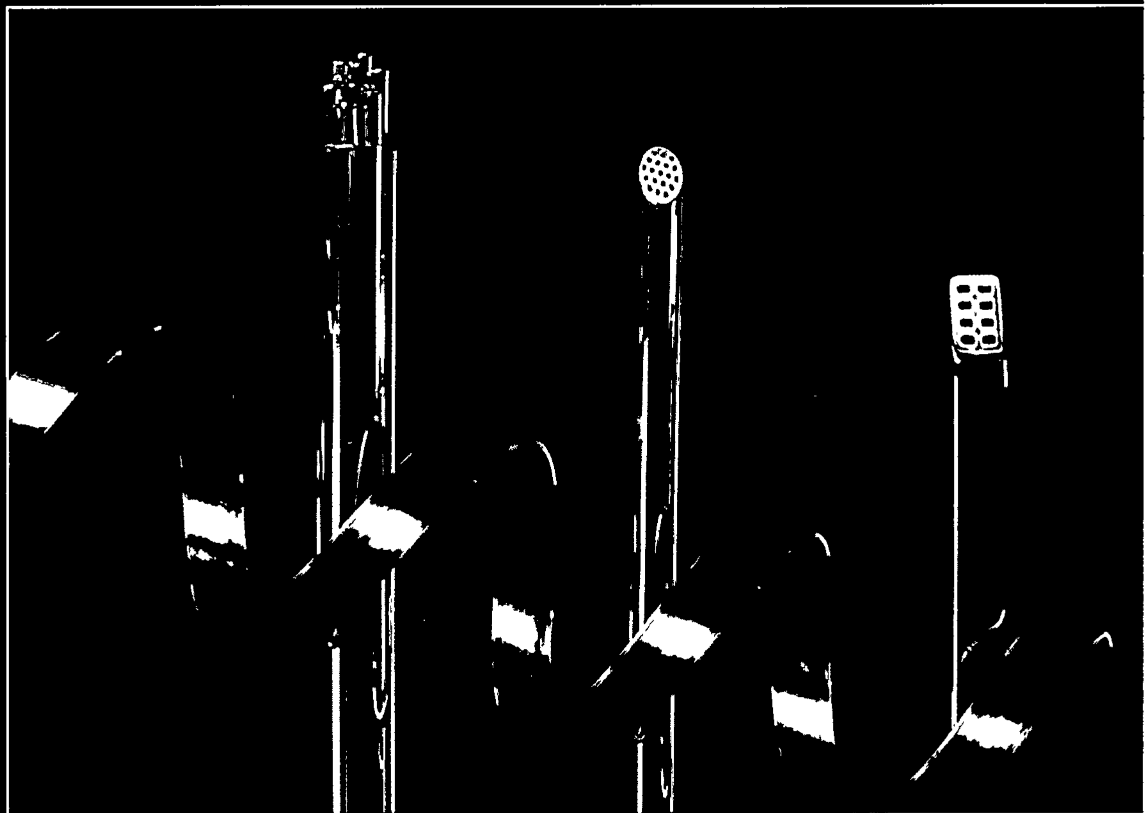

Superconductivity for Electric Systems Program Plan

FY 1996–FY 2000

U.S. Department of Energy

Cover photo: Flexible HTS wires are made of fine filaments of superconductive ceramics embedded in silver.

Credit: American Superconductor/PIX01607

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Table of Abbreviations and Units of Measure

A	Amperes
A/cm^2	Amperes per square centimeter
ANL	Argonne National Laboratory
ASC	American Superconductor Corporation
BSCCO	Bismuth-Strontium-Calcium-Copper-Oxide
DOE	Department of Energy
$/Am	Dollars per ampere-meter
EPRI	Electric Power Research Institute
FY	Fiscal year
GE	General Electric Company
HBCCO	Mercury-Barium-Calcium-Copper-Oxide
hp	Horsepower
HTS	High-temperature superconductivity
I_c	Critical current
IGC	Intermagnetics General Corporation
J_c	Critical current density
J_e	Engineering current density
K	Kelvin
LANL	Los Alamos National Laboratory
MRI	Magnetic Resonance Imaging
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
SPI	Superconductivity Partnership Initiative
TBCCO	Thallium-Barium-Calcium-Copper-Oxide
T	Tesla
T_c	Critical temperature
WDG	Wire Development Group
YBCO	Yttrium-Barium-Copper-Oxide

Introduction

High-temperature superconductivity holds a key to affordable electricity, bringing greater industrial competitiveness and improving the public's quality of life.

In late 1986, scientists discovered that an obscure branch of ceramic oxide compounds could conduct electric currents without losses from electrical resistance. They labeled this phenomenon "high-temperature superconductivity" (HTS). Since then, researchers have made steady progress toward creating the technology necessary for U.S. industry to proceed toward commercial development of super-efficient electric power technologies. This advanced power equipment has the potential to dramatically increase productivity and energy efficiency because it can be built smaller and still handle substantially larger currents than ordinary power equipment.

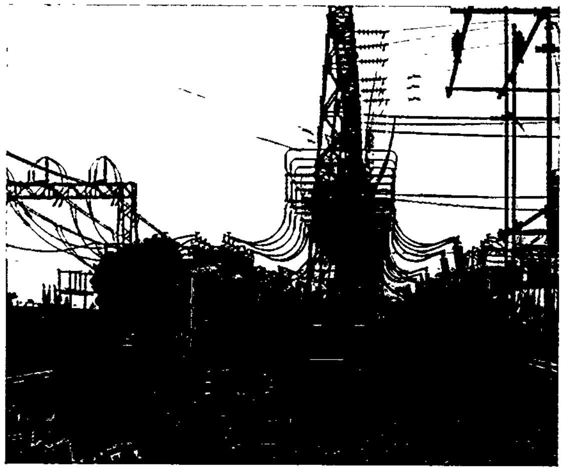
Today, applications only dreamed of in 1986 are within reach. However, HTS technology development remains a high-risk, high-payoff research and development activity. Much progress has been made, but much work still needs to be done for this breakthrough to have its predicted impact on the global economy.

Vision

By 2010, the U.S. power systems equipment industry will regain a major share of the global market by offering superconducting products that outperform the competition. In the United States, the power grid will gain increased efficiency and stability by incorporating many kinds of HTS devices.

Global Impact

Incorporating HTS components into commercial electric power equipment will provide global strategic advantages for U.S. industry in the 21st century. The potential impact of HTS applications was reinforced by a recent projection that the total global superconductivity market



Lockheed Martin/PIX03587

This Southern California Edison substation, and others like it around the United States, will become more reliable, efficient, and flexible thanks to innovative technologies like HTS transformers, fault-current limiters, and power cables.

(applications including electronic and electric power devices) will be worth $6 billion by the year 2000 and $45 billion by the year 2010. The forecast was made by an international superconductivity group representing the United States, Japan, and Europe.[1]

The National Critical Materials Council described HTS as a critical technology for American global competitiveness in the 21st century.[2] In addition, the White House and Congress have identified the development of HTS applications as a critical test of this country's ability to bring scientific discoveries to the marketplace.[3]

Increased Efficiency

Huge amounts of energy are lost in pushing electricity against the electrical resistance of conventional wires—usually made of copper. This results in everyone's electrical bill being higher because this energy would otherwise be used in lighting lamps or running appliances. Superconductivity gives an immunity to resistance—a way to both increase energy efficiency

The next generation of super-efficient electric power equipment will incorporate HTS components. Motors and generators will operate with half the losses and transformers will perform more efficiently and be less flammable.

[1] *Second International Superconductivity Industry Summit (ISIS), Hakone, Japan, May 1993.*

[2] *Report of the National Critical Technologies Panel, Office of Science and Technology Policy, March 1991.*

[3] *R. White, Department of Commerce Critical Technologies Workshop, Gaithersburg, MD, February 6, 1992.*

Figure 1

Benefits of HTS Applications to the National Electric System

UTILITY SYSTEM	Generation	Delivery	End-use
HTS Applications	Motors Energy storage (hours of storage) Generators Current leads Inductors	Fault-current limiters Energy storage (minutes of storage) Transmission cables Current leads Inductors/transformers	Motors Energy storage (seconds of storage) Magnets/coils Flywheels Current leads Inductors/transformers
HTS Benefits	Stability Reduced losses Flexible dispatch Reduced emissions	Reduced losses Stability Reliability Deferred expansion	Power quality Reliability Load management Increased efficiency

HTS applications in power equipment will significantly increase the efficiency and reliability of electric utility systems.

and greatly increase the amount of electricity that can flow through a wire.

Motors and generators made from HTS coils will be smaller, lighter, and more powerful and efficient as a result of their larger currents, higher fields, and smaller resistance losses. Transformers using HTS coils will be more efficient, less flammable, and have less environmental impact than conventional transformers. Transmission and distribution cables made from HTS wire will have increased current capabilities because of the high-current/low-loss properties of HTS wires. Inductive fault-current limiters made with HTS wire will provide increased power system stability, safety, and operation at higher voltage and current capacities than conventional equipment. Also, energy storage devices built with HTS coils will increase system stability, reliability, and power quality, and will provide power dispatch flexibility to meet increasing demand.

HTS-based motors, generators, and transmission cables can save 1-2 quads of energy per year in the United States. The potential savings represents 5%-10% of all the electricity presently generated by utilities. To put this in perspective, the total U.S. economy currently uses about 80 quads per year, with 20 quads of electricity generated by utilities. (One quad is equal to 10^{15} British Thermal Units.) Motors are predicted to have the largest near term impact because they currently consume as much as 60% of all the electricity delivered in the United States.[4]

Program Mission

This fiscal year (FY) 1996-2000 Multiyear Plan for the Superconductivity Program for Electric Systems describes a comprehensive, integrated approach for the development of HTS technology for cost-effective use in electric power applications. This approach supports the program's mission: to develop the technology that could lead to industrial commercialization of HTS electric power applications, such as fault-current limiters, motors, generators, transmission cables, superinductors, and superconducting energy storage. The U.S. Department of Energy (DOE) has supported the Superconductivity Program since its inception in 1988 and plans to continue with this support through 2000 when HTS technology is expected to be integrated into commercial electric power devices by the private sector.

