SUPERCONDUCTIVITY FOR ELECTRIC SYSTEMS

Program Plan
FY 2005 - 2009

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January 2005

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OVERVIEW OF SCOPE AND GOALS

Twentieth-century power system components were based on traditional conductors– using copper and aluminum wire. The opportunity now exists to modernize and expand the nation's electric grid with equipment using an emerging new capability – practical superconducting wires that have 100 times the capacity of conventional without energy loss due to electrical resistance. This breakthrough enables a new generation of reliable grid equipment with typically twice the capacity of same-sized conventional with only half the efficiency losses. Commercial versions of the superconducting power cables, transformers, generators and motors are now under development and are expected to be available after 2010 – in time to accommodate expected load growth as well as to replace existing equipment – most of which will exceed their design lifetimes during the next 15 to 20 years. Meanwhile, the R&D activities described address the technical and economic barriers to future commercial introduction.

DOE's superconductivity program focuses on two major goals: 1) solving the difficult problem of manufacturing electrical wires from HTS materials – which need special processing before realizing their ability to carry large currents, and 2) designing super-efficient electrical systems that use these wires for transmission cables, generators, transformers, and motors.

The HTS Program works in partnership with industry to conduct pre-commercial R&D to advance the scientific knowledge needed to develop the next generation of electric power equipment and to facilitate the effective deployment of these technologies in order to maximize their benefits to the nation.

The DOE vision is that at the end of this planning period (2010), the U.S. will regain a major share of the large and growing global market for cables, motors, transformers, and generators by using groundbreaking superconductivity technology. The higher initial cost anticipated for superconducting equipment will be repaid through energy efficiency savings during the first 2 to 4 years of operation. A world market for new HTS equipment purchases is expected to reach $50 billion/year in 2020.

The program consists of three sub-elements described below: 1) conductor research, 2) superconductivity partnerships with industry, and 3) strategic research.

Conductor Research

Conductor research focuses on materials processing methods that result in high performance HTS wires, low manufacturing costs, and favorable application characteristics, such as durability, flexibility, and tensile strength.

The crystalline structure of HTS materials "anisotropic," meaning that properties are very direction dependent and processing more difficult. A processing goal is to attain near-perfect alignment within the superconducting material to maximize electricity flow.

Misorientation of more than a few degrees creates "weak links" between grains and can substantially reduce current flow. HTS wires must also be able to hold magnetic field lines in place, a phenomenon known as “flux pinning.” If the magnetic field lines drift freely, energy is lost and current flow is again reduced. Researchers are focusing on eliminating weak links and producing strong flux pinning centers.

First Generation (1G) HTS wire, the BSCCO (Bismuth-Strontium-Calcium-Copper-Oxide) material-based “powder-in-tube” wire, is now a mature technology and has been commercialized by industry. Current density can still improve significantly (50% or more), and cost will continue to decline with performance improvements and economies of higher volume production. Longer-term wire research activities concentrate on Second Generation (2G) superconducting wire, using YBCO (Yttrium-Barium-Copper-Oxide) materials. 2G wires have inherently lower cost and potentially performance advantages compared to 1G wire.

In 2G wires, a 1-5 micron (a micron is one-millionth of a meter) thick coating of HTS material is deposited on a specially prepared metal substrate that induces a high degree of alignment. The HTS material than performs as a single crystal though the entire length may be very long (the 2003 goal was 100 amperes in 10 meters which was met). Commercialization of 2G technology is expected to take four to five years, during which time the 1G wire will continue to be the workhorse of the emerging HTS industry.

The industry-led conductor research activities exploit discoveries at DOE national laboratories and universities that promise unprecedented current-carrying capability in HTS wire. Industry teams are working with national laboratory scientists to scale-up discoveries to commercial processes.

