investigators from other laboratories including university and industrial laboratories, also participate and play a major role in research at the facilities.

Brookhaven is also proud of a materials program, which though small, has participated in the discovery of the first new high temperature superconducting compounds. Facilities are being constructed to make these new materials using thin film techniques. This hold promise both for high current applications and for the "construction" of new materials.

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Research on High- T_c Superconductivity at Lawrence Berkeley Laboratory:

The Lawrence Berkeley Laboratory program on high- T_c superconductors spans the areas of basic science, research on thin films and thin-film based devices, and research on processing related to the fabrication of high-current conductors. Interactions and collaborations with industry are an important feature of the program, and a workshop to develop additional industrial contacts and to identify new program elements of interest to industrial collaborators will be held in the Fall.

The basic science phase of the program includes theory, synthesis of new materials, and measurement of physical properties. It is directed to obtaining an understanding of the mechanism of superconductivity in known high- T_c materials with the ultimate goal of obtaining new materials with still higher T_c and/or better mechanical properties. Substantial contributions to the synthesis, measurement and interpretation of the physical properties, and microstructural characterization of the La- and Y-based compounds have already been made. The thin films research is directed both to exploiting the opportunities for gaining fundamental knowledge that are presented by thin-film samples, and to the development of applications -- SQUIDs that operate at liquid nitrogen temperatures, superconducting interconnects for application in microelectronics, etc. The research on processing for high current applications is largely in the planning stage but will encompass methods for producing conductors with properties suitable for technical applications.

1) Program Objectives

- Synthesis and Characterization

- Characterization of known high- T_c materials; chemical composition, crystal structure, microstructure, and physical properties.

- Theoretical interpretation of properties and first-principles calculations of BCS and other mechanisms.
 - Identify electronic, lattice, and structural properties critical to high- T_c superconductors.
 - Synthesis of new high- T_c materials with optimum properties.
 - Thin Films and Devices
 - Study of thin films for both scientific and technical applications.
 - Development of thin film devices.
 - Processing
 - Processing for homogeneous, high-density, high-critical current conductors.
 - Optimization of mechanical and electrical properties for technical applications.
- 2) MCSD Research Accomplishments

- Synthesis of $La_{1-x}M_xCuO_4$ ($M = Ca, Sr, \text{ or } BA$), $YBa_2Cu_3O_7$, and compounds related by substitution.
- Investigation of microstructure and chemical homogeneity by electron microscopy techniques.
- Measurement of transport properties.
- Measurement of specific heat.
- Upper limit to resistivity of $10^{-17} \Omega \text{ cm}$ established.
- Infrared-absorption determination of energy gap.
- Pressure dependence of T_c measured.
- Elastic properties measured.

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Additional information may be obtained by contacting one of the following program development coordinators.

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Los Alamos has a High Temperature Superconductivity program which integrates three activities: basic research, exploratory R&D and applications development. Our basic research is multidisciplinary and provides a foundation for our exploratory R&D and applications development. Basic research activities include theory, chemistry, materials science, physics and physical measurements principally carried out at the Laboratory's Center for Materials Science, Center for Nonlinear Studies, Los Alamos Neutron Scattering Center, Condensed Matter and Thermal Physics Group, and the Theoretical Division.

Our exploratory R&D (applied research and exploratory development) focuses on the development of generic enabling technologies that form the basis for application of the new high temperature superconducting oxides to the national defense and commercial sectors. The exploratory R&D activities fall into seven categories: (1) bulk synthesis and processing, (2) thin film and coatings synthesis and processing, (3) characterization of microstructure, (4) physical properties, (5) chemical, thermodynamic and mechanical properties, (6) IT Detectors, and (7) magnetic shielding; and are carried out principally in our Materials Science and Technology Division, Mechanical and Electrical Engineering Division, and Physics Division. The organization and management of these efforts pays particular attention to the interfaces with basic research on the one hand and product (applications) development on the other. Industrial involvement and interaction is encouraged.

Applications development are for DoD, DOE, and industrial customers in those areas where Los Alamos has unique capabilities.

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At Oak Ridge National Laboratory there is a research program "Investigation of Superconductors with High Critical Temperatures." The research efforts are focused in four major areas.

- I. Synthesis. Preparation of high T_c cuprates; growth of single crystals of these materials; search for new materials; ceramic processing.
- II. Characterization and Analysis. Structure determinations, transport measurements, magnetization measurements, electron and optical spectroscopies, etc. The goals of these measurements are to support the synthesis and to provide insight into the superconducting mechanism in these materials.
- III. Thin Films. The preparation of thin films of these superconductors by different processes, such as evaporation or sol-gel. Emphasis on single crystalline films. The use of ion-beam techniques for processing films.
- IV. High Current Conductors. Measurements of critical currents and studies of the nature of the current carrying state. Effect of anisotropy. Enhancement of critical currents: Research on preparation of current-carrying cable.

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Superconductivity Program at Pacific Northwest Laboratory

The activities at Pacific Northwest Laboratory (PNL) are focused upon (1) materials synthesis and characterization and (2) the applications of superconducting materials.

