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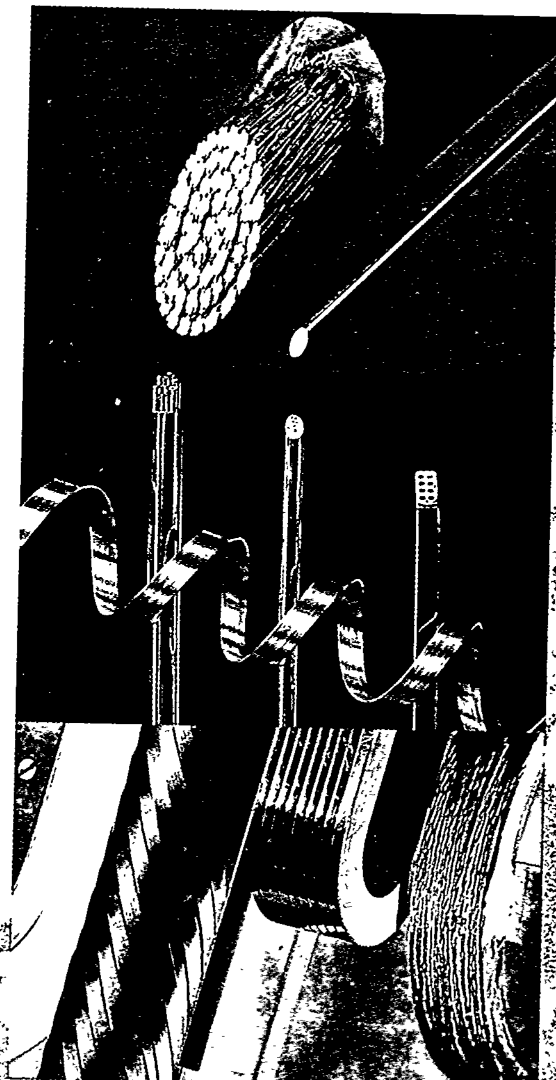
SUPERCONDUCTIVITY FOR ELECTRIC POWER SYSTEMS



PROGRAM OVERVIEW

Superconductivity for Electric Power Systems
Program Overview

Contents

Cover photos top to bottom: Conventional stranded copper cable next to a thin, high-temperature superconducting (HTS) wire; flexible HTS wires made of fine filaments of superconductive ceramics embedded in silver; electromagnetic coils based on HTS wire and used in motors, generators, and energy storage devices.

DISCLAIMER

INTRODUCTION

"...I'm especially interested in the whole issue of superconductivity, which I think has enormous potential for drastically changing the way we do things..."

— President Bill Clinton,
Speaking with Space Shuttle Crew,
February 7, 1994

High-temperature superconductivity, the ability of certain materials to conduct electricity with very high efficiency, can directly influence the competitiveness of the United States in the world industrial market. The opportunity to develop electric power applications that use high-temperature superconductors provides the United States with a chance to establish a new technologically advanced industry that will create high-paying jobs. These advanced products will also help industry gain an edge in the highly competitive, multi-billion-dollar-a-year, international market for electric power equipment.

Largely due to government and private industry partnerships, *only 7 years after the discovery of high-temperature superconductivity,* electric power applications based upon high-temperature superconductivity are now being designed and tested. These applications offer many benefits to the national electric system:

- increased energy efficiency (reduced losses),
- reduced equipment size,
- reduced emissions,
- increased stability and reliability,
- deferred expansion, and
- flexible electricity dispatch and load management.

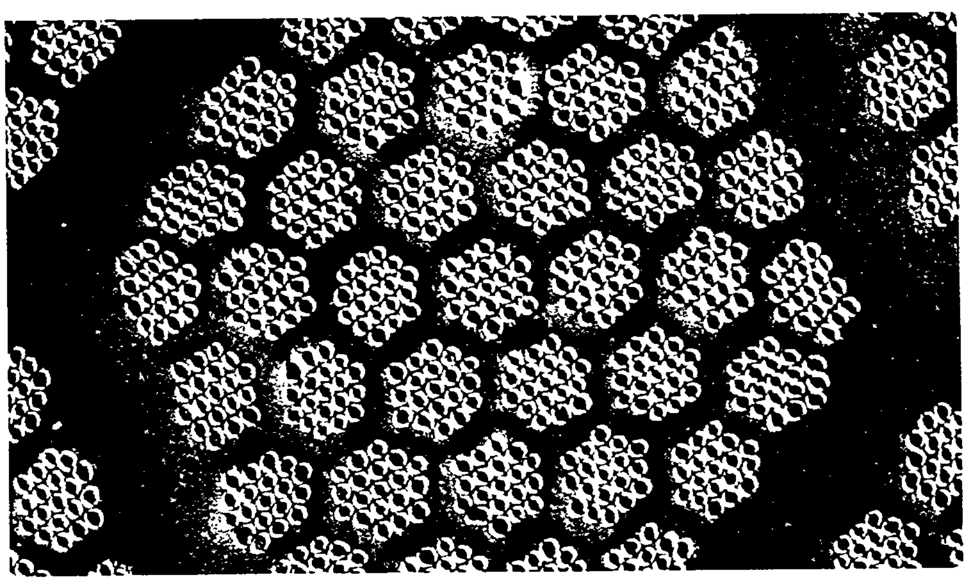
All of these benefits have a common outcome: lower electricity costs and improved environmental quality.

In light of the benefits offered by high-temperature superconductive electric power applications, the United States Department of Energy (DOE) sponsors research and development (R&D) through its Superconductivity Program for Electric Power Systems. This program will help develop the technology needed for U.S. industry to commercialize high-temperature superconductive electric power applications.

Through this R&D, DOE envisions that by 2010 the U.S. electric 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 electric power system will gain efficiency and flexibility through increased use of high-temperature superconductive devices. In turn, this will boost U.S. productivity and efficiency, especially within industries that are large users of electricity.

What is Superconductivity?

Superconductivity is the ability of certain materials to conduct direct electrical current with no resistance and extremely low losses. Typical electrical conductors, such as copper, are limited in the amount of electricity they can carry by large losses due to electrical resistance. Superconductive materials can carry larger amounts of current with essentially no losses compared to conventional electrical conductors. This ability to carry larger amounts of current can be applied to electric power devices such as motors and generators. Superconductive electric power devices therefore are more efficient, more compact in size, and produce larger magnetic fields than conventional devices using copper conductors.



Cross section of a flexible, high-temperature superconducting wire made from a multifilament composite material.

How has Superconductivity Evolved?