Superconductivity Partnerships with Industry (SPI)

The Superconductivity Partnerships with Industry (SPI) research area supports aggressive industry-led projects to design, build, and test advanced electrical applications. The SPI is designed to accelerate introduction of HTS products into the marketplace with financial incentives for development of first-of-a-kind superconducting power devices. SPI requires a 50 percent or greater cost-share by industry aimed at field-testing pre-commercial HTS power products. SPI projects include generators, transformers, motors, transmission cables, flywheel energy systems, and magnetic separation systems. A unique SPI feature is that each project involves vertically integrated teams (typically including an electric utility, a system manufacturer, and a superconducting wire supplier as well as one or more national laboratories). This vertical integration has proven to be a powerful way to include customer focus and leverage resources. In addition, this teaming arrangement allows for critical commercial readiness reviews at the conceptual and final design phases. These reviews identify and correct potential problem areas and ensure successful demonstrations.

Each SPI project typically lasts 3-4 years. To provide opportunities for new SPI teams, competitions for new SPI projects are held every 3-4 years.

Continuing SPI projects include:

- 100 MW HTS Generator, (GE)
- 100 kW Flywheel Electricity System, (Boeing)
- 30 MW HTS Distribution Cable at an Industrial Installation, (Southwire)
- 5000 HP HTS AC Synchronous Motor, (Rockwell)
- HTS Reciprocating Magnetic Separator, (DuPont)
- 10 MW HTS Transformer, (Waukesha)
- 40 MW HTS Tri-axial Cable at an American Electric Power (AEP) Substation, (Southwire)

New SPI projects include:

- Transmission-level (138 kV) HTS Fault Current Limiter, (SuperPower)
- Bixby substation cable project, using 13.2 kV, load rating 3.0 kV, 69 MVA, triax cable design, cold dielectric, splice, underground, multiple 90 degree bends, length 330 m 48 MW
- HTS Distribution Cable on the Niagara Mohawk Grid, (SuperPower)
- 600 MW HTS Transmission Cable on the Long Island Power Authority (LIPA) System, (American Superconductor)

The government-industry cooperation develops complete pre-commercial prototype systems, and after successful field-testing, the industrial team members are ready to commit to HTS equipment commercialization.

Strategic Research

The Strategic Research program area provides the underlying knowledge base needed for the success of the industry-led projects. Strategic research is led by the national laboratories and focuses on research to address fundamental technological issues that will result in a better understanding of the relationships between HTS materials microstructure and their ability to carry electric currents over long lengths. This activity relies on the close working relationships between the national laboratories and universities.

Strategic research includes efforts in basic materials processing, benefits analysis and planning, and cryogenic systems. Strategic Research continues to focus on wire processing as well as exploratory research on innovative systems. Process evaluations will help improve current capacity and lower processing costs of wires and applications through optimization and new discoveries. Economic analysis will provide an assessment of capital and operating costs of HTS electric power devices. Results from this activity provide the basis for predicting the potential market penetration and national benefits of HTS power equipment that could soon be in use on the U.S. electricity grid.

In addition, research and analysis are conducted on issues associated with the integration of superconducting systems into an increasingly competitive and restructured industry framework. A key issue is the development of cryogenic systems that are robust, efficient, low cost, and tailored to the cooling load. Existing HTS devices need to be maintained at 25K to 77K. Cryogenic refrigeration systems can be categorized as: closed loop systems that use a cryocooler to provide refrigeration; open loop systems that use once-through cryogens to provide refrigeration, and; hybrid systems that use both approaches. Suitable cryogenic systems need their performance evaluated based on criteria such as efficiency, reliability, and cost. The final configuration must optimize these criteria in a way that enables HTS devices to be acceptable for utility operation and to allow wide spread adoption into the national electric system.

METRICS/PERFORMANCE INDICATORS

The strategic goals of the HTS Program are to:

- Develop HTS wire with 100 times the power capacity of the same size conventional copper wires at a cost of $10/kiloamp-meter
- Develop HTS electric power equipment with one-half the energy losses and one-half the size of conventional units.