Mission

The mission of the Superconductivity Program for Electric Systems is to develop the technology needed for U.S. industry to proceed to commercial development of electric power applications of HTS.

[4] *"Energy Applications of High Temperature Superconductivity." Oak Ridge National Laboratory/Electric Power Research Institute, 1989.*

Program Overview

Several major manufacturers are now developing entire electrical power systems based on HTS wire, a signal that HTS is now viable for use in utility applications.

After the exciting scientific discovery of HTS in 1986, industry around the world quickly recognized the enormous technological potential of the phenomenon. U.S., Japanese, and European researchers soon began a challenging, high-stakes race to apply HTS technology.

To help U.S. industry meet the challenge and capture the benefits of developing HTS electric power devices, DOE created the Superconductivity Program for Electric Systems in 1988. The program marries the entrepreneurial drive of high-tech companies with the vast technological resources of DOE's national laboratories to meet the enormously complex research challenge of developing HTS technology for electric power applications, breaking new ground as a highly interactive team effort among industry, national laboratories, and universities. This strong team effort is necessary to address the challenges inherent in developing electric power applications from the highly complex class of HTS materials.

The DOE national laboratories have a key basic research role in developing the fundamental technology necessary for HTS applications. The national labs will also participate as members of industry-led multidisciplinary teams that may also include universities. Private companies thus participate in the creation of new technology and gain immediate access. The strength of this approach is evident from the technology leadership position small U.S. industrial program participants have achieved against industrial giants in Japan and Europe.

Available program funds are allocated annually to projects that show the greatest promise for success and the greatest interest and commitment from industry.

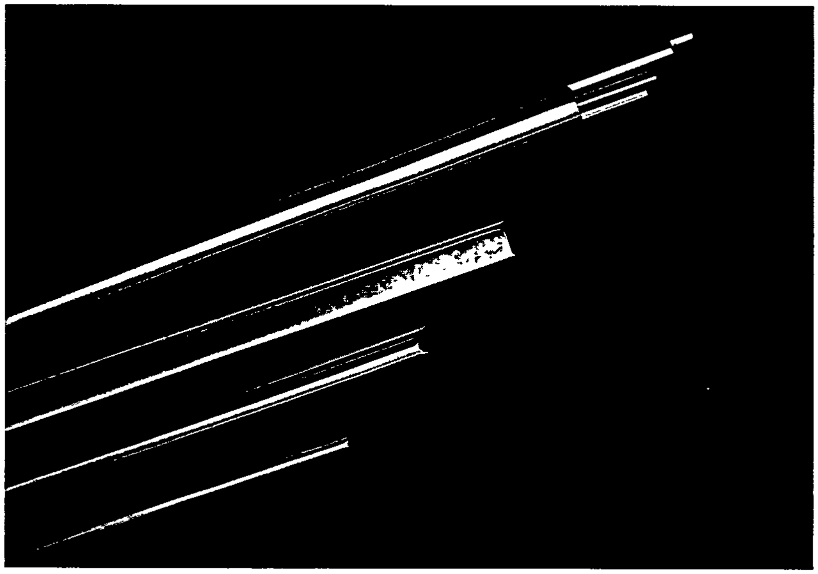
Program activities are organized into three categories. Together, they act to meet the program mission of developing the technology needed so that U.S. industry can proceed to commercial development of HTS electric power applications. These activities include:

Basic research in

- Wire technology, and
- Systems technology.

Applied research in

- The Superconductivity Partnership Initiative.



American Superconductor Corporation/PIX1604

A variety of HTS wire forms are used in the powder-in-tube wire manufacturing process.

Wire Technology

The underlying requirement for commercial electric power applications is a flexible and strong HTS wire capable of carrying large current in a magnetic field. The amount of current a given wire can carry before losing superconductivity is called its critical current, I_c. Another measure of a wire's ability to carry current is critical current density, J_c. Critical current density is simply the total amount of current a wire can carry (I_c) divided by the superconductor cross-sectional area. For optimum performance and cost effectiveness, wire I_c and J_c need to be maximized.

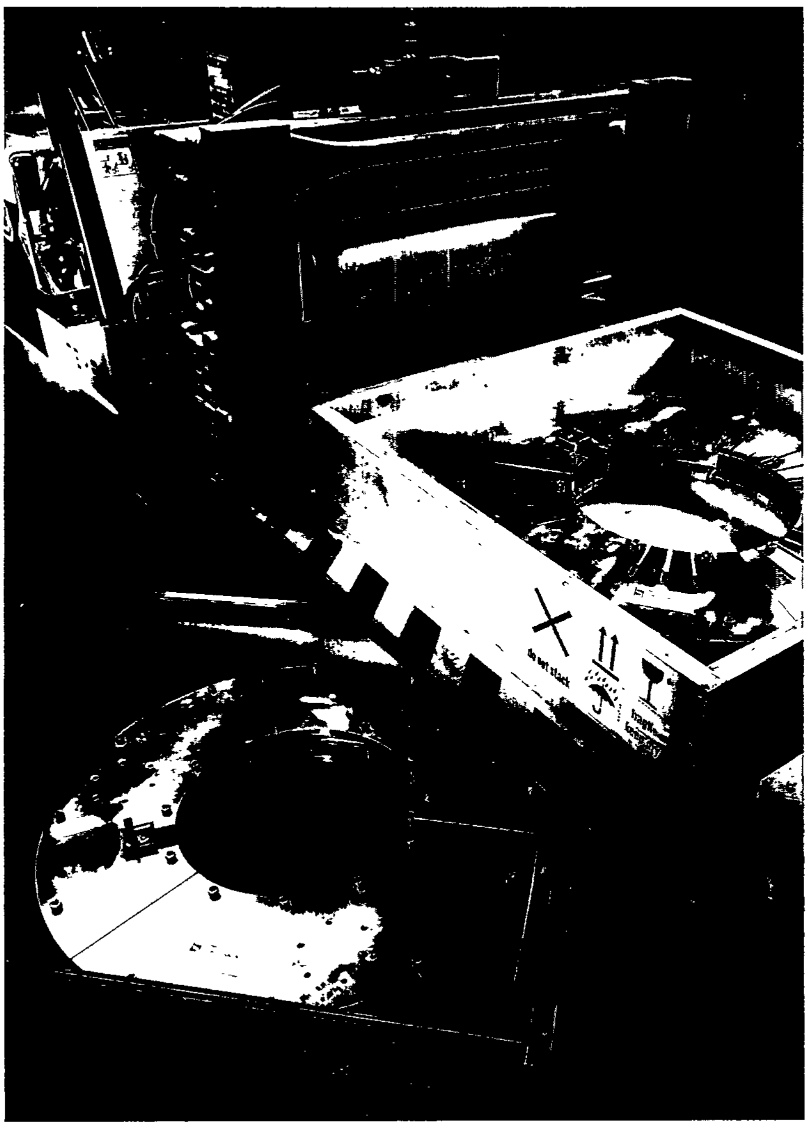
Presently, HTS wire fabrication technology needs improvement to meet cost and performance requirements for widespread application. To date, the program has supported both basic research and materials processing to improve the current-carrying capacity of short wire samples and scale-up of promising long-length manufacturing processes.

The development of HTS wire depends on solving problems related to current carrying capacity and mechanical strength with a continuous, cost-effective wire fabrication process. DOE national laboratories will have a lead role in research to develop the underlying technology for HTS wire and materials, collaborating with university researchers to understand issues such as flux pinning, weak links, and mechanical properties. The laboratories will do this research as members of laboratory/industry teams to develop HTS wire technologies that are scalable and amenable to integration with industry's continuous, cost-effective wire fabrication processes.

Systems Technology

Research efforts in this part of the program are focused on initial investigations of novel systems concepts and issues that are unique to superconductivity, which must be addressed before a mature HTS industry can develop. Long-length HTS wire and prototype components need to be designed, constructed, and tested, and the integration of HTS components into systems, as well as systems into the existing electric utility grid, must be carried out. These systems technology activities will also be collaborative projects with industry.

For insight into the progress and market for these devices and systems, and to help ensure that program funds are being directed to the most promising applications, industry and national laboratories will undertake benefit studies and other assessments. Industry will have the lead role in developing commercial HTS wire-making processes, components, and systems. DOE national laboratories will assist industry with underlying research challenges to help speed the development process. Special subcontractors will be funded through the laboratories to carry out specific tasks such as market assessments or materials characterization.



American Superconductor Corporation/PIX03588

These HTS coils are packed for delivery and ready for testing in the Lockheed Martin HTS fault-current limiter.