Superconductivity was discovered early in the 20th century yet remained a scientific curiosity until the 1960s, when new materials were developed that could be cost-effectively used in applications. These materials, called low-temperature superconductors, must be cooled to below 20 Kelvin (K) (-253° Celsius (C)) in order to become superconductive. Above this critical temperature the materials lose superconductivity. Low-temperature superconductors are now widely used in magnetic resonance imaging machines. Other applications are in the fields of high-energy physics and nuclear fusion. Further commercial use has been largely limited by the costs associated with cooling to such low temperatures.

In 1986, scientists discovered a new class of superconductors. Unlike the previously known low-temperature materials that are metallic or semimetallic, these new compounds are ceramic. Another defining feature is that the new materials superconduct at temperatures up to 135 K (-138° C). This large increase in possible operating temperature, and the fact that the critical temperature is more than 100° higher than that of low-temperature superconductors, led scientists to call the new compounds "high-temperature superconductors."

Industrial Competitiveness

DOE's role in assisting U.S. economic competitiveness is described in the 1994 strategic plan, *Fueling a Competitive Economy.* The Superconductivity Program for Electric Power Systems supports industrial competitiveness and DOE's first priority, according to the plan—helping the President achieve his vision of an investment-driven economy capable of creating high-wage jobs that increase the incomes of the American people.

"Industrial competitiveness requires partnering with industry and other federal agencies to put the vast assets of the Department of Energy and its laboratories and facilities to the best use in advancing the U.S. position in a global market that is increasingly competitive."

— Fueling A Competitive Economy: Strategic Plan, U.S. Department of Energy, April 1994

The international market for electric products such as generators, motors, and transmission cables is worth several billion dollars a year; advanced products employing superconductivity can capture this market due to improved efficiency and performance. DOE's superconductivity program is assisting U.S. industry in exploiting this market, thereby capturing economic benefits in this country and energy benefits worldwide. To achieve this vision, the program is supporting four consortia of private companies, each committed to commercializing a different product in the Superconductivity Partnership Initiative. In parallel with this product-oriented thrust, the program assists individual companies through technology partnerships that are bringing the key manufacturing technology—making electric wires from high-temperature superconductors—to maturation.

Superconductivity Partnership Initiative

DOE established the Superconductivity Partnership Initiative in 1993 to recognize the progress made by wire-development partners, and to assist companies committed to developing wire-using products. A competitive solicitation was offered that asked respondents to consider a new approach to bringing technology to the marketplace. The respondents were encouraged to form multidisciplinary teams that include the product user, to engineer applications while the underpinning technology is being improved, and to pursue several applications simultaneously.

"At Intermagnetics General Corporation, we have been able to stay competitive with larger organizations, in a sense to act like a large company with a comprehensive, broad-based effort, by forming relationships with people at six different national laboratories. Their contributions will help us compete in international markets in the future."

— Dr. Pradeep Haldar, Intermagnetics General Corporation

Technology Partnerships

U.S. companies that have formed technology partnerships with DOE laboratories since the program started in 1988 have become international leaders in the manufacture of long lengths of high-temperature superconducting wire. These partnerships have built upon two major U.S. strengths: private company entrepreneurship and the resources—people and facilities—of DOE national laboratories. This combination has given small U.S. companies the ability to challenge major corporations in Europe and Japan for the lead in wire manufacture. These small companies are also key members of the Superconductivity Partnership Initiative consortia. In the first 7 years of the program, 87 agreements were formed for joint projects between companies and national laboratories. At the end of 1994, 35 were active. Industry has shared approximately 40% of these projects' costs.

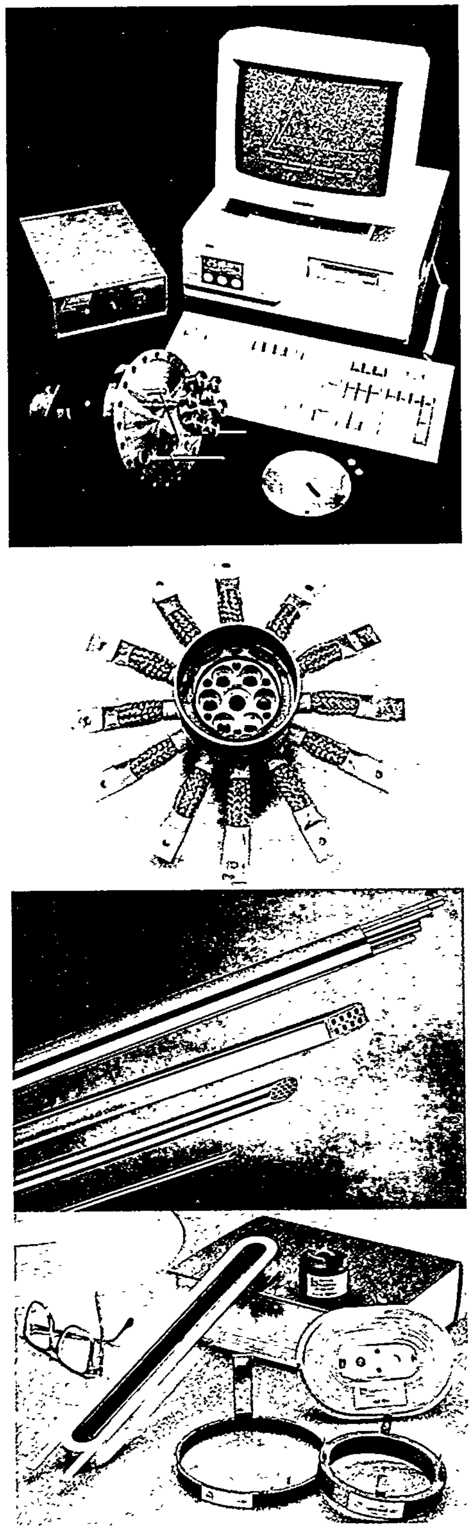
"American Superconductor Corporation has had excellent collaborations with DOE and many important developments—we look forward to more."

— Dr. Alex Malozemoff, American Superconductor Corporation

Commercial Products

With direct program assistance, industry has already introduced a variety of commercial products. Two companies, Seattle Specialty Ceramics and Superconductive Components, Incorporated, sell high-temperature superconducting powders. Neocera, Incorporated, sells a device that deposits multilayer films of high-temperature superconductors. American Superconductor Corporation and Intermagnetics General Corporation sell experimental samples of high-temperature superconducting wire and coils—components necessary for manufacturing motors and generators. And a variety of companies sell electric power leads made from high-temperature superconductors.