To maximize the critical current density, HTS coating needs to behave like an infinitely long single crystal. This result can be created if a textured substrate template results in perfectly aligned grains in the deposited superconductor layer. The manufacturing process causes misalignment of the grain boundaries and other microstructural defects. Important measures in HTS wire fabrication are:

- Less than 10 degree grain misalignment
- Less 5% variation in electrical properties along the wire length
- current increasing proportionally with HTS coating thickness
- substrate costs ($1/meter or less)
- mechanical and electrical requirements of power system applications met

The key to making HTS technology commercially viable is making the manufacturing process cost-effective. The price of 1G wire has been declining about 20 to 30 percent a year. The price is based on the kiloamp meter, the cost of one meter of wire capable of transmitting 1,000 amperes of electrical current. 1G wire now costs about $100 to $200 per kiloamp meter, compared to about $25 per kiloamp meter for copper. The cost of 1G wire is expected to drop to about $50 per kiloamp meter. 2G wire is expected to cost $10 per kiloamp meter by 2010.

Performance Indicators for 2G HTS Wire

Metric	A/cm width 77K, SF	Length	Cost	Annual Production
Current Status	100	10 m	—	—
2005	300	20 m	—	—
2006	500	100 m	—	—
2007	500	1000 m	$50/kA-m	200-1000 km
2008	800	1000 m	$30/kA-m	1000 km
2009	900	1000 m	$20/kA-m	2000 km
2010	1000	1000 m	$10/kA-m	10,000 km

Performance Indicators for HTS Electric Power Equipment Prototypes

	HTS Motors		HTS Generators		HTS Transformers		HTS Power Cables		
Metric	**Voltage**	**Power**	**Voltage**	**Power**	**Voltage**	**Power**	**Voltage**	**Power**	**Length**
Current Status	**4 kV**	**0.75 MW Tested in 2001 (Reliance)**	**10 kV**	**1.7 MW Tested 2003 (GE)**	**13.8 kV**	**1.7 MW Tested 2001 (Waukesha)**	**12.5 kV**	**25 MW**	**100 foot Operating Since 2000 (Southwire)**
2005			13.8 kV	170 MW	13.8 kV	10 MW			
2006							34.5 kV	30 MW	0.2 miles
2007	4 kV	5 MW			138 kV	50 MW	138 kV	600 MW	0.5 miles
2008			13.8 kV	340 MW					
2009							138 kV	600 MW	2 miles
2010	10 kV	5 MW	13.8 kV	850 MW	345 kV	340 MW	345 kV	750 MW	2 miles

Superconductivity Research and Development Plan

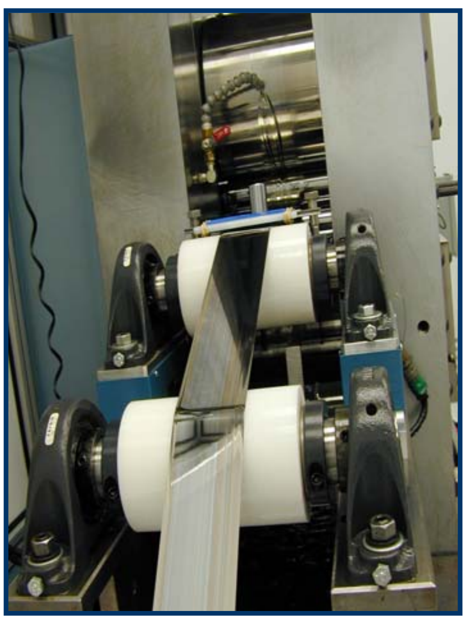
DOE leads the U.S. national effort to develop HTS wire and to demonstrate prototype electric power applications using the best wires available today. The HTS program has mobilized the resources of U.S. industry, national laboratories, and universities in a high-risk, high payoff parallel development approach: research on the underlying technology, superconducting wires, is being done to bring wire performance closer to meeting system requirements, while at the same time systems technology is being developed. This approach will effectively accelerate commercialization of full-scale systems by the private sector.

The HTS R&D plan consists of the following coordinated activities.

