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Superconducting Power: Meeting the Challenges

J.G. Daley
U.S. Department of Energy
Washington, DC 20585 USA

R.A. Hawsey
Oak Ridge National Laboratory
Oak Ridge, TN 37831 USA

J.S. Badin
Energetics, Incorporated
Columbia, MD 21046 USA

Abstract: Superconductivity has the potential to bring a more fundamental change to electric power technologies than has occurred since electricity use became widespread over a century ago. The potential is 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 greatly improves efficiency and capacity. The economic and energy impacts are predicted to be huge. Many challenges had to be addressed in order that superconductivity could play this important role in the U.S. electric power system. The U.S. Department of Energy has worked in partnership with industry to solve the difficult challenge of manufacturing electrical wire from the ceramic high temperature superconducting (HTS) materials, while in parallel, creating designs of super efficient power devices that use these wires. The benefits will be substantial: HTS wires that are a resistance-free alternative to conventional wires while carrying 100 times the amount of electricity; and electrical equipment that is environmentally benign, with half the energy losses and half the size of conventional alternatives.

Keywords: High temperature superconductors, superconductivity, electrical equipment, electric power applications.

I. INTRODUCTION

The deregulation and restructuring of the electricity industry will cause large-scale changes in electricity transmission patterns. The nation's electric grid will need to be able to handle large and unexpected new demands flexibly and reliably as more states—and potentially the entire country—open their markets to competition. Meeting these new demands requires significant upgrading to the existing electricity infrastructure. Upgrading will also be needed to accommodate expected load growth as well as to replace existing equipment – most of which will exceed design lifetimes during the next 15 to 20 years. Commercial versions of the superconducting power equipment now under development will become available during the next 3 to 10 years – matching the large window of opportunity presented by the need for more efficient, higher capacity, reliable equipment. Meanwhile, the R&D projects described below are being done to address the technical and economic barriers to commercial introduction.

II. U.S. DOE PROGRAM

The U.S. Department of Energy (DOE) leads the U.S. national effort to develop high-temperature superconducting (HTS) wires 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 the time to commercialization of full-scale systems by the private sector. The HTS program synergizes two major U.S. strengths: the research and development resources of national laboratories and universities with the entrepreneurial drive of private companies. This synergy has resulted in a program structure with two industry-led initiative elements and a government lead research element.

The very successful Superconductivity Partnership Initiative (SPI) element supports aggressive industry-led projects to design advanced electrical applications. SPI projects include generators, transformers, motors, transmission cables, current controllers, 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 a powerful way to include customer focus and leverage resources.

The industry-led Second-Generation Wire Initiative is exploiting breakthroughs at Los Alamos and Oak Ridge national laboratories that promise unprecedented current-carrying capacity in high-temperature superconducting wires. These breakthroughs, which made headlines worldwide, allow long superconducting wires to behave much like single crystal, thus eliminating internal barriers to current flow that limit the performance of wires now being manufactured. Several industry teams are now working with the national laboratories to scale up the new discoveries (see Table 1).

The Strategic Research program element provides the underlying knowledge base needed for the success of the above industry-led projects. Strategic Research continues to focus on wire processing as well as exploratory research on innovative systems. In addition, research and analysis will be conducted on issues associated with 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.

Table 1.

U.S. Companies Developing YBCO Coated Conductors		
Company	HTS-Deposition Approach	Substrate
3M	E-beam co-evaporation (*in-situ* and *ex-situ*)	IBAD, RABiTS
Oxford Superconducting Technology	PLD (research stage)	RABiTS
MicroCoating Technologies	CCVD (open atmosphere CVD), also TFA	RABiTS
EURUS Technologies	TFA	RABiTS
American Superconductor	TFA	RABiTS
Intermagnetics General – Super Power	PLD, MOCVD	IBAD

Notes: PLD – pulsed laser deposition
CCVD – combustion chemical vapor deposition
TFA = trifluoroacetate precursor
MOCVD – metallo-organic chemical vapor deposition
IBAD – ion-beam-assisted deposition
RABiTS – rolling assisted biaxial textured substrates

III. WIRE TECHNOLOGY

Wire research seeks methods to produce wire that has higher current carrying capacity, reduced manufacturing costs, and better real-world application characteristics, such as durability, flexibility, and tensile strength. Near-term research in this area focuses on further improving the more mature BSCCO (Bismuth-Strontium-Calcium-Copper-Oxide) material-based "powder-in-tube" wire. Current density can still improve significantly (50% or more), and cost will continue to decline due to performance improvements and economies of higher volume production. Longer-term wire research activities concentrate on second generation superconducting wire, principally research on YBCO (Yttrium-Barium-Copper-Oxide) material-based "coated conductor" wires, as well as the investigation of underlying superconductivity physics.