By the end of 1995, industry will design, build, and test prototype electric power devices, including a 125-horsepower (hp) motor, a 100-megavolt-ampere (MVA) generator coil, and a fault-current limiter—a device that protects an electric utility's transmission and distribution system from abnormal current pulses. These devices, if successfully developed and tested, will lead to large-scale commercial products such as 1000-hp motors, 100-MVA and larger generators, underground transmission cables, and fault-current limiters, all of which promise healthy domestic markets and much larger global markets.



Commercial products include (top to bottom) Neocera's multi-layer deposition machine, a current lead component by Argonne National Laboratory, and a variety of wires, (third photo) and electromagnetic coils (bottom) by American Superconductor Corporation.

PROGRAM APPROACH

The underlying requirement for most high-value commercial applications of high-temperature superconductive electric power devices is a flexible, mechanically rugged, high-temperature superconducting wire. This wire must be capable of carrying a large current in the presence of a magnetic field and be available at an acceptable price. Presently, fabrication technology cannot provide high-temperature superconducting wire for all the electric power devices being considered for development. Prototype device components need to be designed, developed, and tested for commercialization to occur.

In light of these parallel needs, technology and product development occur concurrently: progress in underlying technology allows more advanced prototypes to be built and tested. Feedback from applications testing allows engineers to make additional improvements to the underlying technology.

Recognizing these R&D needs, DOE has organized the Superconductivity Program for Electric Power Systems around two types of activities:

- technology development through R&D with individual companies, and
- product development by several companies formed into consortia.

"The Superconductivity Partnership Initiative could represent a classic model for both technology transfer and defense conversion."

— Dr. Bruce Merrifield, Wharton Business School, University of Pennsylvania

Technology development activities focus on two areas: wire development and electric power applications development.

Wire development activities are devoted to understanding how processing affects the wire and improving wire fabrication processes. Work also focuses on increasing the amount of current, described as the critical current density (J_c), that can flow through a wire.

Superconductivity Partnership Initiative Teams

Fault-Current Limiter Team

- Martin Marietta Corporation
- American Superconductor Corporation
- Southern California Edison Company
- Los Alamos National Laboratory

100-MVA Generator Coil Team

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

125-hp Motor Team

- Reliance Electric Company
- American Superconductor Corporation
- Centerior Energy
- Electric Power Research Institute
- Sandia National Laboratories

115-kV Transmission Cable Team (to start in 1995)

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

Electric power applications development activities focus on making long-length wire, coils, and other components and improving and understanding the systems, such as cryogenic refrigerators, that support high-temperature superconductive devices. These activities build upon work in the wire development area and, at the same time, feed back crucial information.

Product development activities, represented by the Superconductivity Partnership Initiative, focus on three teams that have been funded to develop high-temperature superconductive prototypes. The first team is developing a fault-current limiter; the second team, a 100-MVA generator coil; and the third team, a 125-hp motor. Each team is led by a private industry systems manufacturer. These manufacturers have agreed to introduce high-temperature superconductive devices to the marketplace upon the successful development and testing of prototypes.

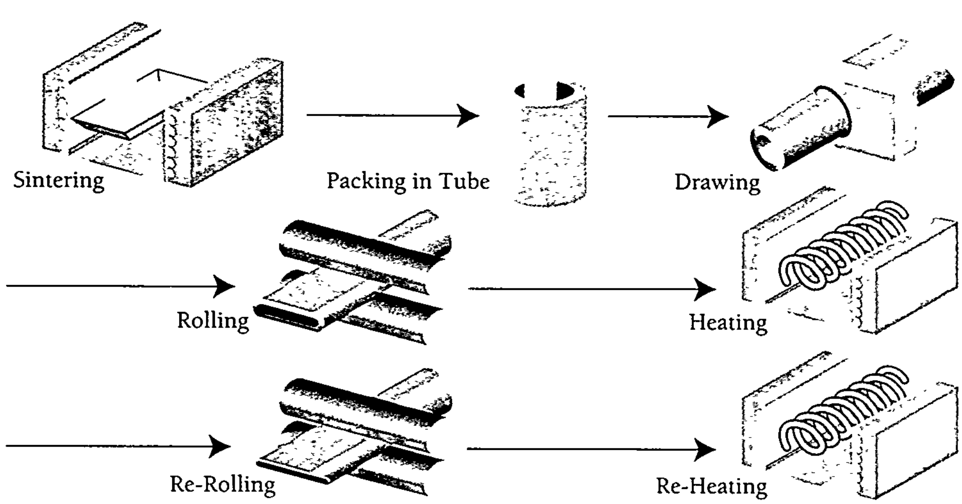
Technology Status

Materials used to produce high-temperature superconducting wire are inherently difficult to process into usable forms for electric power applications. This situation is the opposite of that for typical metallic electrical conductors, such as copper. And this fact presents processing obstacles that must be overcome to manufacture devices that can actually be used in electric power system applications.

Powder-in-Tube Method

High-temperature superconducting wire considered for use in electric power applications is currently made by the powder-in-tube method. In this method, high-temperature superconducting precursors are loaded into a tube made of silver and processed by a variety of standard, low-cost metallurgical manufacturing techniques such as drawing, rolling, and heat-treating to reach the final high-temperature superconducting wire form. To achieve the desired superconducting state, many variables must be balanced under manufacturing conditions. Important processing variables include heat-treatment temperatures, the duration of heat treatment, the number of times a wire is rolled, and whether the wire is heat-treated before or after it is wound into a coil.

Optimizing these variables is difficult and expensive. Therefore, a large part of the program to date has been devoted to fabricating short high-temperature superconducting wires with exceptional current carrying capabilities. As optimal processing conditions evolve for short-length wire, the manufacture of long-length wire can be improved by transferring short wire processing knowledge to long wire processing. This transfer of knowledge is central to many of the collaborative agreements between the national laboratories and private industry. In this case, the national laboratories work on improving short-length wire, then transfer



Powder-in-tube wire/coil making process.

their results to industry where improvements can be made to their long-length, commercial wire making processes.

The program continually monitors wire development progress, assessing wire characteristics to ensure that future wire will possess the properties necessary for use in electric power devices. Critical current density, J_c, the current per cross-sectional area of the superconductor "core," is the common electrical parameter used to rate the performance of high-temperature superconducting wire. Most electric power applications require J_c in the range of 10^4 to 10^6 amperes per square centimeter (A/cm^2) at operating conditions. Commercial Bi-2223 (see the table for compound descriptions) powder-in-tube wire manufactured today that is longer than 20 meters can carry up to 20,000 A/cm^2 at 77 K and in no magnetic field.