Materials Synthesis

- Monoliths
Cold pressing and sintering as well as hot pressing of:
 - Powders produced by traditional methods
 - Powders produced by chemical routes
 - Powders produced by freeze drying
- Films
Sol-gel
Reactive sputtering
- Fibers
Sol-gel

Materials Durability

The degradation of superconducting properties with environmental reactions (particularly moisture) is being investigated. These investigations utilize laser Raman spectroscopy, X-ray photoelectron spectroscopy, and the interaction with isotopic water, $D_2^{18}O$, and subsequent nuclear microprobe analyses to determine quantitative uptake and reaction depth.

Applications

Applications of high critical-temperature (T_c) superconducting materials at PNL are mainly directed toward eventual problems of integrating new electrical power equipment into the utility transmission and distribution system. A Hanford site-wide initiative with heavy private vendor industry involvement is planned to define and motivate an aggressive electrical energy systems engineering effort in parallel with basic R&D on high T_c superconductivity performed by the national laboratories, universities, and other private R&D institutions. The long-range goal is to provide advanced experimental and test facilities in order to attack the problems of systems integration of new generators, motors, superconducting magnetic storage devices, and transmission cables as well as associated problems of control and protection.

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Sandia National Laboratories High Temperature Superconductivity Program

The Sandia high temperature superconductivity program consists of three complementary activities: (1) novel materials synthesis and processing of high temperature superconductors, (2) device applications, and (3) fundamental solid state/materials science studies. The thrust of this program is toward device applications in these unique materials. This effort thus includes, as a specific objective, development of both bulk and thin film superconducting material forms which can be incorporated into new devices.

The motivation for our efforts is the possibility that these high temperature superconductors may have significant implications for both weapons and energy programs, and the involvement of a nominal fraction of the Research Organization will best prepare the Laboratories for the possible use of these important new materials.

A primary emphasis of our program is to exploit certain unique capabilities that we possess at Sandia Laboratories. That is, to develop a niche in which the Laboratories may be able to make singular contributions on the national level. One of these is the ability to formulate these materials using unique methods, such as the chemical preparation of ceramic superconductors using solution techniques and their consolidation into bulk form.

Another is the deposition and processing of thin film forms by a variety of techniques that have been developed to a high level of understanding at Sandia. We believe our emphasis in these areas can complement extensive efforts elsewhere, and it will be our policy to broadly share our results with other national laboratories, industry and universities. This will be accomplished through participation in meetings, publications, and other information exchange processes.

Materials Synthesis

Unique capabilities in the growth, such as chemical preparation using solution techniques and consolidation into bulk forms, will be employed. Single crystal growth techniques and various thin film synthesis routes, such as sputtering, vapor deposition and CVD will be emphasized. These thin film synthesis approaches will be combined with our broad array of surface modification (ion implantation, ion beam mixing, electron beam or laser processing and transient annealing) techniques to optimize film properties. In addition, bulk processing will be developed to provide high density ceramics via controlled particle size, sintering and hot pressing to produce high strength materials.

Materials properties will be optimized by close coupling of the synthesis to our broad range of characterization techniques including compositional (ion beam analysis), structural (x-ray and optical scattering, and with ANL and LANL, neutron scattering), electrical (resistivity and thermopower), magnetic (susceptibility, NMR, EPR, magnetization, magnetoresistance, Schubnikov deHass and deHass van Alphen and Hall effect) and thermal (thermogravimetric analysis, differential calorimetry

and heat capacity) analysis. Key processing steps for device fabrication, such as development of capping layers for long-term oxygen retention and of thin dielectric layers for Josephson junction fabrication will be developed.

Device Research

Our device development will involve both passive and active electrical devices as well as IR devices. These devices hinge on successful fabrication of thin film materials. The passive devices would operate on the principle of classical electromagnetic coupling, eliminating losses which would make normal conductor devices impractical. The simplest device is a planar transformer analog. Approaches for IR detectors include use of high T superconductors as both the base plate and common contact for a thermocouple array and various bolometric devices. A second approach involves Josephson junction technology. We will also explore vortex flow transistor concepts based on these new materials.

Fundamental Studies

In the fundamental area we will emphasize the important questions of anisotropy and detailed structure on the properties of both bulk single crystal and thin film structures in these Cu-O based superconductors. To characterize materials formed by various techniques, we will exploit our demonstrated capabilities in the study of small single crystals as a function of high magnetic fields and pressures. Non-conventional theoretical models (non-BCS and/or non-phonon coupled) as well as one electron and bipolaronic models will be investigated.

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Superconductivity Related Activity

The Energy Technology Engineering Center (ETEC) is a development engineering facility operated for the U.S. Department of Energy by Rockwell International. The laboratory tests systems and components for liquid metal reactors, and provides technical assistance and consultation on heat transfer systems and power conversion applications. Energy program areas being studied include fission, fossil, solar, conservation, geothermal and fusion power engineering.