A. Powder-in-Tube Conductors

The HTS wires now being manufactured world-wide use a process that starts with HTS powders being packed into silver tubes. A schedule of thermal and mechanical processing steps is then followed that results in long lengths of multi-filimentary wire. The DOE program supports national laboratory-industry-university research teams such as the Wire Development Group (WDG). The WDG recently won the Collaboration Success Award from the Council for Chemical Research for its outstanding contribution to the advancement of HTS wire technology. Several U.S. companies are able to manufacture kilometer lengths of high quality powder-in-tube tapes. Joint research now focuses on reducing the amount of silver, raising current density, and reducing cost.

B. Coated Conductors

A second generation of wires based on coating specially prepared metal strips with HTS thin films is a program priority. Using thin-film processing techniques in wire manufacturing poses a serious challenge to both industry and national laboratories. Thin-film techniques are widely used for other purposes – for example, making semiconductor wafers in the electronics industry. However, adapting these techniques to HTS materials is a difficult challenge, as is developing continuous processing methods needed for long superconducting wires.

In 1995 DOE's Los Alamos National Laboratory announced an important invention - achieving current densities of over one million amperes per square centimeter in a thin film on a flexible metal strip. This was followed in 1996 by a competing process discovered at the Oak Ridge National Laboratory. The two methods: Ion-beam-assisted deposition, or IBAD, at Los Alamos; and rolling-assisted biaxial textured substrates, or RABiTS, at Oak Ridge are being intensely developed by the laboratories and their industrial partners.

The IBAD technique involves the use of lasers and vacuum chambers. A polycrystalline nickel-based superalloy tape is placed in the chamber where a very thin, highly structured buffer layer is added by pulsed laser deposition and use of an assisting ion beam removes material not having the desired alignment. The buffer layer, or layers, material is selected to have a close match to the crystal structure desired in the HTS film that will later be applied. This close crystal match is enhanced by removing misaligned material with the assisting ion beam. The buffer layer then causes the superconducting film to adopt this near-perfect structure, resulting in extremely high current densities.

The RABiTS technique involves mechanically rolling a strip of high-purity nickel and certain nickel alloys to produce a close match to the structure needed in the superconductor. The match is further enhanced by the addition of a buffer layer(s) using vacuum or non-vacuum techniques. When the superconducting film is added, a very high degree of alignment is induced with corresponding high current densities.

Coated conductors pose an extremely difficult challenge and will take two years or more before becoming available in long lengths. This year the program has begun a "coated conductor initiative" to better equip the national laboratories

to assist their industrial partners in scaling up this important new technology.

An exciting possibility is the ability to carry 1000 amperes in a 1 cm wide metal tape through an HTS film 10 microns thick – the thickness of a few human hairs. This July, Los Alamos announced achieving 430 amperes through a film on one side of the tape (eventually the tapes will be double-sided). This confirmed that 1000 amperes is achievable and set a new world record. Equipment designs are likely to dramatically improve when this new capability becomes available.

C. Private Sector Involvement

There are six private companies and three major universities researching coated conductors in the U.S. The six companies, the selected YBCO deposition approach, and the selected substrate technology are shown in Table 1.

IV. SYSTEMS TECHNOLOGY

Systems research and development activities focus on power systems applications of HTS technology and include both laboratory- and industry-led projects. Researchers investigate adaptability issues for using superconducting wire in power system applications, which include transmission cables, transformers, current limiters, and flywheel electricity systems. In addition, program efforts target end-user applications in energy-intensive industries, including large electric motors and magnetic separators. Table 2 presents a brief profile of each SPI project.

A. Transmission Cables

Underground HTS cables can be designed to provide more efficient and economical ways for utilities to transmit power. Underground power cables using HTS wires have the potential to carry three to five times more power than cables of the same size made from copper wires. The use of HTS wires would, therefore, result in more efficient transmission, more effective use of existing rights of way, reduced environmental stress and cost-effective replacement of worn-out infrastructure. This is very attractive both to urban planners who need to retrofit aging infrastructures with increased power capacity and to suburban engineers who find it increasingly difficult to secure clearance for overhead transmission lines. At least two underground copper cables are required to replace one equally rated overhead transmission line, whereas a single HTS cable could replace one equally rated overhead line. Moreover the liquid nitrogen used to cool underground HTS cables is less expensive and presents less environmental risk than the dielectric oil used in copper cables. Fig. 1 shows an HTS cable being field-tested under real environmental stresses and real electrical demands at Southwire Company's

Table 2.