- Conductor Research
    - Pilot Production Facility (DOD Title III)
- Superconducting Partnerships with Industry (SPI)
    - Power Delivery Reliability Initiative (PDRI)
- Strategic Research
    - Conductor Design and Engineering Initiative (CDEI)
    - Cryogenic Initiative

Conductor Research

Conductor research activities continue to expand our capabilities to process long-length conductors. Our objective is to bridge the gap between tape fabrication and wire manufacturing to meet power system requirements. Technical challenges include finding cheaper ways of making the substrate template and faster ways for growing the deposited superconductor on the template, achieving end-to-end uniformity where the amount of current possible over short lengths is possible over long lengths, and getting current to scale with superconductor thickness.



2G RABiTS Production (ORNL)

Spool of 2G HTS Wire (AMSC)

Conductor research will continue to focus on both rolling-assisted biaxial textured substrates (RABiTS) and ion-beam assisted deposition (IBAD) substrate texturing methods. These methods are both being intensely developed by the national laboratories and their industrial partners.

At this stage, it is not at all clear which of several paths to a 2G wire will be most economic. Wire design is such that a substrate thickness of about 50 microns is needed to support 1 to 5 microns of YBCO, giving a superconductor fraction of between 5 and 10% of the cross-section, compared with the 25-to 50% for the first generation conductors made by conventional composite metal-working techniques.

Processing improvements need to be made in both coating and preparation of the underlying metal substrate. Coating improvements include faster processes, thicker films with higher current densities, and improved uniformity in long lengths. In order to improve process control and optimization, process diagnostics need to be developed for *in situ* and *ex situ* continuously processed YBCO coated conductors.

An exciting possibility is the ability to carry 1000 amperes in a 1 cm wide metal tape through an HTS film 5 microns thick – the thickness of a few human hairs. Equipment designs are likely to improve dramatically when this new capability becomes available.

Pilot Production Facility (DOD Title III)

The Title III mission is to create assured, affordable, and commercially viable production capabilities for items essential for national defense. This is achieved by establishing partnerships and providing incentives to industry to create, expand, or preserve economically viable production capabilities. This DOE and DOD partnership will ensure a domestic supply of affordable, long length YBCO coated conductor. This could significantly accelerate customer adoption by 5-7 years. The Title III activity will cost-share in the development of a pilot production facility that would improve and scale-up manufacturing processes, enhance quality, and lower costs. This activity could significantly accelerate the development of next generation weapons and electric power systems.

Superconducting Partnerships with Industry (SPI)

The objective of the SPI activity is to cost-share with industry in funding projects with potential benefits to the entire electric power sector: from generation to transmission and distribution to end-uses. The continuing focus is on technologies that will reduce the cost of superconducting wire, transformers, cables, generators, and motors, together with supporting technologies such as high-performance cryogenics. The present portfolio of SPI projects offers a unique opportunity for electricity infrastructure change. It offers electric power equipment with new capabilities; double the capacity and half the losses. Commercialization readiness reviews of all SPI projects will continue. After successful field tests, industry pursues commercialization. Competitions for new SPI projects are held every 3-4 years to ensure opportunities for new teams and for a broader and stronger portfolio of power applications.

Of particular interest are two new cable projects in New York. They will be energized in FY 2006. By FY 2008, these projects will have demonstrated the capability to double the power carrying capacity of transmission and distribution cables compared with that available in 2000. By 2010, the capability to increase by three to five times the power capacity of distribution cables within existing urban ducts will have been demonstrated.

Power Delivery Reliability Initiative (PDRI)

The PDRI is designed to be part of the OETD strategic thrust: The National Transmission Infrastructure Initiative. The PDRI will establish world-class research facilities to address critical HTS power application issues in partnership with manufacturers and utilities. It will help remove key barriers in developing electric products based on 2G HTS wires. Modeling and analysis activities will help establish the reliability of HTS power applications. The PDRI will also explore the transition to direct current power use in transmission and distribution. This will enable efficient, reliable, two-way power flows via DC cables. R&D activities will include: complete feasibility analysis, planning, research, design and construction of the first superconducting links in a DC transmission system, and partnerships to deploy HTS cables in long-length DC transmission grids. In addition, developmental issues concerning power electronics will be addressed via partnerships with DOD and NASA.