Figure 2

Recent HTS Highlights

Progress in Wire Technology

YBCO Wire

- 1.2 micron thick YBCO on Ni substrate with textured YSZ buffer layer yields 1,200,000 A/cm^2 at 75 K and 0 T and 200,000 A/cm^2 at 75 K and 1 T (LANL)

BSCCO Wire

- Rolled, multifilamentary Bi-2223 wire yields 44,000 A/cm^2 at 77 K and 0 T (ASC/WDG)
- Short, pressed Bi-2223 wire yields 74,000 A/cm^2 at 77 K and 0 T (ANL)

TBCCO Wire

- Electrodeposited wire made from Tl-1223 on Ag foil yields J_c of 68,000 A/cm^2 at 77 K and 0 T (NREL)
- Spray pyrolyzed Tl-1223 on ceramic yields J_c=325,000 A/cm^2 at 77 K and 0 T (GE/ORNL)

Progress in Systems Technology

Long-Length Wire

- 1180 meters, Bi-2223/Ag powder-in-tube wire manufactured by ASC with J_c=12,500 A/cm^2 (WDG)
- 1260 meters, Bi-2223/Ag powder-in-tube wire manufactured by IGC with J_c=12,000 A/cm^2 (ANL)

Coils

ASC: Bi-2223 coils

- At 4.2 K, B (field) = 3.3 T
- At 30 K, B = 2.6 T
- At 77 K, B = 0.6 T

IGC: Bi-2223 coils

- At 4.2 K, B = 3.2 T
- At 27 K, B = 2.2 T
- At 77 K, B = 0.38 T

Oxford: Bi-2212 coils

- At 4.2 K, B = 1.1 T
- At 15 K, B = 1.0 T

Systems and Components

- Recently began 2-year, $900,000 Southwire-led transmission cable project. Initial 1-meter cable yielded I_c of 800 A at 77 K at self-field (ORNL)
- Announced HTS transformer project with team members Waukesha Electric and Rochester Gas & Electric (ORNL)
- Demonstrated cryocooled HTS magnetic system that produces 0.82 T at 20 K and 0.15 T at 72 K with magnet I_c of 21 A at 77 K (IGC)
- Completed and tested 3.3-T HTS magnet for magnetic separator system to be demonstrated in 1996 (ASC/LANL)
- Flywheel energy storage: extremely low coefficient of friction demonstrated in prototype units suitable for >90% round trip efficiency (Commonwealth Research/ANL)
- Current leads: Demonstrated 1500-A HTS leads for Superconductivity, Inc. (ANL)
- Current leads: Designed and built components for 16-kA current lead system for Babcock and Wilcox (ASC/ANL)

Superconductivity Partnership Initiative

- Lockheed Martin successfully tested a 2.4 kV HTS fault–current limiter at a Southern California Edison substation
- 125-hp HTS motor and 100-MVA generator coil subset testing will be completed in early 1996
- 115-kV HTS transmission cable project is on track for successful test in 1998

Technology Partnerships and Transfer

- Signed a total of 97 Superconductivity Agreements with 38 active agreements including 9 CRADAS
- Granted 4 licenses for use of national laboratory technologies
- Issued 3 Technology Transfer reports to Congress
- Funded 4 Superconductivity Partnership Initiative projects worth over $10 million

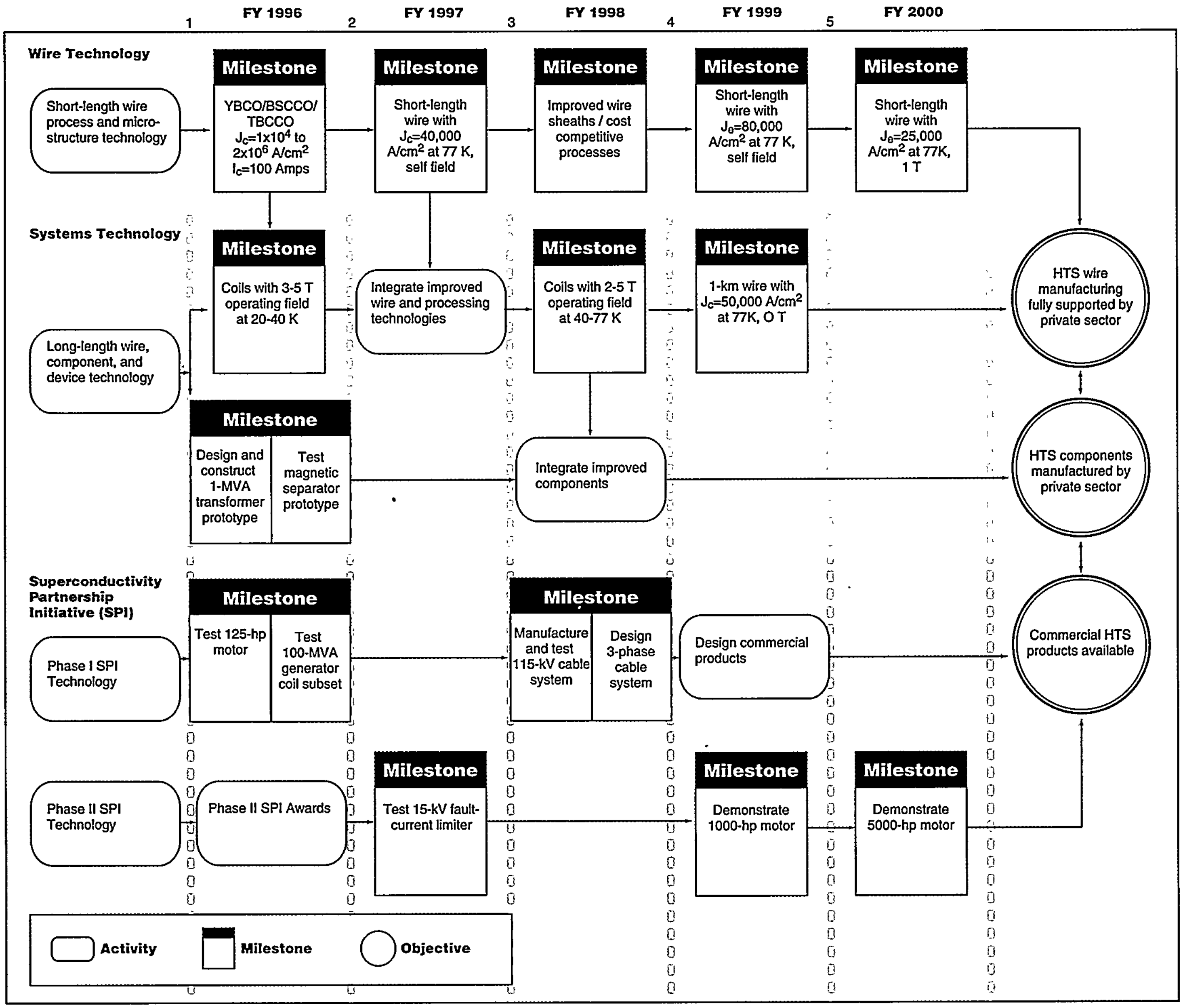
Commercial Products Derived from Program Discoveries

- Current leads (ASC/ANL)
- HTS powders via aerosol pyrolysis system (Superconductive Components, Inc. and ASC/ORNL)
- Cryogenic dewar coolant level sensor (Illinois Superconductor/ANL)
- Non-contact rapid screening system (Lakeshore Cryogenics/LANL)
- Sputtering Targets (Consultec Scientific/ORNL)
- Automated multilayer deposition system (Neocera/ORNL)

Researchers in DOE national laboratories and in private industry have made a number of advances in HTS technology in recent years. The advances include progress in developing HTS wire technologies and power applications.

Figure 3

Program Activities Flowchart



This flowchart summarizes the program plan through FY 2000. The goal of the plan is to have HTS commercial products produced by U.S. companies available early in the next century.

Superconductivity Partnership Initiative

The Superconductivity Partnership Initiative (SPI) is an integral part of the program and is designed to accelerate the introduction of HTS electric power devices to the marketplace. It is organized around vertically integrated teams that develop complete systems. All aspects of development are addressed in parallel by wire and component manufacturers, systems integrators, and utilities. End users are involved to encourage focused, relevant effort. The industry-led projects sponsored under the initiative also benefit from progress made in wire and systems technology.

Each SPI project includes the design and testing of experimental systems. Upon successful completion of testing, the project team leaders are encouraged to begin commercialization activities.

In addition, conceptual designs of HTS devices are included in the systems technology area of the program.

Figure 2 (page 7) illustrates recent HTS highlights. These highlights are largely the result of collaborative projects within the program. Since inception, DOE and the private sector have spent over $64 million on these collaborative efforts.

Program Plan

The successful transition of HTS technology from research laboratories to commercial industry hinges on the concurrent development of wire, components, and system prototypes.

The overall program plan is based on meeting the program mission. This plan, or road map, is presented in Figure 3, and details the concurrent research and development tracks used to manage the large-scale technology development challenge that HTS presents. As shown by the figure, successful translation of HTS technology from the laboratory to industry relies heavily on parallel development of wire, systems, and prototypes. Continued simultaneous progress in HTS wire technologies provides the pathway to an industrial manufacturing base.

To accomplish these plans, large, integrated efforts are required in all program areas. These efforts will be supported through basic HTS research at national laboratories, and collaborations among the national laboratories, industry, universities, and other organizations. The role each organization plays will be discussed in the following sections.

Intermagnetics General Corporation/PIX03589

This Bi-2223 HTS tape has been made in continuous lengths of over 1200 meters by Intermagnetics General Corporation in collaboration with Argonne National Laboratory.

Wire Technology

Research has concentrated on processing the superconducting compounds presented in Figure 4. These compounds are in the superconducting families of yttrium-barium-copper-oxide (YBCO), bismuth-strontium-calcium-copper-oxide (BSCCO), and thallium-barium-calcium-copper-oxide (TBCCO). Recently, HTS was discovered in another family, mercury-barium-calcium-copper-oxide (HBCCO), which shows superconductivity in certain phases and under certain conditions up to 160 Kelvin (K).

Figure 4

HTS Compound Families

FAMILY	SPECIFIC COMPOUND	T_C (K)
Yttrium-Barium-Copper-Oxide (YBCO)	$YBa_2Cu_3O_{7-\delta}$ (Y-123)	92
Bismuth-Strontium-Calcium-Copper-Oxide (BSCCO)	$Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223)	85 110
Thallium-Barium-Calcium-Copper-Oxide (TBCCO)	$TlBa_2Ca_2Cu_3O_{9+\delta}$ (Tl-1223) $Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$ (Tl-2223)	122 125
Mercury-Barium-Calcium-Copper-Oxide (HBCCO)	$HgBa_2CuO_{4+\delta}$ (Hg-1201) $HgBa_2CaCu_2O_{6+\delta}$ (Hg-1212) $HgBa_2Ca_2Cu_3O_{8+\delta}$ (Hg-1223)	94 117 135

Research areas include the synthesis and heat treatment of HTS wires; forming of monofilament and multifilament composite wires and thick films; design and fabrication of HTS/metal interfaces; characterization of HTS electrical and mechanical properties; and fabrication and evaluation of wire forms, such as coils and cables, which are necessary for HTS wire use in electric power applications.