Superconductivity Partnership Initiative Projects	
SPI Project	Major Objectives
Boeing Flywheel Electricity Systems (FES)	• Build and demonstrate a 10 kWh FES optimized for low power consumption, load leveling applications • Install and test a FES of up to 100 kW for high output UPS applications (5 to 10 minute discharge)
Pirelli/EPRI Superconducting Cable	• Integrate HTS wire into a 3-phase cable assembly with refrigeration system • Install and demonstrate cable system in an existing network at a Detroit Edison substation, replacing conventional copper wire
Lockheed Martin HTS Current Controller	• Demonstrate performance of 15-kV fault current limiter for utility power surge protection
Reliance Electric Superconducting Motor	• Design and build a prototype 1000 hp A-C synchronous motor with rotating HTS field coils for testing in 2000 • Design a 5000 HP HTS motor for demonstration in 2002
Dupont HTS Magnetic Separator	• Develop and build ¼ commercial scale reciprocating magnetic separator using an HTS magnet • Demonstrate the unit in both kaolin separation and titanium dioxide processing environments
ABB 10 MVA HTS Transformer	• Build and test a 10 MVA, 69 kV/15kV HTS transformer • Install and demonstrate the transformer in utility service in 2001 • Using the results of testing and demonstration, develop a design for a 100 MVA HTS transformer;
Waukesha 5/10 MVA HTS Transformer	• Build a 5/10 MVA alpha prototype cryocooled HTS power transformer based on 1 MVA transformer tested in 1997 • Install and operate the transformer on the Wisconsin electric grid
Southwire Superconducting Cable	• Develop a 100 foot, 3-phase HTS power cable rated for 12.5 kV at 1250 A • Integrate the cable into a power line that feeds two Southwire manufacturing facilities and test under real-use conditions

industrial facility. It is expected that the first significant demonstration of utility networks using HTS-based power transmission cables will occur in 2001.

Fig. 1 A 30 meter, 3-phase, 12.5 kV, 1.25 kA HTS cable installation, switchyard, and control room building at Southwire Company in Carrollton, GA.

B. Motors

HTS motor coils and cryocoolers for use in high-horsepower electric motors are being developed and fabricated with the potential for use in industrial and utility applications. HTS motors utilizing these rotor coils are expected to be half the weight and size of conventional motors and would provide greater operating efficiency. Since industrial electric motors consume most of the electricity used in a typical manufacturing operation, increased efficiency should yield significant savings in power costs. Under the U.S. DOE Superconductivity Partnership Initiative, both a 1,000 and 5,000 horsepower (hp) motor are being developed.

C. Transformers

Utilities and industrial power customers use transformers to increase and decrease voltage levels. HTS transformers are expected to offer a number of improved features relative to conventional transformers as well as entirely new functionality with important utility systems benefits. Such functionalities include current-liming features and overloadability without loss of transformer life. HTS transformers are expected to be half the size and weight of conventional transformers, which would increase existing substation capacity, reduce land area needed for new substations, and greatly relieve transportation challenges currently faced by electric utilities for conventional transformers. In addition, HTS transformers would replace the dielectric oil, which surrounds the copper coils in today's power transformers with low-cost, environmentally safe liquid nitrogen, which would eliminate the spill and fire risks associated with dielectric oil. This is expected to lower associated insurance costs and allow transformers to be installed closer to large load centers even within large cities.

D. Current Controllers

The conventional method of limiting fault current is through the use of higher rated circuit breakers and power fuses. Upgrading the current circuit breaker systems and substation buswork would require considerable expense. HTS current controllers are designed to react to and reduce unanticipated power disturbances in the utility grid, preventing loss of power to consumers or damage to utility grid equipment. Utilities can reduce or eliminate the cost of circuit breakers and fuses by installing HTS current controllers. Fig. 2 shows a 15 kV controller being shipped for testing at a Southern California Edison substation. Further, it is estimated that widespread installations will result in significant cost savings and operational benefits that will create a potential domestic market of several billion dollars in the next 15 years.

Fig. 2. The 15 kV HTS current controller was delivered to the Southern California Edison Center Substation for testing in 1999.