ETEC plans to assess the engineering applications of superconducting devices based on the imminent development of a process for coating fine wire with very thin layers of a superconducting glass/ceramic composite.

Superconducting coils made with flexible, glass-coated wire can be used for:

- 1) Weight and size reductions on space-based power systems by minimizing or eliminating the large radiators now needed for power conversion heat dissipation.
- 2) Energy storage rings for industrial or private sector use, including space power applications.
- 3) Long distance transmission lines for electric power utilities.

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Research Activities in High Temperature Superconductivity - July 8, 1987

Summer study on applications of superconductors for defense and energy,
John Holtzrichter.

Theoretical Investigations

Chemical Structure Simulations, Nicholas Winter

Band Theory, Andrew McMahon.

General Theory of the Superconducting State, Edward Teller.

Many Body Theory of the Superconducting State, Robert Laughlin.

Materials Preparation - Powder Metallurgy, Powder Compaction, Physical Vapor Deposition, Reactive Sputtering. Eltron Kaufmann, Troy Barbee, Richard Landingham.

Physical Measurements - Radiation Effects, Positron Spectroscopy, Materials Properties, High Pressure, Microcrystal Techniques. Evan Mapoles, Michael Fluss, William Nellis, Peter Hahn, Michael Guinan.

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Superconductivity Technology Activity

At the Idaho National Engineering Laboratory (INEL); two organizations, Materials Technology and Physics, are investigating processes and applications for superconducting materials.

Materials Technology:

INEL is pursuing process research aimed at producing superconducting yttrium barium copper oxide as a coating on copper substrates. The eventual goal is a method of manufacturing complex shapes such as wire coils and superconducting patterns on flat and complex substrates. Two approaches are being pursued: (1) sol-gel synthesis and coating of a viscous film on the metal substrate followed by drying and firing, and (2) deposition of an yttrium barium copper liquid alloy on copper. In the latter case, the alloy is liquid well below the copper melting point and completely wets the copper substrate. After deposition and freezing of the alloy, it is partially oxidized to the mixed oxide at controlled temperature and oxygen pressures.

Physics:

The Physics group provides theoretical support in the development of applications of high temperature superconductors to advanced energy technologies. Applications of the technology to the Strategic Defense Initiatives and other Department of Defense missions, as well as space technologies are the thrusts of the program. A small scale superconductivity laboratory for measurement of properties of materials manufactured at the INEL is planned.

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The largest superconducting installation in the world is installed at Fermilab and operating very successfully. This is the Fermilab Tevatron, the most powerful particle accelerator ever built. The Tevatron consists of a string of about 1000 superconducting magnets in a four mile circle. It has now been in operation for three years. It is an excellent example of a national laboratory working with industry to create new types of materials and new cryogenics to attack and solve unique problems.

1. Work at Fermilab and other federal laboratories carried superconductivity from a laboratory curiosity to a billion dollar industry in the period 1961-1986.
2. This work had a significant impact in accelerating the application of magnetic resonance imaging to medical diagnosis. It is estimated that this application was accelerated by two years.
3. The Tevatron work has had a pervasive effect on the current cryogenic and superconductivity industrial sector. A July 1987 High Technology article illustrates this. More than half of the companies listed in their table of players are either Fermilab Industrial Affiliates, participated in the Tevatron construction, or both.
4. Fermilab has served as the lightning rod for the Cryogenic Engineering Conference and the International Cryogenic Materials Conference for many years. These have been the principal venues for academic-industrial relations and professionalizing this area. Both meetings were recently (June 14-18) held near Fermilab.

One could call this the cold fashioned superconductivity. We don't yet know how the new high T_c superconductivity will develop. If most of the work centers on liquid nitrogen, much of the infrastructure already developed by Fermilab and other federal laboratories will continue to be germane. Even if we have room temperature conductors much of the Fermilab work remains relevant. Examples include areas like quench protection and schemes for restraining powerful magnetic forces.

Fermilab efforts on the new high T_c superconductors are focused on understanding the work of others and starting to probe to understand what is involved in making useful magnets out of them.

B) DEPARTMENT OF DEFENSE

The following material represents preliminary input from DOD laboratories:

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NRL SUPERCONDUCTIVITY PROGRAM

The Naval Research Laboratory has established a comprehensive program in the area of High Temperature Superconductivity (HTS). The program is based on a strong basic research effort aimed to provide a scientific basis for understanding and controlling the behavior and properties of the newly discovered class of HTS materials. Implicit in this part of our overall program is both a strong experimental effort to fabricate and measure the properties of these materials as well as a major theoretical effort to develop fundamental theories relating processing and fabrication procedures to atomic and microstructural characteristics and ultimately to their electrical, magnetic and superconducting properties.

This part of our overall program will specifically address the following issues:

- What are the fundamental mechanisms responsible for the high temperature superconductivity?
- What are the intrinsic properties and limits of the materials?
- What are the material parameters which permit control of the superconducting properties?
- What are the fabrication processes which would permit these materials to be fabricated into technologically useful forms?