The principal focus of wire technology activities is to transform brittle HTS ceramic materials into long, flexible wires and tailor HTS wires to remain superconducting in the presence of high magnetic fields. Figure 5 describes why researchers need to gain a better understanding of how to improve flux pinning and minimize weak links between the grains. Weak flux pinning allows external magnetic fields to adversely affect operating temperature and critical current. Weak links adversely affect critical currents.

Research activities involve all three HTS materials families, since each HTS materials system possesses a different combination of weak link and flux pinning problems. For example, bismuth-based compounds exhibit good grain linkage but poor flux pinning at temperatures above 35 K. Yttrium- and thallium-based compounds tend to have better flux pinning than

Program researchers are studying a number of compounds with desirable characteristics that become superconducting at critical temperatures, T_c, substantially above those of previously known superconductors.

Figure 5

Obstacles to Large Currents in Magnetic Fields

Researchers are working to overcome two challenges in developing HTS materials: weak links and lack of flux pinning. Weak links occur when crystalline grains are poorly bonded, either due to the presence of impurities or imperfections, or because of improper alignment. Weak links reduce the critical current, J_c, of the material. Lack of flux pinning allows the magnetic field lines to move within the material, which dissipates energy and causes losses.

The various HTS materials systems each display characteristic flux pinning and characteristic linkage between the grains. The YBCO system suffers from poor intergranular current flow due to weak links, but it displays excellent flux pinning. The BSCCO materials can be made with strong links between grains, but flux pinning is poor. The TBCCO system falls between the other two with reasonably strong links and moderate flux pinning. In the search for high-current, high-field wires at 77 K, none of the systems give complete performance.

BSCCO is currently the system of choice by the HTS wire industry. However, wires are severely limited in the ability to perform above 1 T (35 K). YBCO materials have not lent themselves to standard wire manufacturing techniques, but recent textured substrate developments at several national labs have led to coated tapes which display current densities in excess of 1,000,000 A/cm^2. Work continues on both systems.

bismuth materials, but these compounds can have weak link problems that limit current flow.

A final complexity in the wire technology problem is the anisotropic nature of HTS materials—their properties are not the same in all directions. Because of their anisotropic properties, HTS materials are extremely difficult and complicated to process. The goal is to align the HTS grains, creating "texture" to achieve the best possible links between grains and, therefore, the highest current flow possible.

Understanding of the basic science of HTS wire fabrication and processing has progressed to the point where researchers are focusing on a few promising materials—Y-123, Bi-2212, Bi-2223, and Tl-1223 compounds. Shapes other than wires, such as current leads and magnetic bearings, are usually manufactured from Y-123. Techniques for making wire vary, but the best results in long lengths are currently obtained using the powder-in-tube process. The manufacturing improvements have been

Wire Technology Goals

- *Develop processing technology for fabricating HTS wire that meets the application requirements for high current density in magnetic fields, flexibility, strength, chemical stability, low-cost, and large-scale processing.*
- *Fabricate HTS wire possessing all of the following minimum performance characteristics:*
  - *Current: 100-1000 A,*
  - *Current density: 10,000-100,000 A/cm^2,*
  - *Geometry: 0.1-1.0 mm^2 HTS cross-section, 100-1000 meter length,*
  - *Strain tolerance: 0.5-0.7% with minimal loss of critical current density,*
  - *Magnetic field tolerance: 2-5 T (for devices requiring field tolerance), and*
  - *Operating temperature: 4.2-77 K (depending on target application).*
- *Improve the magnetic flux pinning of Bi-oxide HTS materials to improve critical current in magnetic fields. This improvement can be accomplished by introducing defects in the HTS core or by adding impurities that act as pinning centers.*
- *Minimize weak links in Y- and Tl-oxide HTS materials in order to raise critical current, operating field, and operating temperature. This minimization can be accomplished by developing improved starting materials, and understanding the relationships between wire processing and phase development.*
- *Increase the strength and decrease the cost of the sheathing used in powder-in-tube type wires. Currently, high purity silver is used as a sheathing material because of its chemical inertness with the HTS core material and its permeability to oxygen. For HTS wires to be economically viable, alternative, less expensive, higher strength sheaths need to be developed.*
- *Improve wire processing techniques to eliminate density variations induced during tube loading and processing, and improve HTS core texture. This can be accomplished by developing new powder loading techniques, monitoring processing in real time by nondestructive techniques, and understanding the relationships between phase formation and processing variables.*

accomplished by better understanding the interrelationship between the micro-structure of HTS materials, processing variables, and electrical performance.

Organizational Roles: To accomplish the activities described above, industry, national laboratories, and universities assume complementary roles. The national laboratories are crucial to solving the underlying basic research and engineering problems in HTS wire making and in supporting the transfer of HTS wire technology to industry by providing research in the following areas:

- Materials synthesis and properties,
- Critical currents and microstructures, and
- Fabrication processes.

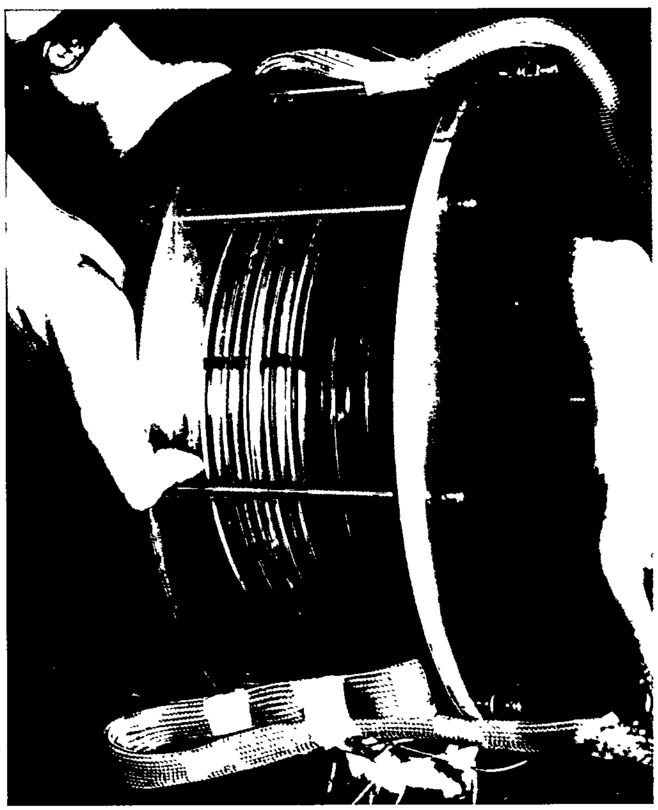
Universities will provide expertise in areas where their capabilities meet program needs and provide support in the following areas:

- Microstructural studies,
- Precursor synthesis, and
- Other HTS materials science and engineering issues.

A significant recent accomplishment is the development of long, flexible textured substrates for HTS wire that allow near perfect alignment of HTS grains. This outstanding alignment virtually eliminates weak links and yields HTS wire J_c values that exceed 1,000,000 A/cm^2 at 77 K. Presently these techniques are only available in the lab, but major efforts by industry and national laboratories are underway to determine if these new techniques are scalable and cost effective for manufacturing.

Universities will work with the national laboratories through multiparty collaborative agreements with industry or through subcontracts.

Industry will lead multidisciplinary teams that include researchers from the national laboratories and universities, as well as their own companies. These teams will jointly develop the new technical capability to manufacture HTS wires that meet cost and performance requirements. Industry will have primary responsibility for scale-up issues while the national laboratories and universities have key basic research responsibilities. Teams will also develop innovative new designs for wire, using systems such as generators, motors, and transmission cables. This industry-led creation of new technology ensures that the program goal of rapidly bringing HTS to the marketplace will be achieved.



Intermagnetics General Corporation/PIX03581

This 3.2 Tesla high-field magnet was built by Intermagnetics General Corporation in collaboration with Argonne National Laboratory. The magnet uses over 2 kilometers of Bi-2223 HTS wire.

Systems Technology

Long-length wire development remains a crucial aspect of the program. Combining the progress from short-length samples and processing scale-up techniques, industry continues to set new HTS wire performance records. Figure 6 shows recent U.S. long-length wire results. For example, a 1160-meter length of BSCCO/Ag powder-in-tube type wire with a J_c of 12,700 A/cm^2 along the entire wire length was fabricated by American Superconductor Corporation. The wire now produced can be incorporated into near-term applications such as motors, generators, power transmission cables, and fault-current limiters.

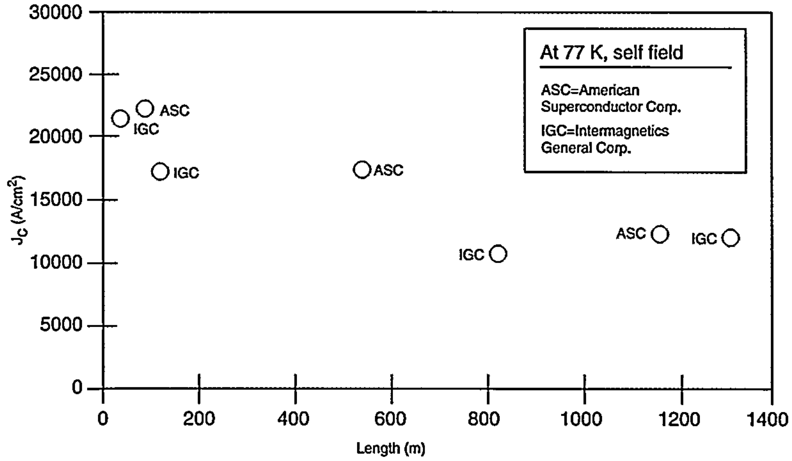
Coils made with Bi-2223 wire are now being manufactured and tested. Presently, the fields produced by the coils at 77 K exceed 0.5 Tesla (T). This should improve as high current, long-length HTS wires are developed. Figure 7 (page 14) describes the recent progress in U.S. coil development. These coils will be thoroughly tested and characterized, allowing feedback for improved design and manufacture. Simultaneously, cooling and other operating equipment will be designed and tested. The parallel efforts of device testing, characterization, and other support will provide a solid base for systems technology activities.