In general, the smaller the magnetic field in which a high-temperature superconducting wire must function, the more current the wire can carry. However, most electric power applications require magnetic fields of 2 to 5 tesla (T) when operating efficiently. At 2 to 5 T, Bi-2223 powder-in-tube wires must be used at temperatures below 35 K, because of limitations in the superconducting properties of Bi-2223. Below 35 K and in fields up to 2 T, Bi-2223 powder-in-tube wires have a J_c that is useful for prototype electric power devices. Additional improvements in J_c need to be made for commercial Bi-2223 powder-in-tube wire to be used in large-scale commercial devices such as motors and generators.

Another compound, Tl-1223 (see the table), possesses the necessary properties for wire designed to be used in 2- to 5-T fields above 35 K. The development of wires made from Tl-1223 is a few years behind the development of Bi-2223 wires, and today the best performing short Tl-1223 powder-in-tube wires have a J_c of 15,000 A/cm^2 at 77 K and 0 T. Because Tl-1223 is more difficult to process in powder-in-tube wires than Bi-2223, the national laboratories are exploring alternative approaches to Tl-1223 wire manufacture. Low-cost, commercial wire manufacturing processes such as electrodeposition and coextrusion show promise, but still need significant development before they are practical for production of high-temperature superconducting wire.

HIGH-TEMPERATURE SUPERCONDUCTING COMPOUND FAMILIES USED TO MAKE WIRE

Compound	*Family*	*Critical Temperature, T_c (K)*
(Y-123) $YBa_2Cu_3O_{7-\delta}$	Yttrium-Barium-Copper Oxide (YBCO)	92
(Bi-2212) $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2223) $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$	Bismuth-Strontium-Calcium-Copper Oxide (BSCCO)	85 110
(Tl-2223) $Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$ (Tl-1223) $TlBa_2Ca_2Cu_3O_{9+\delta}$	Thallium-Barium-Calcium-Copper Oxide (TBCCO)	122 125
(Hg-1223) $HgBa_2Ca_2Cu_3O_{8+\delta}$	Mercury-Barium-Calcium-Copper Oxide (HBCCO)	135

Cost

Of course, much work remains to be done, particularly on reducing cost. Regardless of performance gains, high-temperature superconducting wires will not become commercially competitive until the cost of wire is reduced. Currently, the cost of high-temperature superconducting wire, in dollars per kiloampere-meter, is predominantly driven by high manufacturing costs and high material costs. Private industry, with program assistance, will continue to explore novel methods to reduce manufacturing expenses and lower the material costs of wire. Some of these techniques are discussed later in more detail. For the successful development of applications using high-temperature superconducting wire, the cost of the wire along with total equipment costs and performance needs to be competitive with existing technologies.

Coordination

Key to the development of commercial high-temperature superconducting products is the search for better superconducting materials. To leverage government activities, the Superconductivity Program for Electric Power Systems coordinates with DOE's Basic Energy Sciences group, which explores basic materials, mechanisms, and physical phenomena; and searches for new compounds with higher critical temperatures and better mechanical properties. These discoveries are then carried over to the Superconductivity Program for Electric Power Systems for improvements in wire and applications development.

Conclusion

At present, short wires possess excellent properties, but the real need for applications is long-length wire—100 to 1000 meters or longer. Private industry can now manufacture 100- to 1000-meter wires on a small scale, but the need is for the repeated manufacture of uniform, long-length wire that is stable, flexible, multifilamentary, capable of carrying large currents in magnetic fields, and cost competitive.

To address this need, technology development is proceeding on two fronts: raising current density in short-length wire and transferring process and material improvements to long wire lengths, and increasing critical current and wire length in commercial manufacturing processes in which uniformity is the key. Progress in both areas is necessary so that high-temperature superconducting wires will soon be used in place of conventional wires in electric power devices.

The Superconductivity Program for Electric Power Systems has made excellent progress in wire development, electric power applications development, and the Superconductivity Partnership Initiative, continuing the advancing trend toward commercially available superconducting electric power products.

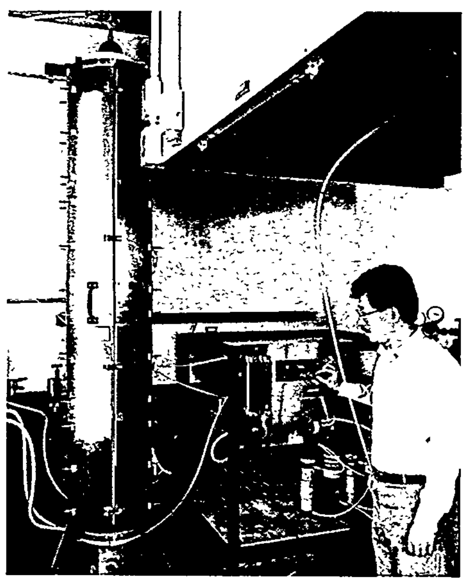
Highlights

- Intermagnetics General Corporation set a world record by manufacturing a high-temperature superconducting (HTS) coil that generates 2.6 T at 4.2 K and 1.8 T at 27 K, eclipsing the 2- to 5-T range necessary for commercial devices.
- American Superconductor Corporation set a world record in Bi-2223 wire development by manufacturing a 1160-meter HTS wire with a J_c of 12,700 A/cm² at 77 K and 0 T.
- Argonne National Laboratory received an R&D 100 Award in 1993 for developing a novel two-powder synthesis approach for manufacturing HTS precursors. This approach will enable the manufacture of higher performance HTS wire.
- American Superconductor Corporation set a world record by manufacturing a 1-meter HTS power cable that carried 2300 amperes, eclipsing the 2000 amperes required for commercially viable systems. This progress will be used in the 115-kV, 30-meter transmission cable prototype.

TECHNOLOGY DEVELOPMENT

Wire Improvement

To ensure continuous improvements to high-temperature superconducting wire, R&D needs to continue on the first step of wire manufacture—the synthesis of high-temperature superconducting powders that yield optimum electrical and physical properties after the wire is processed. In addition, researchers need to increase their understanding of the relationships between powder properties before wire manufacture and the final electrical and physical properties of the wire. Any improvements must be amenable to cost-effective manufacturing. Knowledge in this area is increased by exploring novel approaches to the synthesis of high-temperature superconducting powders and characterizing the properties of the powders.



Oak Ridge National Laboratory and Superconductive Components, Incorporated, commercialized an aerosol spray powder-manufacturing technique that results in powders with fine grain size and chemical homogeneity.