To answer these questions, research in this program will meld strong efforts in materials fabrication and characterization with equally strong efforts in superconductivity theory and property determination. Proper interpretation of experimental results, which are vital input to a developing technology base, depends on well characterized samples; thus, considerable effort in this program will be devoted to sample preparation

and characterization. Samples will be fabricated by a variety of techniques ranging from the more standard ceramic processing procedures to more sophisticated film preparation techniques.

The key to these material fabrication efforts, and the necessary link between property determination, theoretical interpretation, and a sound technology base in the ability to characterize the samples-structurally and chemically. To this end, the program will focus a large range of sophisticated diagnostic tools to the purpose of providing such information.

Determination of the superconducting properties is an obvious crucial element of this research program. Thermodynamic properties such as the critical magnetic fields, critical temperature and specific heats; flux flow; and quantum mechanical properties such as electron tunneling, Johsephton effect, and infrared absorption will be measured. These results will be used to develop a theoretical understanding of superconductivity in this new class of materials and to ascertain their application potential.

The NRL program will strive for the rapid transfer of basic research results to systems applications of Naval interest. To foster this transfer, NRL has active programs for developing devices and system applications of the new HTS> Implicit in these widely based technology efforts are system design studies including trade off analysis with competing technologies. As the program develops, we will focus first on the near term applications, as determined by the status of the material developments, to ensure practical results as soon as possible. As more advanced materials are developed we will continue with the longer term projects.

Potential applications of interest to NRL range from high power, large scale systems such as in shipboard electric propulsion drives to low power, small scale systems such as in magnetic sensors or radiation detectors. Development of these specialized applications will depend on active collaborations with NRL and with other Naval Centers. These developments will be focused on specific Navy needs as determined through active involvement in planning and assessment studies.

A specific listing of applications of interest to the Navy and to NRL are:

- | | |
|---|-----------------------------|
| 1. Magnetometers | 9. Motors and Generators |
| 2. Infrared Sensors | 10. Pulsed Power Systems |
| 3. Millimeter Wave Receivers | 11. Energy Storage Systems |
| 4. Digital Systems | 12. Directed Energy Weapons |
| 5. Hybrid Semiconductor-Superconductors Systems | 13. Magnetic Bearings |
| 6. Elf Communications | 14. Mine Sweeping |
| 7. Electric Ship Propulsion | 15. Free Electron Lasers |
| 8. Millimeter and Micro Wave Sources | |

To ensure a fully integrated program at NRL, the laboratory has established an oversight committee. This committee will formulate and oversee Laboratory-wide efforts in superconductivity and represent NRL's integrated program. The committee will brief NRL's top management periodically on the status of the superconductivity program.

The head of this committee and point of contact for the NRL superconductivity effort is Dr. Donald U. Bugser.

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RESEARCH IN HIGH TEMPERATURE SUPERCONDUCTIVITY AT BENET LABORATORIES

Introduction

The possibility of practical superconducting materials whose transition temperatures will allow their use at liquid nitrogen (or liquid air) temperatures will have a profound influence on the technology used by the Army. This report will detail the extensive and long standing experience and background that Benet Laboratories, CCAC has in the high temperature superconducting field and will describe ongoing research in two novel applications of superconductivity to rail gun technology developed at Benet.

Since 1979, an outgrowth of a High Pressure Research program was the discovery of pressure-quenched CdS_xCl_{2-x} materials which exhibited high temperature superconducting behavior of magnetic flux exclusions. (The results of this research led to a U.S. Army patent.) Simultaneous changes in electrical properties with the magnetic transitions consistent with the interpretation of high T_c superconductivity were also observed. This material was difficult to prepare chemically and zero resistivity could not be demonstrated directly.

Other efforts at Benet during this time included theoretical analysis of the enhancement of transition temperatures for Type I superconductivity of amorphous metals and experimental investigations of the palladium hydride superconducting system using electrolytic and ion implantation sample preparation techniques.

The researchers involved in these programs remained in close contact with these fields by collaboration with RPI and SUNYA research personnel to the extent that a joint paper was presented at the recent APS meeting on High Temperature Superconductivity in New York in March 1987 which described new work on CdS_xCl_{2-x} system. In addition, a publication detailing other new developments in this system were recently published. Benet Laboratories also has facilities and experience in the cryogenics and vacuum technology required to develop large scale superconducting systems.

Benet personnel have been investigating the possibility of applications of superconductivity to armaments. This has led to two novel applications of superconductivity to EM launch technology.

Application of Superconductivity to EM Launch Systems:

The first innovation was the use of a superconducting augmentation coil to enhance the performance of rail gun barrels. A demonstrator Superconducting Augmented Rail Gun (SARG) has been developed at Benet and will be tested this year. The superconducting coil will a) provide additional force to the projectile from the superconductor's magnetic field and b) the utilization of the flux trapping property of a superconducting coil to reduce the magnetic field energy lost at the end of launch.