It is also anticipated that the program will continue to assess the benefits of HTS wire and systems technology. Technology, market, and economic evaluations will be conducted using a systems perspective to evaluate the probability of achieving technical and commercial success for HTS components in the midterm. The types of studies to be conducted include:

- Life-cycle cost studies to identify the operational benefits of installing HTS devices into systems versus non-superconducting or low-temperature superconducting devices,
- Technical assessments of various design approaches for HTS technology (motors, generators, transmission cables, fault-current limiters, etc.),
- Assessments of the potential market size for HTS technologies and an analysis of the energy and economic benefits that might accrue to the nation if the market were realized, and
- Assessments or models to evaluate the environmental benefits of incorporating HTS technologies.

Figure 6

Current Densities in HTS Wires



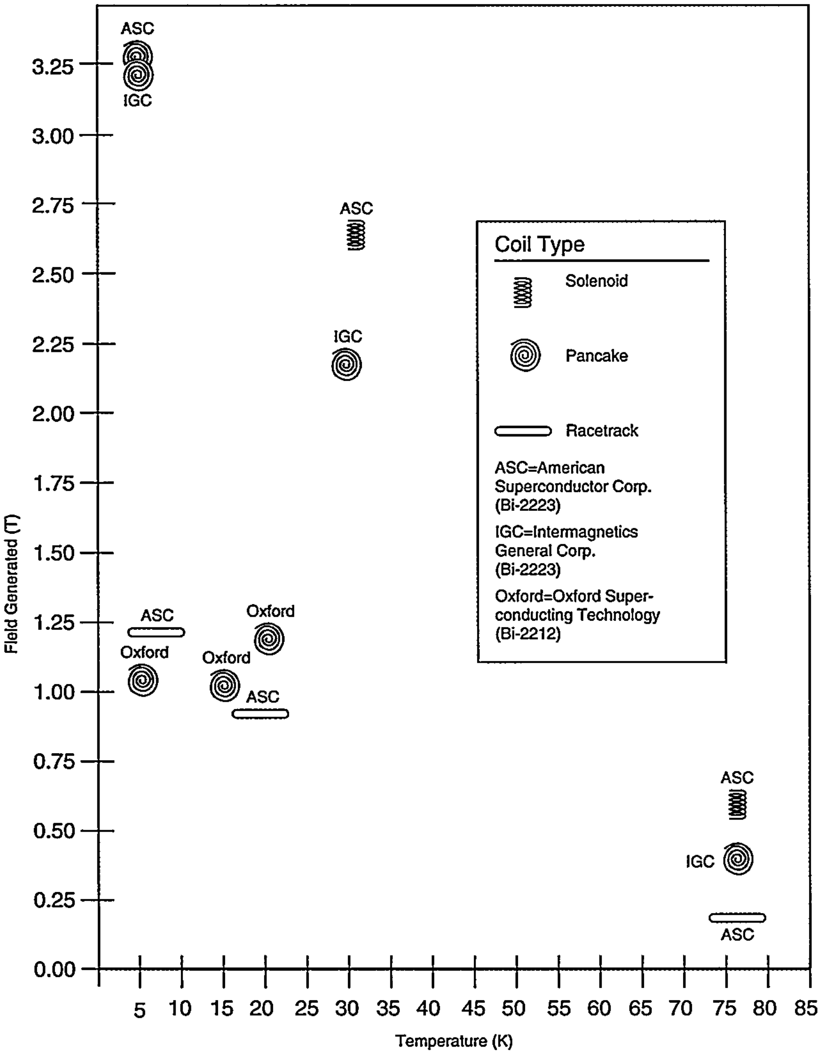
Several U.S. companies have recently developed HTS wires in relatively long lengths. The remaining challenges are to lower cost and increase performance to meet application requirements.

Systems Technology Goals

- *Develop properties suitable for use in electric devices, including fault-current limiters, transmission cables, motors, magnetic resonance imaging units, magnets, and generators;*
- *Assist industry in producing long-length HTS wire that can support the development of applications such as fault-current limiters (2.4 kV), motors (125 hp), transmission cables (30 meters, 115 kV, 1000 A dc) and small generator coils (100 MVA);*
- *Configure wires into cost-effective, strong-field forms (coils) suitable for use in electric power devices;*
- *Configure wires into cost-effective, high-current forms needed for electric transmission cables; and*
- *Support the development of high-magnetic-field equipment and high-current applications such as transformers, flywheels, transmission cables, motors, generators, magnetic separators, current limiters, current leads, and magnetic energy storage.*

Figure 7

HTS Coil Performance



Three U.S. companies have recently produced HTS coils that can sustain larger magnetic fields at low temperatures and can also operate at relatively high cryogenic temperatures. The challenge is to produce coils that can operate with both high magnetic fields and high temperatures.

Organizational Roles: To accomplish the activities and objectives described above, flexible planning for systems technology will be key to taking advantage of HTS advances as they occur. These advances may include improved long-length HTS wire processing or improvements in refrigeration technologies.

In systems technology, industry assumes a larger and more direct role than in wire technology. National laboratories again act as centers of excellence to solve problems beyond the scope of industry. Industry participates through collaborative agreements with national laboratories. These agreements are directed toward solving key problems in developing scalable, cost-effective HTS wire processes; systems integration; and other technologies such as cryogenics and modeling. Most systems technology activities are highly leveraged, with industry typically cost sharing 50% of a project.

Superconductivity Partnership Initiative

The purpose of SPI is to accelerate the time to initial commercial introduction of energy-saving HTS systems. To do this, SPI fosters vertical teaming among HTS wire manufacturers, component suppliers, and end users, with help available from national laboratories. SPI specifically addresses Section 1202 of the Energy Policy Act of 1992[5] which covers demonstration and commercial application projects for renewable energy and energy efficiency technologies and amends Section 6 of the Renewable Energy and Energy Efficiency Technology Competitiveness Act of 1989. Three awards for SPI resulted from a competitive solicitation in the summer of 1993. A fourth award was announced in the fall of 1994. Industry cost sharing for the four SPI awards is 48%. Additional DOE funds support national laboratory research supporting the SPI teams.

Current SPI activities focus on the following applications: motors, fault-current limiters, generators, and transmission cables. Figure 8 describes the pertinent features of the SPI and outlines the members of each of the four teams. DOE's investment is contributing to a strong, emerging HTS industry in the United States, which is already making wires in lengths and capacities useful for many applications.

Organizational Roles: The funding mechanism for the SPI differs from typical national laboratory and industry collaborations. Each SPI project has a team leader that is funded directly from DOE through financial assistance awards. Each team then divides the funding as described in its contracts. SPI teams can request the assistance of national laboratories. This assistance is arranged through conventional collaborative agreement mechanisms.

[5] *"Energy Policy Act of 1992, Public Law 102-486, October 24, 1992.*

Figure 8

The Superconductivity Partnership Initiative

- The unique SPI structure of vertically integrated teams forms alliances along the market channel and joins forces in an impressive cooperative effort between government and industry.
- The goal is to accelerate the development and initial commercialization of HTS products with introduction to the marketplace within the next 5 to 10 years. This will create a new generation of power equipment within the next decade.
- It will create a relationship of trust and partnership between the government and the private sector, which is ready to commit to HTS equipment commercialization.

The project teams are:

Team 1: Fault-Current Limiter
- Lockheed Martin
- American Superconductor Corporation
- Southern California Edison
- Los Alamos National Laboratory

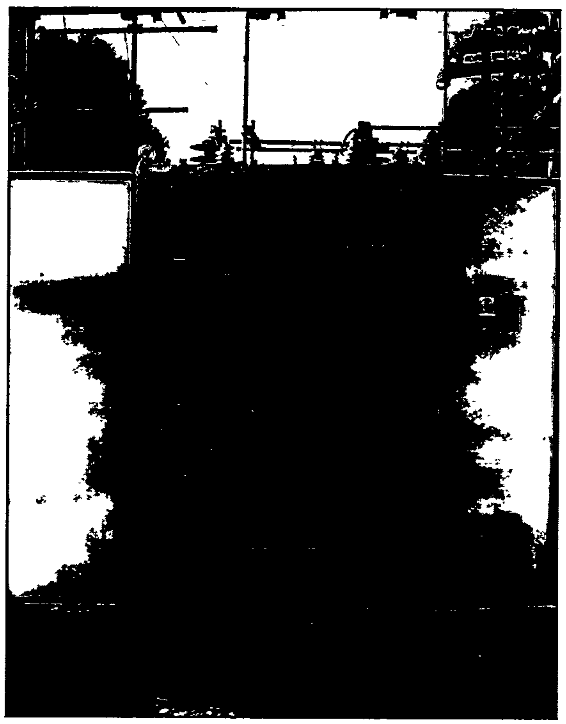
Team 2: Generator
- General Electric Company
- Intermagnetics General Corporation
- Niagara Mohawk Power Corporation
- Electric Power Research Institute
- New York State Institute on Superconductivity
- New York State Energy Research and Development Authority
- Argonne, Oak Ridge, and Los Alamos National Laboratories

Team 3: Motor
- Reliance Electric Company
- American Superconductor Corporation
- Centerior Energy
- Electric Power Research Institute
- Sandia National Laboratories

Team 4: Transmission Cable
- Electric Power Research Institute
- Pirelli Cable Corporation
- American Superconductor Corporation
- Los Alamos and Oak Ridge National Laboratories

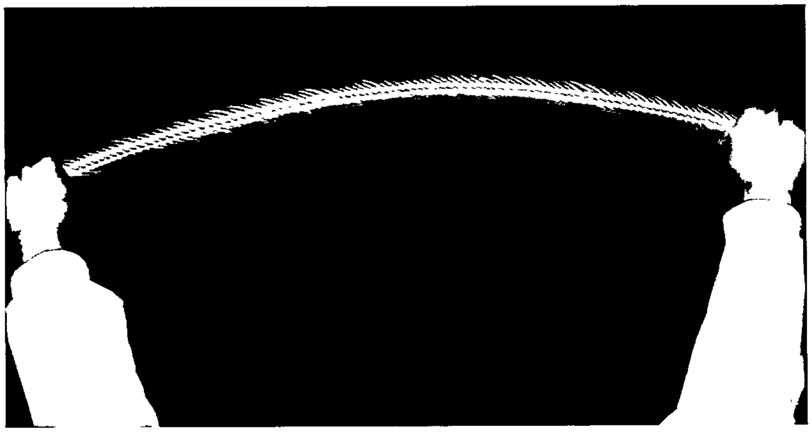
Industry has the lead role in the SPI projects, carrying out HTS technology development activities that will lead to the design, building, and testing of electric power applications. National laboratory support is directed toward specific, high-value development issues such as modeling and design that complement industry's capabilities.