Materials Synthesis and Properties

For example, in 1993, Argonne National Laboratory developed a novel, two-powder process for synthesizing Bi-2223. This new process allows more precise control of the final powder makeup, which directly influences the current-carrying properties of the resulting wire. Critical current densities in short lengths of the wire made from these powders have been measured up to 50,000 A/cm² at 77 K and 0 T. This process incorporates a novel synthesis route, vacuum calcination, for which Argonne received a 1993 R&D 100 Award. In future projects, researchers will apply this technique to industrial wire development processes to enhance the properties of long-length wire.

Oak Ridge National Laboratory also contributed to the progress of the program's powder processing activities by licensing an aerosol spray manufacturing technique to Superconductive Components, Incorporated. This process produces powders with well controlled properties. It results in a narrow distribution of particle sizes, fine grain size within individual particles, and excellent chemical homogeneity. Superconductive Components is now selling these powders produced at their facility using the process developed by Oak Ridge.

In 1994, researchers also made significant progress in developing powder for other compounds, especially Tl-1223. Tl-1223 is more difficult to process than Bi-2223 in the powder-in-tube wire process. The control of Tl-1223 powder characteristics is crucial for producing wire with the properties necessary for use in electric power applications.

Los Alamos National Laboratory and Sandia National Laboratories made advances in the control of Tl-1223 powder characteristics leading to Tl-1223 powder-in-tube wires with a J_c approaching 15,000 A/cm². The National Renewable Energy Laboratory, in collaboration with the State University of New York at Buffalo, fabricated Tl-1223 powder-in-tube wire with a J_c near 10,000 A/cm² using "electrodeposited" precursor powders.

National Laboratories Involved in the Program

Laboratory	*Location*
Argonne National Laboratory	Argonne, IL
Brookhaven National Laboratory	Upton, NY
Los Alamos National Laboratory	Los Alamos, NM
National Renewable Energy Laboratory	Golden, CO
Oak Ridge National Laboratory	Oak Ridge, TN
Sandia National Laboratories	Albuquerque, NM

Critical Currents and Microstructures

One crucial limiting factor for eventual applications of high-temperature superconducting wire is the amount of current the wire can carry. Current in high-temperature superconductors is influenced by many factors:

- operating temperature,
- operating field, and
- superconductor microstructure.

Operating temperature and field are external factors—they can be controlled independently of the high-temperature superconducting wire—and are directly related to the amount of current a given wire can carry. In general, the lower the operating temperature, the more current a wire can carry. Operating fields have a similar effect. The smaller the field, the more current a wire can carry. Unfortunately, many electric power applications must operate in high fields—up to 5 T. In addition, the applications will run more cost effectively at higher temperatures, which require less cooling, less insulation, and lower cost cryogen. So, for commercial devices to be cost effective, wire designed for electric power applications must be able to operate in high fields at temperatures that are at least 20 K or more.

The superconductor microstructure is an internal factor and is heavily influenced by the materials used to make the wire, the processing techniques, and the final wire form. The microstructure also offers great potential for improvement. Critical current densities in wires are still 10 to 100 times less than in oriented thin films made from high-temperature superconductors. Thin films are generally used for electronics applications and possess the best high-temperature superconductor properties known. The properties that thin films possess are targets for wire developers. The challenge for researchers is to figure out how current flows through superconducting wires and how to maximize the current that can be produced in a wire by a given process.

In 1993, a breakthrough in the understanding of the superconductor microstructure of Tl-1223 was made when researchers at Oak Ridge National Laboratory and General Electric Company identified a possible microstructural origin of high critical current densities in Tl-1223 thick film deposits produced by General Electric Company. These films possess the best current carrying capabilities—J_c up to 325,000 A/cm^2 at 77 K and 0 T—of any non-thin film type manufacturing process. This discovery is extremely important for the development of Tl-1223 long-length wires because researchers now have insight on why these thick films carry more current than high-temperature superconductors produced by other processes, including powder-in-tube wire. No other potentially low cost manufacturing method is known that produces such high critical currents. The challenge for researchers now is to translate the laboratory process to a cost-effective, large-scale manufacturing process that can produce wires with these excellent properties.

Fabrication Processes

In conjunction with understanding the microstructure of superconducting wire, fabrication processes that can produce the desired microstructure need to be further developed and refined. Various manufacturing techniques exist to produce wire, and the powder-in-tube approach is the one most commonly used. But this process has limitations. So, while incremental improvements to the powder-in-tube method are being made, new techniques need to be explored.

Techniques to Increase Wire Strength and Flexibility. All practical methods for manufacturing high-temperature superconducting wire use silver as a sheath material. Silver is used because it is compatible with the superconducting ceramics, it is highly ductile, it is permeable to oxygen, and it can conduct electricity. Silver may even play a role in aligning the grains of Bi-2223 during formation processes.

Unfortunately, silver is expensive and mechanically weak. The expense of silver is not in itself enough to prohibit its use as a sheath material in cost-effective wires, but because it has low strength, engineers must use large amounts of it during wire processing to protect the ceramic core. The large amount of silver needed can quickly become a cost issue. In addition, the thick sheath limits the amount of superconducting powder in the wire. Specifically, in commercially manufactured samples, only 25% of the total powder-in-tube wire is powder. This limits the total current that wire can carry.

J_c, J_e, or $J_{overall}$?

J_c is the critical current density that can be carried by the superconducting core of a wire.

J_e is the critical current density that can be carried by the entire wire, including the superconducting core and the supporting or protective sheath.

$J_{overall}$ is the critical current density that can be carried by the entire superconducting device including the superconducting core, matrix or metallic sheath, insulation and/or structure, and potting and interstices between the conductors.

While high-temperature superconducting (HTS) wire development was in its earliest stages and applications development was far off, J_c was the most appropriate way to judge the performance of high-temperature superconducting wire.

Now that application prototypes are being designed and tested, J_e is a more appropriate way to describe the performance of the wire. This is because engineers must design a device using the overall properties of wire, not just special parts like the superconducting core.

$J_{overall}$ may be the most appropriate way to describe the overall effective current needed for a complete superconductive winding or device.

Now that coils and complete devices are being designed, constructed, and tested, HTS magnet and wire developers have room to improve J_c, J_e, and $J_{overall}$. This will be achieved by improving the superconducting core, sheath, and coil assembly.