The second innovation involves the use of superconducting coils in an internal flux compressor device: as an alternative to pulse power generating equipment (homopolar generators, capacitive stores, etc.) currently being used in rail gun systems. Essentially, the flux compressor, which will be configured to fit into the cartridge case of the propellant (approx. 2 MJ/lb.) into an electrical pulse to drive the rail gun. Additional projectile propulsion from gas expansion is possible in this configuration.

Flux compressors, which operate under the conditions of conserved magnetic flux Φ (i.e. $\Phi = LI = \text{constant}$), have achieved current multiplications of more than 30 when the expansions are powered by explosives for pulse widths of 1×10^{-4} sec. However propellants must be used in the chamber of a gun to lower the peak pressures which increase the pulse width to the order of a few milliseconds. The physical question of magnetic flux loss during this extended expansion time is being studied. The application of superconducting elements to the flux compressor device can reduce the amount of flux loss, enhancing the possibility of the development of a practical internal flux compressor for the rail gun system.

Program: A program has been proposed by Benet Labs, in superconducting research and development, in two general categories.

- a) High T superconducting materials, both CdS_xCl_{2-x} and the perovskites will be studied to determine the structural basis for the superconductivity to determine their efficacy as Army materials and to possibly develop new materials having higher transition temperatures.
- b) The application of superconductivity to EM launch technology through both the SARG and flux compressor concepts as well as other electrical energy storage possibilities, will be continued.

Research in a) above will proceed by characterization of both the perovskite and CdS_xCl_{2-x} materials by X-ray magnetic and electrical, ultrasonic and transition temperature measurements as well as metallography as a function of sample chemistry and physical treatments. Acquisition of the data required will be expedited by our complete facilities in vacuum and cryogenic facilities. In analyzing these data, we should be able to determine optimum fabrication and physical property information to provide useful materials for Army needs and may discover with existing theoretical capabilities the underlying mechanisms for superconductivity in these systems.

By applying superconducting materials to EM gun applications, we can not only increase EM gun technology but gain experience in the application of large scale superconducting devices for Army use.

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DTNSRDC CURRENT SUPERCONDUCTIVITY PROGRAM

The David Taylor Naval Ship R&D Center (DTNSRDC) is developing S/C motors, generators, and related subsystems for application to electric propulsion of Navy ships.

The overall objective of the program is to develop a firm technology base for all critical areas especially superconductivity and cryogenic refrigeration, and demonstrate feasibility through the design, fabrication and tests of full scale and model machinery and related subsystems. This program has been underway since 1969 with an initial effort to design, build and test a 10 KW superconducting generator. The program proceeded into the 70's with the design, fabrication and testing of a 300 KW superconducting electric propulsion system which operated in the laboratory and at sea in a Navy test craft, Jupiter II. This system met all expectations and design goals and paved the way for larger machine developments. This effort was followed in the late 70's and early 80's by the design, fabrication and test of a 2.25 MW superconducting electric propulsion system which also operated successfully in the laboratory and in the Jupiter II test craft at sea. These machines are now in their final phase of testing, scheduled for completion in FY '87. The total expended effort for the Center's superconducting electric propulsion program is approximately 700 man years through FY '87.

The superconductive electric propulsion program includes many critical technologies; among them are: (1) homopolar machine design and fabrication, (2) high performance low loss liquid metal current collectors, (3) high current switchgear and electrical transmission lines, (4) Instrumentation and System Controls, (5) Cryogenic systems and refrigeration, and (6) Superconductivity, superconductors and magnets. Each of these are being pursued to establish an understanding of basic principles and theories and to develop mathematical models and scaling laws. Various design approaches for equipment and manufacturing processes are being developed and these principles are being verified in model laboratory test rigs and machines.

In particular, the technology of superconductivity includes the basic application of superconductive materials to conductor configurations which can meet the system and operational requirements of electric propulsion machinery. These conductor designs take into account the stability of the conductor to flux jumps and external disturbances causing temperature rise and seek ways and means to improve these parameters. Methods of reducing conductor weight by use of Al stabilizing material are being developed with the added advantage of significant improvements in conductor stability. The means of producing this conductor in long lengths with consistent properties has been a problem and is now being developed. The effects of longitudinal strain on the critical current of superconductors was initiated by DTNSRDC with the National Bureau of Standards in the mid 70's. This was pioneering work on an extremely important property which now influences all superconductive systems throughout the world especially where brittle superconducting compounds are used. The use of Nb₃S as the superconductor has been investigated because of its higher transition temperature and critical field. Magnet fabrication techniques, such as wind and react, have been explored to account for its brittleness and lack of strain tolerance. V₃Ga is another conductor which was developed into a useful configuration for propulsion motors and generators and Nb₃N is also being considered because it is not effected by strain which makes it very desirable. Extensive work has been conducted and is continuing on superconducting magnet design, fabrication and performance improvement as

well as modeling and scaling law development. The thermal, magnetic, electrical and mechanical properties of these complex structures are being investigated to meet the operational and environment requirements of Navy shipboard equipment. Many test magnets have been designed, fabricated and tested to improve their performance and conduct systematic tests on magnet quenching, fabricate and analytical model verification.