DOE plans to announce Phase II SPI awards in early FY 1996, depending on availability of funds. Additional Phase I and Phase II projects will be funded in the future to maintain a continuous portfolio of projects designed to take advantage of improvements in HTS wire and component properties as they are developed. These projects will also consist of vertically integrated teams that will initiate commercialization activities after prototype testing. The projects will further add to the technology and manufacturing capabilities developed in other parts of the program and will help develop a commercial market for HTS products supplied by U.S. manufacturers.



Lockheed Martin/PIX03582

This prototype 2.4 kilovolt HTS fault-current limiter was successfully tested by Lockheed Martin in September 1995 at a Southern California Edison substation.



American Superconductor Corporation/PIX1605

HTS power cables, such as this 1-meter section, will be flexible and carry 3-5 times the current of conventional copper cables.

Technology Status

Coordination of utilities, small businesses, systems integrators, research laboratories, and universities has led to outstanding technical progress.

The excellent cooperation among participants in the program has led to astonishing progress in HTS technology. World records have been set for the highest magnetic field, the highest current, the largest current density, and the longest wire ever made from HTS. The following section describes the status of HTS technology as applied to electric power systems and how progress to date impacts the program, its plans, and strategy.

There are a few key HTS parameters that must be optimized for HTS systems to be commercially viable. These include:

- Critical current,
- Operating temperature and field, and
- Cost.

Critical Current

Equipment used in the electric power industry, such as motors, generators, transmission cables, and current leads, must be capable of carrying large currents and operating in high magnetic fields. To operate efficiently in power equipment, HTS wire must be able to maintain high critical currents (measured in I_c and J_c) in the presence of large magnetic fields.

Figure 9 summarizes the progress made in HTS wire critical currents since the inception of the program. I_c is multiplied by total wire length to give a useful characteristic, in amp-meters, to measure the concepts of wire performance and usefulness. The applications charted are leading candidates for incorporation of HTS components. Applications requiring the highest I_c, J_c, and wire length appear in the upper right corner and the less demanding applications, from a wire performance perspective, appear in the lower left corner. A wire J_c of at least 10,000 A/cm^2 is required for nearly all important electric power applications.

As shown in the figure, the earliest application with sufficient wire performance was current leads. Current leads are now commercially available from several vendors and performance continues to improve as the technology for making them matures. General Electric incorporated HTS current leads in its new, cryocooled magnetic resonance imaging (MRI) unit.

Recent progress in wire manufacturing, specifically the ability of industry to manufacture 100–1000 meter lengths with J_c above 10,000 A/cm^2 at 77 K, has allowed industry to begin

Goals of the Superconductivity Partnership Initiative

- *Develop and test a prototype fault-current limiter, using HTS wire, by late 1995,*
- *Develop and test a prototype 125-hp motor, based on coils constructed of HTS wire, by early 1996,*
- *Develop and test a prototype 100-MVA generator coil, constructed with HTS wire, by early 1996,*
- *Award SPI Phase II projects by early 1996,*
- *Develop and test a 30-meter, 115-kV, 1000-A cable by the end of 1997,*
- *Assist industry in providing marketable fault-current limiters, motors, generators, and transmission cables based on results from Phase I prototype testing, and*
- *Assess the economic and market potential of HTS generators, motors, power transmission cables, and fault-current limiters.*

manufacturing and testing coils and cables from HTS wire. The need now is for uniform, long-length HTS wire with improved flux pinning and reduced weak links that is stable, flexible, and carries even larger currents in magnetic fields.

Operating Temperature and Field

Commercial HTS electric power applications require HTS wire operation in magnetic fields that range from almost negligible (transmission cables) to very strong (motors, generators, and current limiters). As a result, HTS wire not only must carry large currents and have a high current density, but also must maintain these properties in strong magnetic fields.

Performance degradation in magnetic fields is a crucial problem with all HTS materials, and hence, HTS wire. Each type of HTS wire has a maximum field, at specific temperatures, in which it can operate. Each HTS compound has different field characteristics. The goal is to make wire that can conduct high current at the highest fields and temperatures possible.

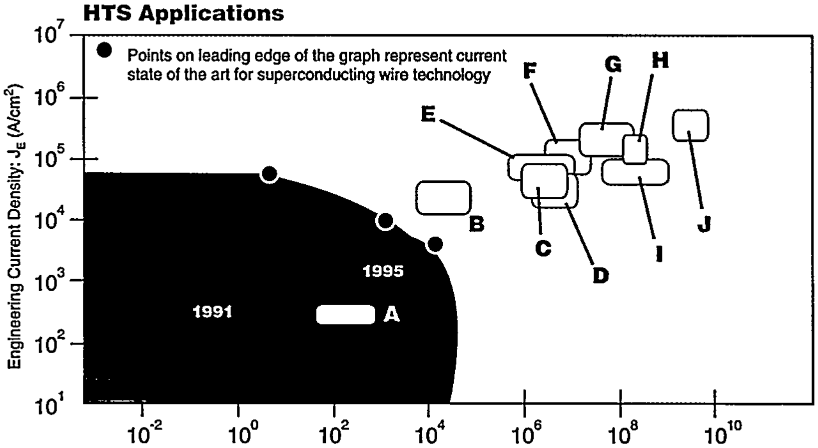
There are vast savings gains possible by operating equipment at higher temperatures than the liquid helium temperature (4.2 K) needed for low-temperature superconductors. Figure 10 (page 18) shows that operation at liquid nitrogen temperature (77 K), saves 90% of this energy. Operating at 20 K, saves 75%. Benefits will vary depending on the actual cooling scheme used. Operating at 35 K and higher is much less demanding on cryogenic equipment, leading to greater system reliability and service life, and lowering capital and operating costs dramatically.

Cost

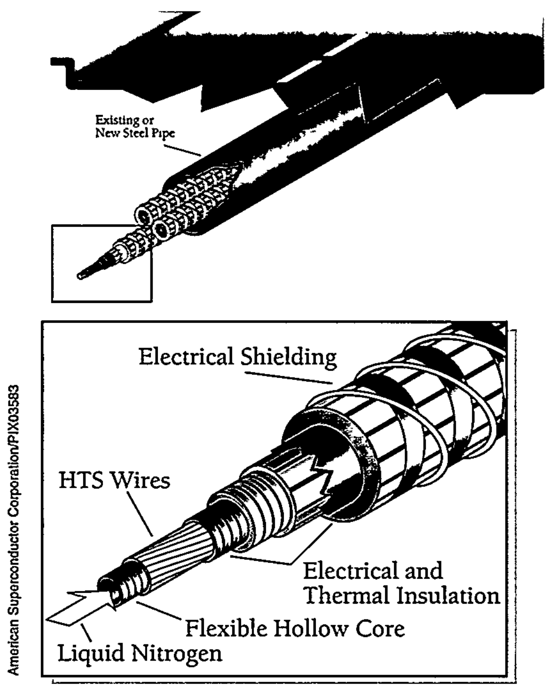
The final, and, arguably, the most important issue is cost. HTS wire cost is evaluated in terms of dollars per ampere-meter, or $/A-m. HTS wire currently costs approximately $1.00/A-m. Systems integrators who will use this wire in HTS-based electric power applications estimate that the cost of HTS wire must drop to around $0.01/A-m before HTS-based systems are expected to achieve widespread application. While lowering cost is an industry effort, any progress in the program that helps industry manufacture longer HTS wires with greater current carrying capabilities will directly lower cost. In addition, improvements to wire strength and starting materials will help improve processing and lower cost.