Despite these limitations, there are many opportunities for improvement. In 1994, the program supported research that could lead to new and improved sheath materials. One technique investigated is dispersion strengthening of the silver sheath. This could lead to a stronger sheath material with the same beneficial characteristics as pure silver. Increased strength would allow engineers to make wires with thinner sheaths, directly increasing the overall current density, $J_{overall}$, without making improvements to the microstructure of the superconducting core. (See the sidebar for more details on $J_{overall}$.) Thinner sheaths could also lead to lower costs because they require smaller amounts of silver.

Another approach being investigated is the development of new, high-strength, low-cost silver alloys that are compatible with the superconducting core. These alloys will not directly lower the materials' cost of high-temperature superconducting wire because silver is still used in large quantities, but the alloys will allow more efficient, lower cost manufacturing of wire with superior strength properties compared to wires with pure silver sheaths.

Wire Forming Techniques. While supporting incremental improvements in the powder-in-tube method through improvements in processing, the program also supported research in other wire forming techniques. These techniques have their own drawbacks, yet they offer solutions to difficult problems that are present in powder-in-tube processing.

In 1994, advances in Tl-1223 processing were made at the National Renewable Energy Laboratory. Researchers were able to produce electrodeposited, thick-film deposits of Tl-1223 on silver foil that yielded critical current densities of 32,000 A/cm^2 at 77 K and 0 T. This is significant because electrodeposition processing offers a viable alternative to powder-in-tube processing.

In another project, researchers at Sandia and Los Alamos National Laboratories, in collaboration with Nuclear Metals Corporation and AT&T, investigated a wire manufacturing method called "hydrostatic extrusion." This technique is amenable to large-scale manufacturing and could drastically reduce the amount of silver needed in the wire sheath compared to the powder-in-tube wire. The technique is promising, but much work is still needed to prove its final usefulness.

Wire Characterization. Increased understanding of the makeup of the superconducting Bi-2223 core is crucial to progress in raising critical current densities. Recently, researchers at Brookhaven National Laboratory showed that the primary limiting factor for critical current density in Bi-2223 powder-in-tube wire is the presence of a large fraction of poor and non-superconducting grain boundaries compared to "clean" or superconducting grain boundaries.

Understanding the relationship between fabrication processes and the final wire is often just as important as finding a viable solution. From here, researchers can investigate processing methods that can lead to improved grain boundaries.

Electric Power Applications

Research in high-temperature superconductive electric power applications supports U.S. industry's effort to produce components such as long-length, high-current, high-temperature superconducting wire, and coils and cables made from high-temperature superconducting wire, and systems such as motors and generators that use high-temperature superconducting components. In 1994, significant progress was made in all these areas.

Component Development

Component development is advancing the state of the art in the following areas:

- long-length, high-current, high-temperature superconducting wire manufacture,
- coil development,
- cable development, and
- coil and cable testing.

Components must have excellent current and magnetic field performance to be incorporated into electric power devices. Presently, component performance is not at the level needed for full-scale commercial devices. In addition, the cost of long-length, high-temperature superconducting wire needs to be reduced by 10 to 100 times to be competitive with other technologies. Program activities in component development include lowering the cost of wire while simultaneously improving electrical properties.

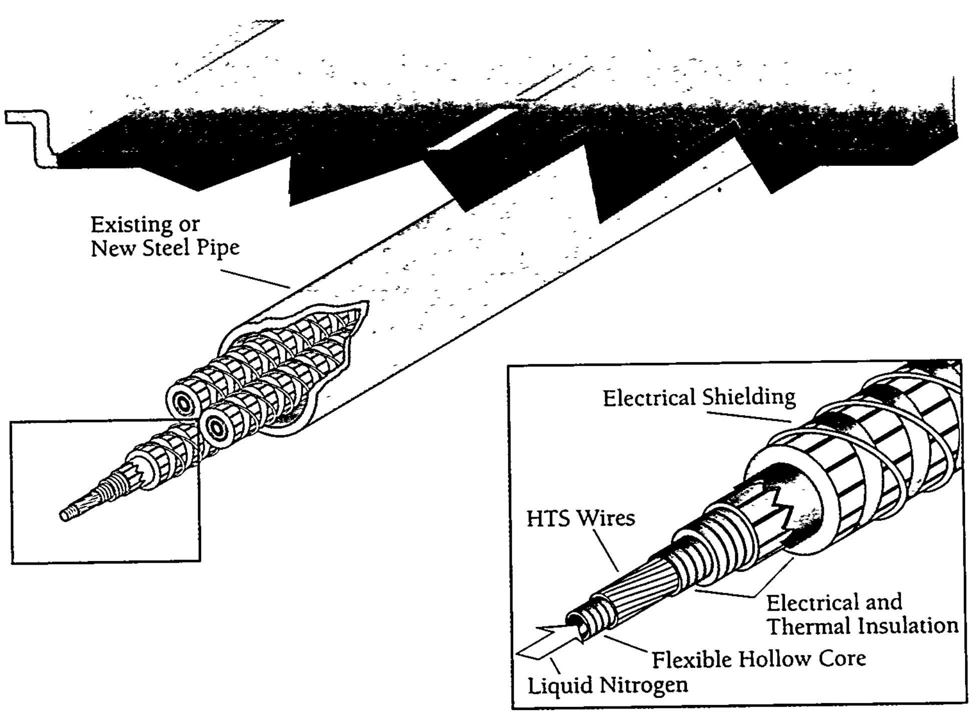
Long-Length Wire. The most significant need in the program is for cost-effective, long-length, high-temperature superconducting wire that is suitable for electric power applications. The program supports collaborative work designed to transfer the manufacturing processes developed for high-temperature superconducting wire from the national laboratories to private industry. Without significant improvements in manufacturing technology, long lengths of wire with the necessary properties will not be developed.

During 1994, the program helped shape many important accomplishments in this area. American Superconductor Corporation, in collaboration with Argonne, Los Alamos, and Oak Ridge National Laboratories and the University of Wisconsin, manufactured 1160 meters of Bi-2223/silver-sheathed wire with a J_c of 12,700 A/cm^2 at 77 K and 0 T. The company also manufactured 100-meter lengths of wire with a J_c of 21,300 A/cm^2 at 77 K and 0 T. In addition, Intermagnetics General Corporation, with assistance from Argonne National Laboratory, manufactured 850-meter Bi-2223/silver wire with a J_c of 10,500 A/cm^2 at 77 K and 0 T.