The new higher T_c material (95K) are being considered for incorporation in propulsion motors and generators as well as other shipboard systems including ship service generators, auxiliary equipment, electric weapons systems, electric power cables, sonar, and magnetic mine sweeping. There is an aggressive program to develop these materials for Navy application by processing these high T_c ceramic superconductors and undertaking the basic research of their environmental stability. Programs have been initiated to develop methods for the sputter application of thin films of these ceramics and the fabrication of short lengths of wires with adequate critical current capabilities for magnet applications. A critical materials properties laboratory is being established as well as an expansion of exiting material processing facilities to more efficiently deal with special processing problems of ceramics. All materials work is part of a team effort involving the machinery and materials communities at DTNSRDC to provide for the transitioning of ceramic superconductors into fleet applications especially electric drive systems.

The Center's experimental facilities are quite extensive. They include, (1) land based superconducting ship propulsion test facilities capable of full power operation to 2.25 MW and a closed cycle helium system capable of 4K operation, (2) a cryogenics laboratory for refrigeration development, (3) superconductive wire and magnet fabrication and test facilities (4) the Navy's Jupiter II test craft, (5) and other laboratory facilities for related critical technology development. The staff includes approximately 30 engineers and scientists with 300 man years experience in superconductivity and related technologies.

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Program Title: CRYOELECTRONICS

Goals: The objective of this research program is to explore the fundamental issues associated with the application of superconducting electronics, and to exploit recent discoveries in high-temperature

superconducting materials by developing affordable cryoelectronic devices for Air Force systems. The need for advanced cryoelectronic devices arises from increasingly more sophisticated DoD missions and functions in navigation, surveillance, identification and communications for command and control.

Scientific/Technical Approaches: The program is broad-based, employing the capabilities of the Solid State Sciences Directorate to conduct research into the preparation and characterization of high-temperature superconducting materials and the Electromagnetics Directorate to develop electronic devices and sensor systems with these materials.

The thrust of the program is toward electronics and this implies the development of superconducting thin film technology. Two and three dimensional superconducting films will be deposited on a variety of single crystal substrates in order to obtain textured materials with favorable grain orientation and to establish thin-film, multilayer structure, deposition techniques, and to evaluate stacking characteristics of device layers.

Property measurements of the new materials include the determination of materials purity, phase stability, structure and microstructure, and mechanical, electrical, magnetic and optical properties. Of specific interest are electronic device characteristics of thin films, and film connectivity and property uniformity along connections. Superconducting properties will be characterized at high frequencies, of fundamental importance for the development of millimeter and sub-millimeter devices. Research will be conducted to determine the sensitivity of superconductors to simulated ground and space radiation environments.

Initial research in the area of device development is being performed in areas in which RADC has much experience. The lossless conductors which super-conductivity provides will be used to improve on existing designs for MMIC and microwave devices. In the MMIC area this will result in lower noise Q resonators due to lower transmission line losses. Applied to microwave acoustic, microwave magnetic and SAW devices this will result in lower insertion loss and higher Q resonators, and enhanced control of dispersion and biasing fields in magnetic delay lines.

Instrumentation and design methodology will be developed for testing and Computer-Aided-Design (CAD) of devices in the terahertz frequency range.

New theoretical models will be developed for microstrip discontinuities and transmission line features and translated into computer software for CAD application at terahertz frequencies. Research will be directed at developing measurement standards for such physical quantities as power, frequency and noise temperature. Test instrumentation will be developed and assembled to permit research into novel terahertz devices, leading to the ultimate goal of establishing a state-of-the-art laboratory for designing, testing and evaluating new devices and concepts in superconducting electronics.

Cryoelectronics will permit the development of active and passive sensing systems in the terahertz frequency regime. In terms of radar this is an unexplored portion of the electromagnetic spectrum. Research will be performed to characterize dielectric properties of materials which are candidates for aerospace applications. Depending on surface properties, scattering from targets at terahertz frequencies may transition from largely specular to specular with a significant diffuse component. This will have implications for target recognition and discrimination beyond the high angular, radial and cross-range resolution afforded at these high frequencies.

In-house radar related work will start with low-power lasers and frequency-multiplied millimeter systems. But as experience is gained with these systems, and as cryoelectronic components become available, such as low-noise mixers, these components will be used as substitutes for existing components. The ultimate goal will be to develop a system employing cryoelectronics for all major functional components.

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Activities in Superconductor Technology

The Naval Underwater Systems Center (NUSC) is the U.S. Navy's principal laboratory for research, development, test, and evaluation in the areas of submarine and antisubmarine warfare. NUSC is located in Newport, RI (headquarters) and New London, CT. In light of new developments in superconductivity at liquid nitrogen temperatures and above, NUSC is examining potential applications in the following areas: propulsion; nonacoustic sensors; battery technology; and others to be identified. The Center is also letting a phase II SBIR contract to develop an undersea acoustic projector using a superconducting driver.