Figure 9

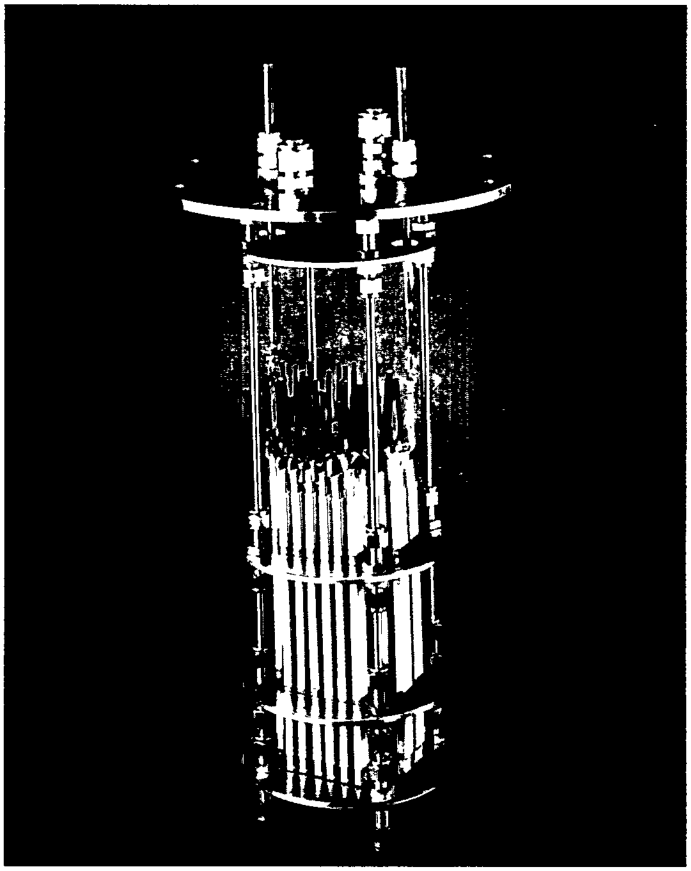
Wire Requirements and Progress for Commercial HTS Applications



A Current Leads
Wire: Current x Length (A-m)
B Fault-Current Limiter
C EPRI Transmission Cable (500 m)
D Transformer (100 MVA)
E European Transmission Cable (500 m)
F Motors (5,000 hp)
G SMES (1 MW)
H MRI
I Generators (300 MVA)
J SMES (0.5 MWh)



HTS underground transmission cables, such as this design developed by the Electric Power Research Institute, Pirelli Cable, and American Superconductor Corporation, can increase power transmission capacity 3-5 times without requiring excavation for new pipes.

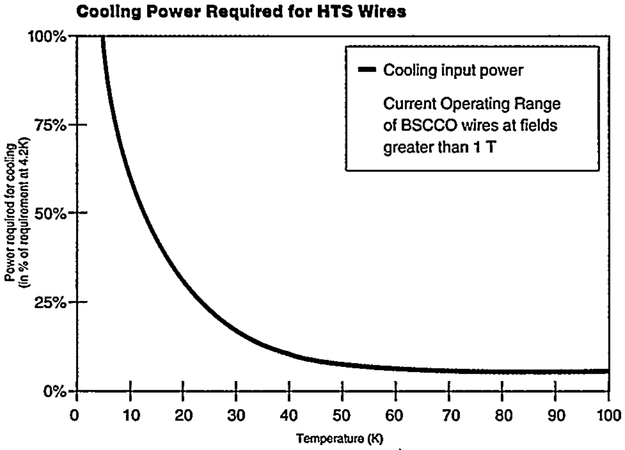


Illinois Superconductor Corporation/PIX3660

Illinois Superconductor Corporation's superconducting fault-current limiter is designed to prevent damage from electrical power surges caused by lightning strikes, short circuits, and other utility grid problems.

Figure 10

Cooling Power Required for HTS Wires



The ideal power required for refrigeration for HTS applications at 35 K is less than 10% of that required for low-temperature superconductivity applications at 4.2 K. Actual power requirements will vary depending on cooling scheme chosen and system efficiency.

Program Strategy

Developing HTS wire is a complex undertaking that no single organization can achieve on its own. Because of this complexity and the trade-offs offered for various wire-making approaches, the program strategy is to develop HTS wire possessing high current density in high fields, conditions necessary for application in electric power systems. Less emphasis is placed on operating temperature, although the higher the temperature at which a system can operate, the simpler the cooling system will be, resulting in lower costs and higher reliability.

In light of this strategy, program participants are focusing on the following approaches:

- Producing the best possible HTS wire with available processing techniques and HTS materials, and
- Improving lab-scale processes that can raise HTS wire operating temperature, current capacity, and magnetic field tolerance.

The first approach is the focus of about half of the wire activities in the program, for which Bi-2223 and Bi-2212 are the compounds used to make wire. These compounds are the most amenable to the techniques currently available to manufacture long lengths of wire with good performance. The operating temperature envelope for these types of wire is 4.2-40 K in magnetic fields and up to 77 K in low or self fields.

National laboratories, universities, and industry work together to improve Bi-2223 and Bi-2212 wire. National laboratories and universities work to improve the understanding of material properties and how processing influences final wire performance. Industry incorporates these findings into their processing schedules, producing wire with ever-increasing currents and lengths.

The wire making technique that leads to the best available HTS wire, the powder-in-tube method, relies on the well-known industrial techniques of drawing and rolling. In this process, silver tubes are loaded with HTS precursors and then processed by a complex combination of drawing, rolling, and heating. The final wire is a core of HTS surrounded by silver alloy.

These wires are currently being made into coil prototypes that will be used in magnetic separators, motors, current limiters, transformers, and in other applications such as transmission cables.

The second approach is the focus of the remaining wire technology activities. Here, Y-123- and Tl-1223-based wires are being developed at national laboratories in collaboration with industry. Wire made from these compounds has potentially superior capabilities in high magnetic fields compared to Bi-based wires. However, rolling and drawing techniques that work for Bi-wire have not worked well for Y-123 or Tl-1223. New techniques have been developed that yield short wire with current densities near 1,000,000 A/cm^2 in magnetic fields. Research is now focused on making these techniques scalable so that industry can develop them into cost-effective processes.

As described in Figure 9 (page 17), HTS wire performance continues to improve as HTS technologies mature. New techniques that promise even better performance wire at high operating temperatures are being developed at national laboratories, universities, and in industry. Each improvement in wire allows systems designers to build more powerful coils and systems. The program will continue to support these efforts until sufficiently high performance HTS wire is commercially available from wire makers.

American Superconductor Corporation/PIX03584

American Superconductor Corporation's HTS wire manufacturing process is capable of repeatedly manufacturing 200-meter lengths of high performance wire.

Jim Yost/PIX1506

The laser ablation process creates extremely high quality films of HTS. The process is not yet feasible for wire manufacturing, but recent developments are promising.

Stakeholders

The enormous potential of HTS power applications has attracted many participants.

Many HTS applications exist in the electric power system, spanning all sectors of the electric utility system—generation, transmission, distribution, and use. As a result, the program has attracted many stakeholders, including utilities, industry, and government.

Utilities

Electric Utilities: Electric power utilities are meeting increased demand while facing competitive forces in a changing marketplace, including pressures to deregulate and mitigate environmental impacts. These pressures to cut costs, improve service, and meet demand are forcing utilities to implement new cost-effective technologies. HTS electric power devices will provide electric power utilities with increased efficiency and flexibility across the entire utility system.

Industry Research Organizations: The Electric Power Research Institute (EPRI) is a key research organization for the electric utility industry. EPRI performs near-term research, funds technology demonstrations, and disseminates findings to its member utilities. EPRI has participated in collaborative agreements and coordinates research with DOE's Superconductivity Program for Electric Systems.

Industry

Manufacturers of Wires and Devices: A large potential electric power market has been identified in industrialized and emerging growth countries. Therefore, industry, from small, entrepreneurial businesses to large systems integrators, has a strong interest in developing commercial products. Industry will remain actively involved in the program through the SPI and collaborative projects with national laboratories.

End Users: End users of electricity, such as paper mills, textile manufacturers, and semiconductor manufacturers, will benefit from increased efficiency, smaller size, flexibility, and power quality offered by HTS electric power devices.

Government

National Laboratories: Research on HTS electric power technologies is performed at the following DOE national laboratories: Argonne National Laboratory, Brookhaven National Laboratory, Los Alamos National Laboratory, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Sandia National Laboratories. The national laboratories carry out core research activities aimed at improving HTS wire performance and designing and testing all types of HTS electric power applications.

Regulatory Agencies: Regulatory bodies have a major influence on the conduct of business, particularly within the utility industry. Utility regulators will be informed about the potential of HTS applications to increase efficiency and improve competitiveness.

Other Federal Agencies: HTS electric power activities cut across several agencies. Activities will be coordinated with the Department of Defense, Department of Commerce, the National Science Foundation, and other agencies.

Foreign Governments: Foreign governments are interested in energy and processing advances. Japan and many European nations have aggressive programs for the development of HTS electric power technologies. Since all industrialized countries are net importers of energy resources, there is a great effort to develop technologies that will increase energy efficiency and thus reduce dependence on foreign fuel supplies. Coordination with foreign governments occurs primarily through the International Energy Agency Implementing Agreement to "Assess the Impact of High Temperature Superconductivity on the Electric Power Sector." Canada, Denmark, Finland, Germany, Israel, Italy, Japan, the Netherlands, Norway, Sweden, Switzerland, and the United Kingdom participate in this agreement, as well as the United States. Semi-annual meetings are held in member countries to discuss recent HTS advances.

U.S. Department of Energy Role

Investment in HTS development is producing systems that meet the needs of utilities, private industry, and consumers.

DOE supports national energy, economic, environmental, and educational interests by providing leadership in developing HTS electric power devices and easing their adoption by the utility industry and private sector.

This leadership is exemplified by:

- Supporting, through a highly integrated program, the development of HTS technology to the point where industry can commercialize HTS electric power applications;
- Involving private industry in the planning, reviewing, and research aspects of the program to realize as many HTS applications as possible; and
- Providing facilities and expertise to private industry to maximize funding leverage and accelerate the development of commercial HTS electric power devices.

Management

The Superconductivity Program for Electric Systems is managed out of DOE's Advanced Utility Concepts Division of the Office of Utility Technologies. Program mission, vision, objectives, and goals are influenced by policy generated in the White House, Congress, and at DOE. DOE's interest in energy resources, as well as the Office of Energy Efficiency and Renewable Energy's interests, determine the program's focus on enhanced efficiency and support of renewable energy sources available from superconducting utility technologies. Energy efficiency efforts affect many sectors of the economy, including electric utilities, industry, transportation, and the public, and will be crucial to continued competitiveness and quality of life in the United States.