Strategic Research

Within the Strategic Research area, R&D is planned for the Conductor Design & Engineering Initiative and for the Cryogenics Initiative.

Conductor Design & Engineering Initiative (CDEI)

The CDEI activities include developing detailed understanding of materials properties and issues limiting applications of today's HTS industry-manufactured coated conductors. For example, CDEI research will result in halving alternating current losses compared to today's geometry. Based on predictive modeling and properties of component materials, "expert systems" will be developed to generate conductor "building block" designs for specific electric power T&D equipment. Initial activities will focus on developing technology for slitting wide webs of substrates and YBCO conductors and developing technology for joining 2G wires. The goal is to develop 2G wires into forms engineered for electric power applications. These engineered conductors will be integrated into systems with power electronics and cryogenics.

Cryogenics Initiative

Cryogenic cooling is required for HTS wires in all electric power applications. The objective of this work is to accelerate the development of needed advanced cryogenic systems. Key goals of the research are to drastically improve the cryocooler efficiency and reliability in systems with capacity to cool future cables, motors, generators, transformers, and other HTS power equipment.

Milestone Summary Chart
FY 2005-2009

FY	HTS Wire	HTS Power Equipment Prototypes
2005	• 300 A/cm-width, 20 m • < 5 degree misorientation • Continuous process to produce 2-sided coatings • Effective resistive joint • Implement AC wire strategy – narrow, filamentized, patterned • Slitting and lamination	• Test of 40 MW HTS triaxial cable at AEP substation • Install and test 48 MW (1G) HTS 350 m Distribution Cable or Niagara Mohawk's grid • Complete design of 100 MW HTS generator • Complete demonstration of HTS MRI
2006	• 500 A/cm-width, 100 m • Conducting buffer and substrate • J_c improvement with thickness • Single (simplified) buffer architecture • Textured substrates at full scale production	• In-grid test of 138 kV HTS fault current limiter • Install and test 30 m 2G HTS cable on Niagara Mohawk's grid (world's first test of 2G HTS cable) • Test 600 MW HTS transmission cable on LIPA system (world's first installation of transmission voltage HTS cable) • Complete testing of 35 kWh flywheel system
2007	• Pilot facility operation with 1000 km/yr capability, 1 km piece length • 500 A/cm-width, $50/kA-m • Dielectrics	• Select 3 new SPI projects
2008	• 1000 km/yr 2G wire production for SPI • 800 A/cm-width • <2 degree misorientation • Superconducting joint • Multi-filamentary geometry: filament size > 10 microns, substrate thickness 25-50 microns	• Demonstrate twice the power carrying capacity of T&D cables • Cryogenics available 5 kW at 77K, 200-300 W at 35-40K • High capacity HTS transformers available
2009	• 2000 km/yr 2G wire production for SPI • 900 A/cm-width • Round wire texture and architecture	• Demonstrate 3-5 times increase in the power capacity of distribution cables within existing urban ducts
2010 Goals	• 1000 A/cm-width at sf, 100-200 A at operating conditions, 1 km, $10/kA-m, 10,000 km/year, 10 cm width	• HTS power equipment is commercially available having half the losses and half the size of conventional units

Benefits

Superconductivity has the potential for bringing a more fundamental change to electric power technologies than has occurred since electricity use became widespread over a century ago. The possibility exists for an energy revolution as profound as the impact fiber optics has had on communications. The fiber optic "information superhighway" was constructed by replacing copper wires with a higher capacity alternative. Superconductivity provides an "energy superhighway" that will greatly improve efficiency and capacity. The economic and energy benefits will be substantial due to HTS wires that are a resistance-free alternative to conventional wires while carrying 100 times the amount of electricity; and to electrical equipment that is environmentally compatible, with half the energy losses and half the size of conventional alternatives.

HTS technology has the ability to replace or enhance present segments of our electric power infrastructure, greatly increasing stability, efficiency, and reliability. Manufacturers have begun developing several HTS applications in order to improve performance and help modernize the existing electric power infrastructure.