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ADVANTAGES OF HIGH TEMPERATURE SUPERCONDUCTIVITY

The Aero Propulsion Laboratory develops lightweight high power machinery, magnets and components for special weapons and radars. The advantages of superconductivity for these applications have been well-known since 1961 when a continuous development effort started. The primary advantages of superconductors are high current density in practical coils (10^4 - 10^5 amperes/cm²) and effectively zero resistance so that intense flows of coolants are not required to operate high power density equipment. The advantage of the new superconductors for power equipment is that they can potentially be operated at 20-77 degrees K in conventional coolants such as hydrogen or nitrogen where reliable refrigeration can be obtained without incurring severe weight, volume and electrical power penalties in the refrigeration cycle. These advantages are especially important for high power space applications where heat rejection penalties from low temperature refrigerations cycles would be exorbitant.

As one example of the importance of superconductors to high power generation, a copper synchronous alternator capable of generating 20 megawatts on the ground will weight 80,000 pounds and occupy 30,000 ft³. Equivalent 20 megawatt superconducting generators already built and new generators now being designed will weigh less than 2000 pounds and occupy only 25 ft³. The new ceramic superconductors will be difficult to fabricate as wires for high power applications, but offer real promise for fabricating magnet coils by replacing the difficult wire forming process by well-known ceramic fabrication methods to directly fabricate monolithic coils and save years of development time.

IMPLICATIONS

Several critical long-term problems must be resolved for the new ceramic superconductors to be used in high power applications. In addition to brittle ceramic processing issues, the most critical superconducting property that must be improved is critical current density. The current

density reported by IBM is an excellent advance in the technology of thin films, but thin films cannot serve as electrical conductors for high power applications. High power conductors will require good connectivity between the ceramic particles which is difficult to achieve on a scale of less than 10 Angstroms. This is a different, more difficult requirement to accomplish than for superconducting metals where connected regions can be separated by 1000 times greater distance and still maintain superconductivity.

If the new ceramic superconductors can be successfully fabricated into coil magnets at high current density (10^7 - 10^8 amperes/cm²), then many high power applications for lightweight components will materialize. These applications include multimegawatt AC and DC generators, magnetohydrodynamic generators, inductive energy storage devices, high current switches, zero loss power transmission lines and low loss of cavities. Most known applications of high power superconductor devices require lightweight technology, but survivable base and missile silo power issues can also be addressed with superconductivity in underground energy storage devices.

AERO PROPULSION LABORATORY EXPERIENCE

The Aero Propulsion Laboratory (APL) has been in the forefront of high power superconducting device development and power conductor development since 1961. APL has been deeply involved in the development of superconducting wires and coils which have low losses in transient magnetic fields. These helium cooled metallic conductors have been the mainstay of the power component development effort with special emphasis on Nb₃Sn which can operate at temperatures as high as 10 degrees K at 1.5×10^7 amperes/cm². Because Nb₃Sn is as brittle as a ceramic, it has presented challenges comparable to the ceramic superconductors. These challenges have been resolved over the past decade in the case of Nb₃Sn. One of the challenges has been to clad the Nb₃Sn conductor with a ceramic dielectric insulation which can survive the 800 degree C temperature needed to react the brittle Nb₃Sn. An APL contractor is delivering 13,000 feet of brittle Nb₃Sn conductor clad with a ceramic insulation for evaluation purposes. In summary, APL is unafraid of the development challenges offered by the new ceramic superconductors.

For the past 3-1/2 years APL has supported a one-man effort to investigate high temperature superconductors. APL was not working on the ceramic material systems, but shifted emphasis in December 1986 after the initial IBM announcement and by January had produced a 30 degree K ceramic superconductor. Today, APL has fabricated and tested nine different ceramic superconductors, seven of which have onset transition temperatures above 85K. APL is one of the few Government Laboratories that produced this many of the new superconductors in the early competition with international giants such as IBM and AT&T.

WHAT NEEDS TO BE DONE

To produce ceramic superconductors in manufacturable form requires a long-term (5-10 year) commitment with multiple approaches. This multiple approach development has worked in evolving the difficult Nb₃Sn superconductor and ceramic insulation system where the Air Force is a world leader. It will be important to work cautiously so that maximum leverage can be gained from the thousands of man-years being invested by other laboratories. APL will work very closely with the Materials Laboratory, as we have in the past (particularly AFWAL/MLLM), to develop an integrated, interactive, intelligent view of the physics/manufacturability issues. Our in-house efforts will concentrate primarily on the science related to multifilament processing approaches and monolithic, multilayer coil fabrication techniques. APL will also be conducting studies focusing on engineering applications of high temperature superconductivity.

The primary thrusts of the Aero Propulsion Laboratory Program in new superconductor technology will be: 1) methods of increasing current density by understanding and establishing magnetic flux pinning mechanisms, 2) development of new ceramic approaches for thermally stabilizing the new superconductors, 3) measuring properties and developing processing constraints on multifilament wires with MLLM, 4) winding and testing coil magnets with ceramic wires and 5) development of monolithic tape cast coil structures with ceramic processing approaches.