E. Flywheel Electricity Systems

Flywheel electricity systems can be used to increase electric utility efficiency in two areas—in electric load leveling including eliminating momentary voltage and frequency changes, and in uninterruptible power systems applications such as providing short-term power supply in the event of grid failure. Flywheel systems can also transform electric energy into kinetic energy via an electric motor, store the energy in the rotation of the flywheel, and use the rotational kinetic energy to regenerate electricity as needed. Fig. 3 shows Boeing's 2 kWh flywheel demonstrator. Larger flywheel electricity systems are being developed. These applications require development of a 10 kWh system for utility applications for which HTS bearings are an enabling technology to increase efficiency by optimizing round-trip energy efficiency. Future commercialization implications are immense—these systems could eventually replace, or at least

augment, the multi-billion dollar standby diesel generator market.

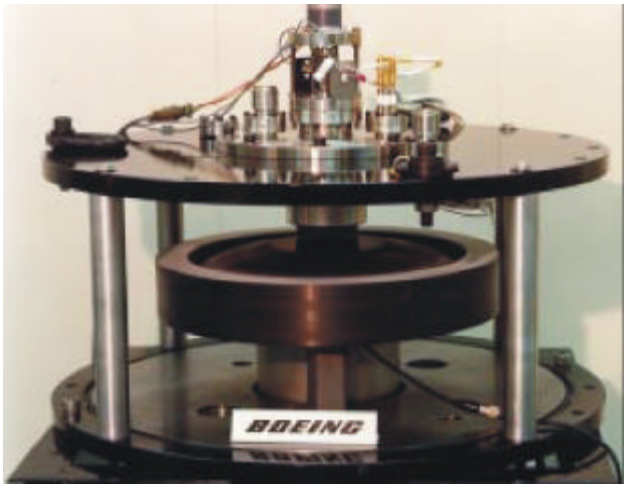

Fig. 3. Boeing's 2 kWh flywheel demonstrator. This experimental flywheel electricity system was the result of an earlier project.

F. Reciprocating Magnetic Separators

Conventional magnetic separators use magnetic force to separate materials of various compositions on the basis of their magnetic properties. The utilization of efficiency-enhancing HTS technology can reduce the operating energy costs by more than 90 percent and permit the use of separators in remote areas where electricity is expensive or not readily available. Magnetic separators have a wide variety of industrial applications, most notably in mineral separation, environmental remediation, and in chemical processing.

V. OUTLOOK

Even though HTS technology has made great strides in recent years, better performance and reduced costs are needed for HTS wire technology to become commercially applicable on a wide scale. Another ten-fold decrease in the cost of HTS wire and doubling of its performance during the next five years would strongly stimulate the availability of commercial devices. Within 10 years, HTS wire could be cost effective for most applications. The economic and energy impacts are predicted to be huge. The international market for superconducting electric power devices is expected to reach $50 billion by 2020. During the same time period, superconducting energy applications are projected to offset the equivalent of 40 medium size conventional generation plants in the U.S. alone. It is imperative that resources remain focused on creating a robust, high-performance HTS wire, and applying it to develop reliable and efficient electric power equipment that addresses the needs of electricity suppliers and other customers.

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VII. BIOGRAPHIES

James G. Daley holds a Ph.D. in Mechanical Engineering from the University of Connecticut. He is the Senior Manager of the Department of Energy's Superconductivity Program for Electric Power which he helped initiate in 1988. Prior to joining DOE, Dr. Daley was on the staff of Argonne National Laboratory where he worked on several advanced energy conversion projects as well as nuclear reactor component projects. Previous employment included positions at General Electric's Transportation System Division and United Technology's Pratt and Whitney Aircraft Division. He has authored over 30 technical papers.

Robert A. (Bob) Hawsey is manager of the Superconductivity Program at Oak Ridge National Laboratory. This industry-driven program is developing the technology needed to fabricate high temperature superconducting (HTS) wire and to demonstrate pre-commercial electric utility applications for that wire. Previously, he was project manager in ORNL's Applied Technology Division for numerous motors, electric drives, and instrumentation development projects. Prior to coming to Oak Ridge in 1980, Mr. Hawsey was a development engineer for the Allied Signal Corporation in Los Angeles where he designed and conducted experiments for high speed rotating machinery. He holds the B.S.-Ed. degree in Physics-Mathematics (Indiana University of Pennsylvania) and the M.S. in Engineering Physics (University of Virginia). He holds two patents for permanent magnet motors and one patent for a laser power meter system. He has organized full-day technical sessions on superconductivity at the annual IEEE Winter Power Meeting.

Joseph S. Badin is an Assistant Vice President at Energetics, Incorporated. He received his M.E. and B.E. in Mechanical Engineering from the Cooper Union for the Advancement of Science and Art. He received his M.B.A. from Virginia Tech. Mr. Badin has supported the DOE Superconductivity Program since its inception in 1988. He has authored numerous technical papers.