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/transformers	Current controllers Energy storage (minutes of storage) Transmission cables Current leads Inductors/transformers	Motors Energy storage (seconds of storage) Magnets/coils Flywheels Current leads Inductors/transformers Magnetic separators
HTS Benefits	Increased efficiency Stability Flexible dispatch Reduced emissions	Increased efficiency Stability Reliability Deferred expansion	Less environmental impact Power quality Reliability Load management Increased efficiency

Specific benefits derived from HTS cables, transformers, generators and motors are listed below.

HTS Cables

- HTS cables can carry 3 to 9 times the AC power of copper cables within the same physical constraint – underground conduit and right-of-way.
- HTS cables can be retrofitted and pulled through existing cable conduits as a direct replacement of old conventional cables. This repowering can relieve electric delivery congestion in urban areas and revitalize economic development in areas with high population density. Also, disruptive effects from construction are minimal.

Underground HTS Cable Installation

- Due to its low impedance, short strategic insertions of the HTS cable achieve the same power flow benefits as lengthier circuits of overhead lines. Effective electrical distances are significantly shortened which expands generator siting options.
- The ability to operate at lower voltages translates into lower costs. HTS has lower reactive power losses, which results in a more uniform voltage profile across the transmission network.
- Ability to change flow patterns on the grid and increase power transfers. HTS cables are more controllable and improve the reliability of the system. They act like controllable DC circuits but without the expense and complexity of AC-DC terminal stations.
- Being underground, HTS cables are less susceptible to damage during storms.
- By relieving load from other sections of the grid, HTS cables provide life extension of conventional cables and improve overall asset utilization.
- Buried HTS cables should be easier to site and permit than overhead lines.
- Will either eliminate or relax regional grid bottlenecks resulting in reduced regional congestion costs.
- HTS cables utilize an environmentally benign dielectric. Liquid nitrogen replaces hazardous materials such as oil.

HTS Transformers

Compact 5/10-MVA HTS Transformer

- Higher efficiency and one half the electric losses of conventional units.
- Can tolerate a doubling of its design load without insulation damage or loss of life.
- Siting and environmental advantages (including indoor siting) due to the substitution of liquid nitrogen for the thousands of gallons of oil and flammable insulation used in conventional transformers.
- Lower impedance and better voltage regulation.
- Potential for fault current limiting capability allowing reduced cost for associated switchgear, breakers, and other devices.
- Lighter and more compact (one half the size) than conventional units. Important for space-limited substations, especially in urban areas. Smaller transformers allow for the placement of an additional train of redundancy for improved contingency response and enhanced reliability.

HTS Generators

- One half the electrical losses and one-third the volume of conventional units.
- Increased operating life due to eliminating thermal load cycling.
- Can increase grid stability by increasing output of reactive power and improved power factor without adding other devices to the power system.

HTS Motors

- One half the electrical losses and one-third the size of conventional units.
- Significant impacts since electric motors consume over 60% of the total industrial demand for electric power.

1,600 hp HTS Motor

Partners

DOE facilitates the integration of industry, national laboratories, other agencies, and universities into a coherent, aggressive program of concurrently developed HTS technology and system design. The program works closely with electric utilities in order to realize the potential benefits. The HTS program has a long history of industry participation and collaborative efforts. Private industry is involved in the planning, review, and research aspects of the program in order to develop as many HTS applications as possible. The program greatly leverages funding in order to accelerate the development of HTS electric power equipment.

Funding Requirements

The planned budget supports the mission of the program, and provides a reasonable likelihood of success. Continued growth is appropriate for this R&D program, which is entering a phase requiring more cost-shared demonstrations and more updated equipment and user facilities. The projected funding requirements over the planning period are as follows:

	($K)			
FY	**Conductor Research**	**SPI**	**Strategic Research**	**TOTAL**
2004	20,000	17,838	10,000	47,838
2005	20,000	25,000	10,000	55,000
2006	20,000	30,000	10,000	60,000
2007	20,000	35,000	10,000	65,000
2008	25,000	35,000	10,000	70,000
2009	30,000	35,000	10,000	75,000

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