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Based on the recent breakthrough in high temperature superconducting materials, the U.S. Army Materials Technology Laboratory (MTL) has initiated a major research and development effort to assess these

materials for medium and large scale Army applications. Major goals of the program include materials characterization, development of generic processing techniques for bulk shapes (eg, wires, ribbons), and the investigation of technical barriers associated with these materials (eg, brittleness, environmental stability).

2. MTL's program will include three major thrust areas:

a) Solid-state Chemistry and Physics of High T_c Superconducting Materials

- Study the effect of atomic structure modification on the physical, electrical, and magnetic properties such as T_c (critical temperature), J_c (maximum current density), and H_c (critical magnetic field)
- Develop new synthetic methods for the production of polycrystalline powders, single crystals, and thin films.
- Develop an understanding of the pairing mechanisms for high T_c superconductivity by theory and experimental measurements (such as solid state NMR).
- Characterize high T_c materials by optical and electron microscopy and x-ray diffraction.
- Produce thin films and analyze these as well as the surfaces of bulk materials using Auger, SIMS, and ESCA.

b) Processing/Manufacturing and Property Evaluation of High T_c Superconductors

- Develop innovative manufacturing and processing techniques based on low temperature chemical routes for bulk materials (such as wires and tapes) with high critical current densities.
- Investigate mechanical properties of superconducting materials targeted for generator, rail gun, and other large structural applications.
- Examine problems of environmental stability (eg. high humidity).
- Investigate fundamental problems associated with the design of high T_c superconducting components (eg. joining and long-term compatibility with other materials).

c) Utilization of High T_c Ceramic Superconductors in Army Applications

- Examine generic technical barriers associated with use in large (eg. EM rail gun) and medium (eg. motors, generators) size weapons.
- Monitor superconductivity developments to assess their impact on on-going technical programs and their utilization.

NATIONAL SCIENCE FOUNDATION

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B) Research Areas:

Mostly grants to universities and colleges based on unsolicited proposals. (Note below)

Basic Research on Superconducting Materials

FY 1987-\$4 million

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Research on Processing of Superconducting Materials

FY 1987-\$600,000

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INITIATIVE FOR RESEARCH ON SUPERCONDUCTING MATERIALS

The National Science Foundation (NSF) has launched a new initiative to speed research on superconducting materials and help put the U.S. in the forefront of what seems certain to develop into a highly competitive industry.

Recent research breakthroughs have brought much closer the enormous advantages superconductors will bring to a wide range of technologies. A critical step has been the synthesis of new oxide materials that are superconducting at temperatures as "high" as 90 degrees Kelvin (about minus 290 degrees Fahrenheit) or more. Scientists and engineers in the U.S. and worldwide have begun intensive efforts to understand, extend and exploit these results.

The NSF effort is directed at conducting basic research on superconducting materials and on processing these materials into useful forms. Major interdisciplinary research efforts, requiring highly sophisticated

experimental facilities, are needed before the materials can be applied technologically. NSF's Directorate for Mathematical and Physical Sciences is awarding \$1 million immediately for research on high temperature superconducting materials by teams at three of its Materials Research Laboratories (MRLs). The teams will involve chemists, physicists, materials scientists and engineers in MRLs at Northwestern, Stanford, and the University of Illinois at Urbana-Champaign. They will take up the central challenge of understanding the complex and subtle fundamental science underlying the synthesis, processing and behavior of high-temperature superconducting materials.

In addition, the NSF's Director for Engineering has initiated "quick start" grants for researchers with good ideas for processing superconducting materials into useful forms, including wires, rods, tubes, films and ribbons. Research on processing superconducting materials into such forms is necessary because the bulk materials are extremely brittle. Innovative processing methods must be developed to create stronger and more flexible forms of the materials for commercial applications. Under the \$600,000 effort, grants of up to \$50,000 will be made for periods ranging from six months to a year in fiscal year 1987. To speed the research effort, handling within the agency will be expedited.

Together, these efforts will boost existing NSF support for research on superconducting materials, which has more than doubled to about \$5 million per year in recent months as materials researchers, chemists and others have shifted their efforts in this direction. NSF has also commissioned a special study by the National Academy of Sciences to review the outstanding recent progress in superconductivity research and recommend any needed actions. The study is scheduled to be completed by mid-summer.

In announcing the new initiatives, Erich Bloch, NSF's Director, said this country's overseas competitors -- especially the Japanese -- will move rapidly to exploit new knowledge of superconductivity. "But American industry," he said, "also has responded aggressively, and American university researchers are pressing the search for practical technologies with enthusiasm. Cooperation between universities and industry is improving, in part because of NSF's initiative in establishing engineering research centers and the new science and technology centers. These efforts to exploit superconductivity are examples of the new speed and flexibility with which our system can respond, as new opportunities arise.