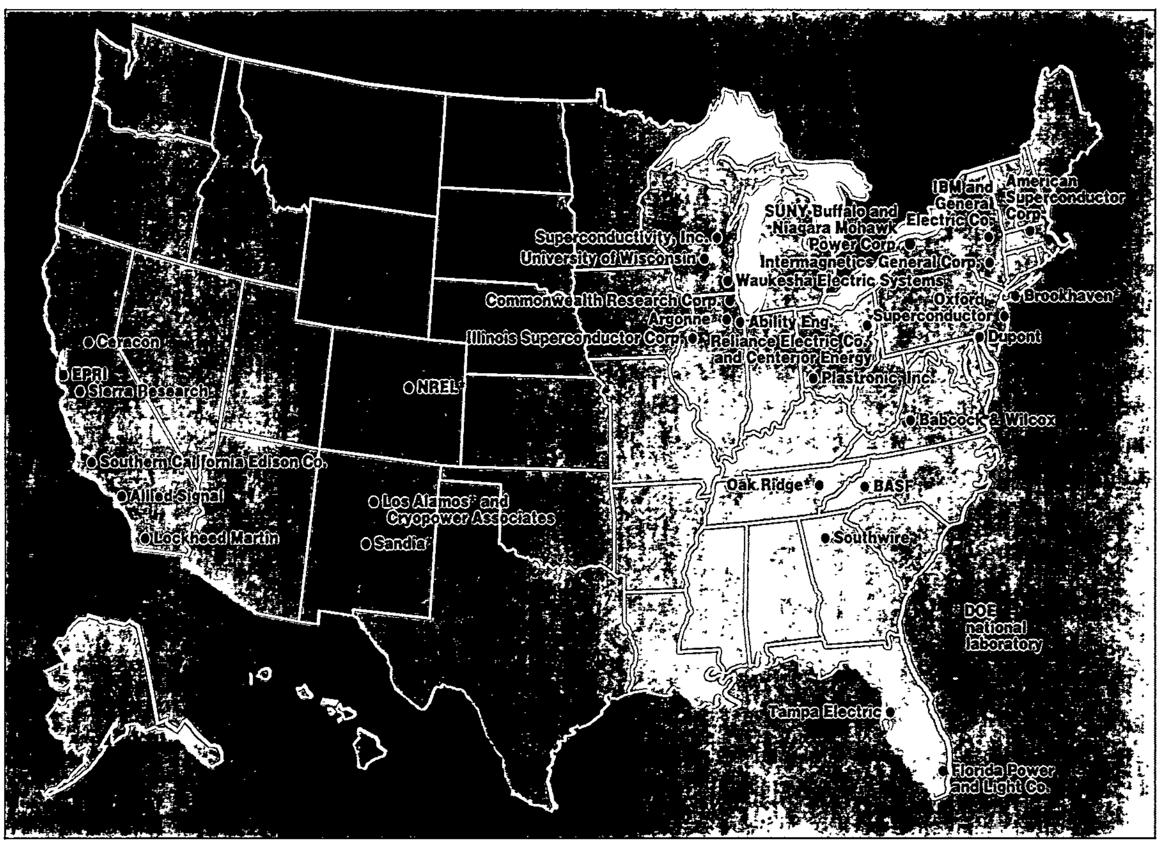
The need to work closely with utilities to realize these benefits is reflected in the organization of the program, which actively includes utility partners. Through this program, DOE is in a unique position to protect the national interest in maintaining strong energy resources, to stimulate superior U.S. competitiveness, and to address future domestic energy needs and the rapidly expanding international energy market.

The program's annual peer review and program milestones are used to critically evaluate progress and plans. Special advisory boards, interagency superconductivity committees, and private sector technology participants submit recommendations that concern program direction. This multiyear plan, an annual operating plan, and several proposal and review cycles are used to assess and maintain program direction and focus.

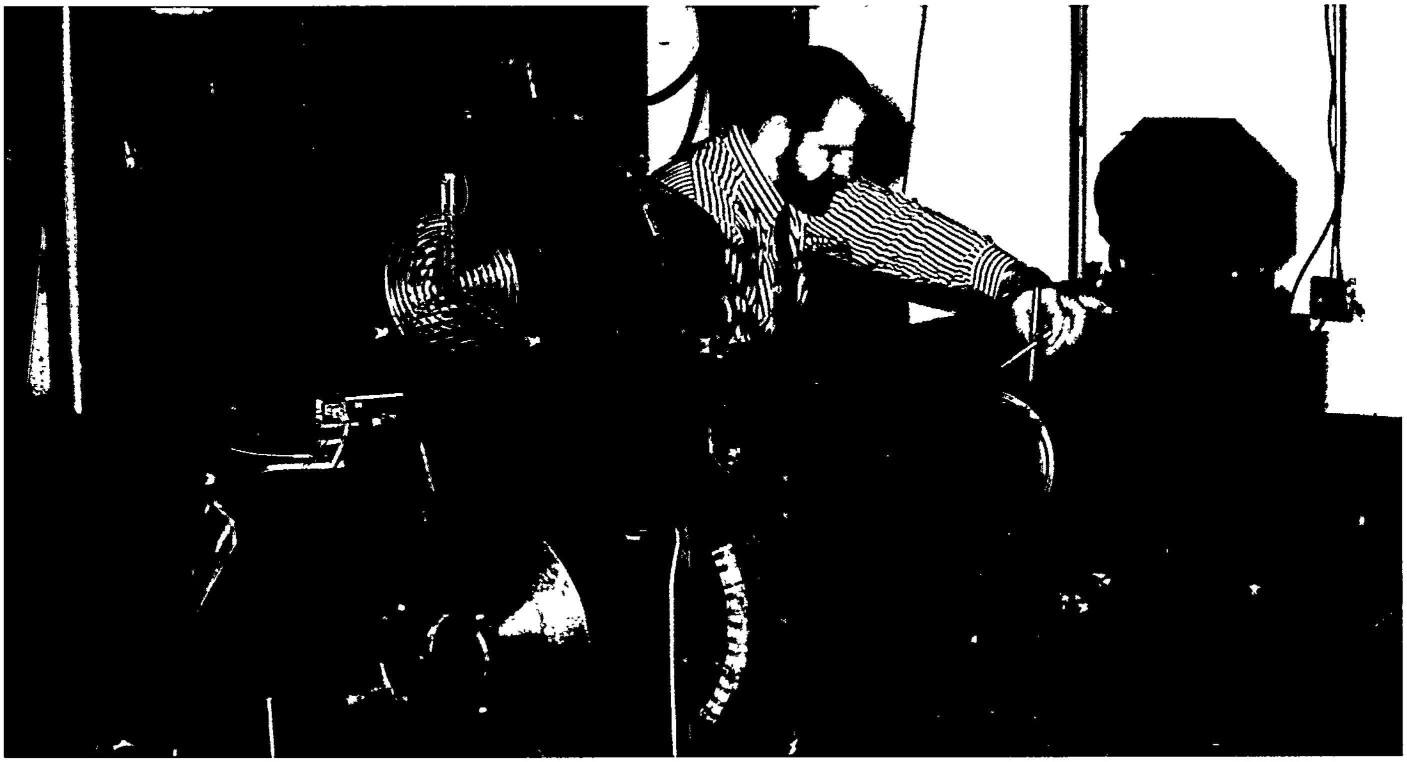
DOE facilitates the integration of industry, national laboratories, and universities into a coherent, aggressive program of concurrently developed HTS technology and system design. By directing general national laboratory research and development activities through the approval of field work proposals, DOE assures that the

Figure 11

National Laboratories and Some Partners Involved in the Superconductivity Program for Electric Systems



Utilities, industry, universities, and national labs are stakeholders in the Superconductivity Program for Electric Systems.



Reliance Electric Compmany/PIX03585

Reliance Electric Company is developing a 125-horsepower HTS motor under the Superconductivity Partnership Initiative.

program will accomplish its mission, stated goals, and objectives.Coordination, integration, and the measurement of accomplishments will be vitally important to the success of the program.

The annual program peer review is open to the public, and private company research is presented, as well as that of national laboratories and universities. This openness has fostered greater public awareness of the program's accomplishments and has led to many additional companies joining the program. In the words of one industrial partner, "The contributions [of the national laboratories] will help us compete in international markets in the future."

Resources

The funding history for the Superconductivity Program for Electric Systems is presented below:

FY	$M	FY	$M
1988	3.9	**1993**	21.9
1989	12.1	**1994**	21.0
1990	12.1	**1995**	19.0
1991	18.6	**1996**	19.0
1992	21.0		

As shown, program funding increased in the first six years and has since leveled. Funding for each year is subject to DOE, the Office of Management and Budget, and Congressional budget constraints. Continued growth to a level post-FY 1997 funding of $30 to $40 million is appropriate for this research and development program while it is experiencing excellent progress and private sector support. Since FY 1994, private sector cost sharing has been approximately 45% and is planned to increase to over 50% by the end of the planning period. Furthermore, the planned budget supports the mission of the program, and provides a reasonable likelihood of success.

Projected funding requirements over the planning period are as follows:

FY	$M	FY	$M
1997	25.0	**1999**	40.0
1998	35.0	**2000**	40.0
			140.0

Conclusion

Harnessing superconductivity will be remembered as one of the greatest milestones in the history of energy use. The challenges and opportunities are too enormous and complex to be addressed by any one organization. Neither can the benefits be realized by specialists working in isolation. A technology this complex requires nothing less than a unified effort of many of our nation's greatest minds in a wide range of disciplines. By working together, we can achieve enormous benefits for industry, the national economy, and the public.

Through the establishment of the comprehensive Superconductivity Program for Electric Systems, this emerging technology can be shepherded through the development process systematically, cooperatively, and efficiently. Thanks to the participation of all stakeholders, the promise of superconductivity brightens our national future.

American Superconductor Corporation/PIX03586

HTS wire, cable, and coils will enable a new generation of electric power systems that are highly efficient, compact, and powerful, helping to transform electric utilities as we begin the 21st century.

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