Coils. Coils that generate and tolerate 2- to 5-T magnetic fields are necessary components for commercial electric power systems such as motors, generators, and certain types of energy storage devices. Coils made from superconducting wire that maintain current performance under high magnetic fields need to be designed, built, and tested. Research in the program supports the design and testing of such coils and investigates such important issues as coil-winding techniques, joining of wire, coil support, and coil performance under the sudden loss of superconductivity—also called quenching.

World-record progress in coil development was made in 1994. Intermagnetics General Corporation developed a high-performance coil that generated 2.6 T at 4.2 K, 1.8 T at 27 K, and 0.3 T at 77 K. The coil was built with assistance from collaborators at Argonne and Oak Ridge National Laboratories. This is the first coil that can operate successfully under these field strengths. The properties of this coil are closely approaching the values necessary for electric power applications.

Cables. High-temperature superconducting wire is available today to manufacture underground transmission cable prototypes. However, the wire cost must be reduced and the system performance verified before the cables will be attractive in the marketplace.



High-temperature superconducting (HTS) underground power transmission cable designed by the Electric Power Research Institute, Pirelli Cable, and American Superconductor Corporation.

Systems Development

Systems development research focuses on designing and testing prototype electric power applications, such as motors, that use high-temperature superconductivity. These systems usually consist of components made from high-temperature superconducting wire, with other supporting hardware such as cryogenics, a support stand, and a utility interface.

In 1993, Reliance Electric Company, a program collaborator, announced that a motor built with high-temperature superconducting coils generated 5 hp—the highest achieved in the world to date. This project is supported by EPRI, and the wire and coils were developed in part through R&D conducted by the national laboratories and American Superconductor Corporation. In coming years, Reliance Electric will develop a 125-hp motor prototype under the Superconductivity Partnership Initiative using the 5-hp motor as a model.

PRODUCT DEVELOPMENT

Superconductivity Partnership Initiative

DOE awarded three Superconductivity Partnership Initiative projects in 1993 based on a competitive solicitation. DOE provides financial assistance to the participating companies that formed partnerships with a systems integrator, a component manufacturer, and an end user. Each project began in early 1994. A fourth award will be made in early 1995 for a transmission cable project. Descriptions of each one follow.

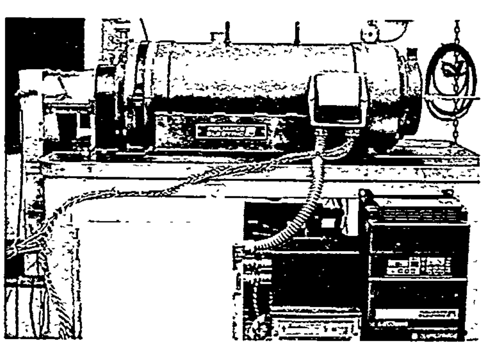
Project 1: Fault-Current Limiter. Team members, led by researchers at Martin Marietta Corporation, will design, build, and test a prototype current limiter with a high-temperature superconducting coil by the end of fiscal year (FY) 1995. The current limiter is designed to protect electric utility transmission and distribution systems from abnormal power surges due to uncontrollable forces such as lightning strikes and storms.

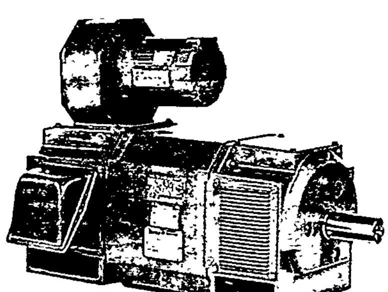
Project 2: 125-hp Motor. By the end of FY 1995, team members, led by Reliance Electric Company, will design, build, and test a 125-hp prototype motor that uses a rotor made from high-temperature superconducting wire. The motor will be smaller and more efficient than conventional iron-core induction motors. If the prototype is successful, motors larger than 1000 hp using the same technology will be commercialized.

Project 3: 100-MVA Generator Coil. By the end of FY 1995, team members, led by General Electric Company, will design, build, and test a prototype 100-MVA generator rotor coil manufactured with high-temperature superconducting wire. They will also design the complete generator and model its interactions with a utility grid. If the prototype is successful, a full-scale generator containing a high-temperature superconducting coil will be developed and commercialized. Superconducting generators may increase machine efficiency beyond 99%, producing energy savings, reduced pollution, and lower life-cycle costs than conventional generators.

Project 4: 115-kilovolt (kV), 30-meter Transmission Cable. The team, led by Pirelli Cable Corporation and overseen by EPRI's Underground Transmission Task Force, will manufacture and test, by conventional industry accepted techniques, a 30-meter prototype 115-kV high-temperature superconducting power cable by 1997. In addition, the team will design a three-phase, 100-meter cable system that can be used in commercial projects.

The transmission cable will be able to carry more than two times the current of conventional power cables, and will allow increased capacity in areas where new rights-of-way are restricted.





Reliance Electric Company demonstrated the first alternating current high-temperature superconductive motor with an output of 5 horsepower (left) and will use it as a model in developing a 125-horsepower motor prototype (right) under the Superconductivity Partnership Initiative.

PROGRAM MANAGEMENT

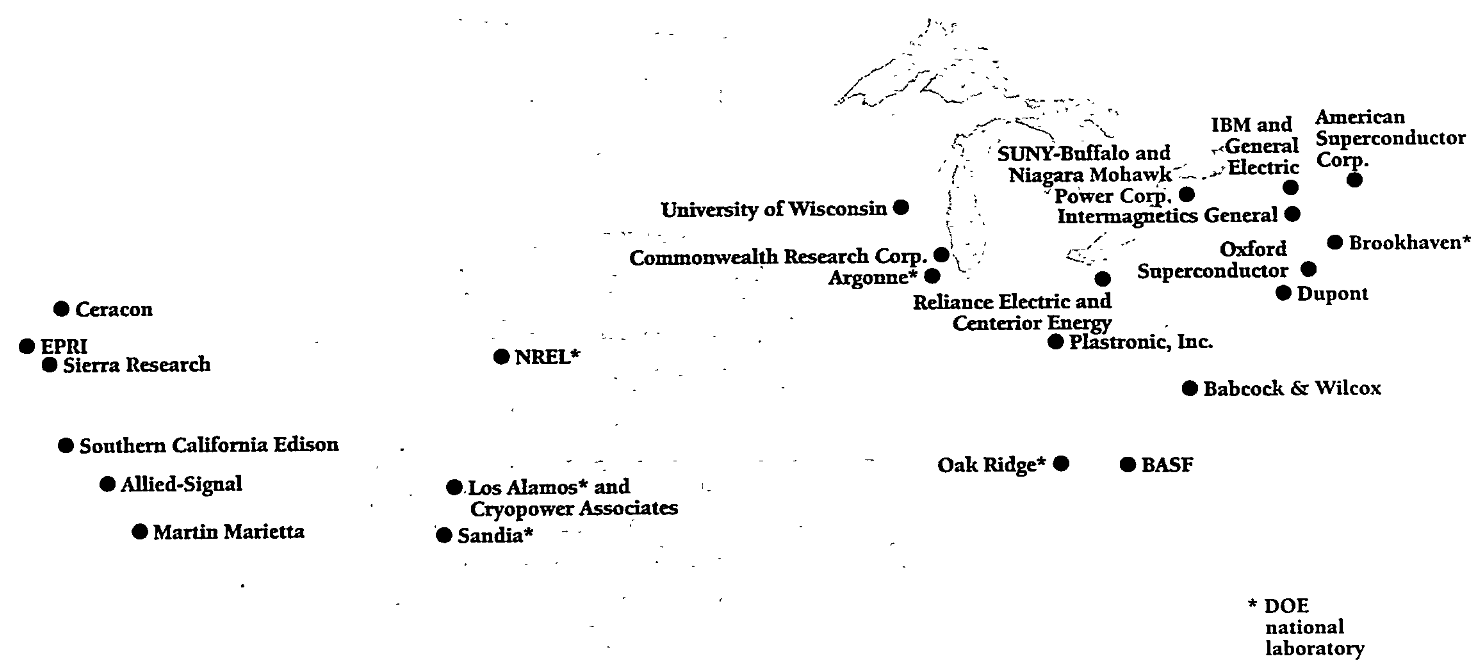
Federal R&D priorities in high-temperature superconductivity are established in response to private-sector needs. Field work conducted by the national laboratories to meet these needs is approved by the DOE program manager.

Industrial involvement and cost sharing are prerequisites for R&D projects undertaken by DOE. Collaborations between national laboratories and industry are approved by the DOE Operations Office that is associated with the collaborating laboratory. Competitive solicitations for cost-shared projects require definitive descriptions of the work proposed, costs, schedules, and plans for commercialization. Projects under the Superconductivity Partnership Initiative are managed directly by DOE's field office in Golden, Colorado. Technical support for the Initiative is provided by the National Renewable Energy Laboratory in consultation with the DOE program manager. The DOE program manager critically reviews progress and plans for the future, adjusting the scope and funding of projects as necessary.

Program Evaluation

To help guide the DOE program manager in making planning decisions, an annual peer review is held near the end of each fiscal year in Washington, D.C. At the review, national laboratories present their latest results, research planned for the upcoming fiscal year, and technology transfer efforts. The projects are rated by a panel of experts in superconductivity who are chosen from industry, academia, and federal agencies. Each reviewer provides a critical analysis of the individual presentations and the overall program. The program manager uses this feedback to support continuing efforts or make changes when necessary.

Recently, private industry projects were included in the review process. Industrial representatives delivered presentations that covered the collaborative efforts they were involved with in the program. Industry's involvement in the peer review process is designed to foster additional openness and cooperation between industry and DOE, and it will be expanded in the future.



National laboratories and some partners involved in the Superconductivity Program for Electric Power Systems.

OUTCOME

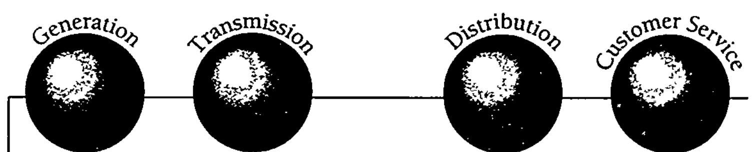
Electricity accounts for 36% of the total energy used in the United States. Electricity is our principal and most flexible means of integrating coal, hydropower, nuclear, and most renewable resources into a usable energy system. Historically, the demand for electricity depends on the nation's economic growth rate, as well as the adoption rate of efficient technologies and conservation measures. In the next 20 years, consumer demand for electricity will increase by 50%, and electricity use will increase to 40% of the total energy consumed by the country.[1]

The electric utility industry faces several challenges in meeting these steadily increasing consumer demands. The siting of new power plants is more difficult now, and stringent environmental regulations such as the Clean Air Act Amendments of 1990 must be met. Transmission corridors are reaching capacity, and new rights-of-way are rarely approved by regulators as opposition groups cite severe environmental impacts of such approvals. Since 1991, the electric utility industry has spent about $2 billion annually on demand-side management programs designed to modify load growth.[2] In addition, utilities must meet increasing demands for large quantities of electricity with high power quality, driven in part by the increasing use of electronic equipment.

The U.S. electric utility market can be divided into four functional areas: generation, transmission, distribution, and customer service. Generation is the process through which primary energy sources are converted into electricity. Transmission and distribution make up the electric delivery system. Customer service focuses on power quality, reliability, and load management on the customer side of the meter.

High-temperature superconducting electric power technologies will have a broad impact on all four functional electric utility areas and will help the utility industry meet each of the challenges described above. Superconducting generators will be more efficient and up to 50% smaller than conventional generators, and can help lessen the need for new power plants and reduce the amount of emissions by reducing the amount of fossil fuel used. Superconducting transmission cables can carry up to twice the current of conventional transmission lines, allowing utilities to double their transmission capacity while taking up the same amount of space. Superconducting motors will be more efficient and smaller than conventional motors, lowering the amount of energy needed from generation and transmission sources while accomplishing the same work. Superconducting current limiters will allow utilities to more efficiently utilize their existing transmission and distribution network increasing its reliability and capability to carry power. Other high-temperature superconductor applications not yet implemented, such as magnetic energy storage, may also contribute to the efficiency and reliability of the electric utility system.

In addition to bolstering energy efficiency and providing stability to an ever-changing utility system, the Superconductivity Program for Electric Power Systems is performing another great service. It is investing in R&D that is leading to products the United States can sell on the world market. This, in turn, will provide new jobs at home; at the same time, it will provide a new avenue on which the United States can enter the high-tech, global marketplace.



UTILITY SYSTEM	*Generation*	*Delivery*	*End-use*
High-Temperature Superconductivity 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
High-Temperature Superconductivity Benefits	Stability Reduced Losses Flexible Dispatch Reduced Emissions	Reduced Losses Stability Reliability Deferred Expansion	Power Quality Reliability Load Management Increased Efficiency

Benefits of high-temperature superconducting applications to the national electric system.

[1] *1993 Energy Outlook*, Energy Information Administration.
[2] *Electric Power Annual*, 1991, Energy Information Administration.