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SUPERCONDUCTIVITY — PAST, PRESENT AND FUTURE

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INTRODUCTION

This paper provides an overview of superconductor research and development activities, with emphasis on the potential of high-T_c materials for future applications. Superconductor applications are grouped under the following categories: electronics/instrumentation, bulk material/castings, research devices, industrial/commercial, electric power, and transportation/propulsion. Near-term applications are typically based on thin film and cast forms of high-T_c materials, while large-scale applications requiring long lengths of wire are considered intermediate to long term. As a major side benefit of high-T_c superconductor research, renewed interest is being focused on the use of low-T_c materials for large-scale applications.

HISTORICAL OVERVIEW

The phenomena of superconductivity was discovered in 1911 when the physicist Kamerlingh-Onnes was investigating material properties at liquid helium temperatures. He discovered that the electrical resistance of mercury abruptly vanished at a temperature near 4 K. The transition temperature at which a material's resistance vanishes is referred to as its critical temperature (T_c), and at temperatures below T_c such materials are in a new thermodynamic state — the state of superconductivity.

There are over 6000 superconductor materials known today, most of which are alloys and compounds rather than pure elements. Niobium has the highest critical temperature of any pure element with $T_c = 9.3$ K. However, development of practical superconductor devices (e.g., high strength magnets) did not occur until the 1960s when superconductors were discovered that could carry sufficiently high currents in the presence of large magnetic fields. Niobium-based alloys, namely niobium-titanium ($T_c = 9.6$ K) and niobium-tin ($T_c = 18$ K), formed the basis of the ensuing superconductor technology development activities. Superconductors with T_c less than about 30 K are commonly referred to as low-T_c superconductors (LTSCs). Liquid helium (4.2 K) is used as the coolant for most low-T_c applications to insure that the superconductors remain well below their critical transition temperature.

A new class of high-T_c superconducting materials was discovered by Bednorz and Muller in 1986 with $T_c > 30$ K. Their initial discovery of superconductivity in La-Ba-Cu-O compounds led to a flurry of research activity involving copper oxide materials at laboratories throughout the world. By 1987 it was discovered that the Y-Ba-Cu-O system was superconducting with a T_c greater than 90 K, which permitted the use of liquid nitrogen (77 K) as a coolant. This was followed by Bi-

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Sr-Ca-Cu-O (max T_c = 105 K)and Tl-Ba-Ca-Cu-O with critical temperatures approaching 130 K. The availability of liquid nitrogen as a low-cost cooling media, rather than liquid helium, has obvious economic implications for future applications.

MATERIALS DEVELOPMENT

HIGH-T_C MATERIALS

Physical properties for the three families of copper oxide superconductors (Y-Ba-Cu-O, Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O) differ according to their chemical phase (e.g., the relative number of atoms present for each constituent in the compound) and the material processing history. In addition to the critical temperature , a major technical challenge for high-T_c materials processing is to increase the critical current density (J_c) which the material can carry without returning to its normal (non-superconducting) state.

High-T_c superconductors (HTSCs) are ceramic materials that consist of individual grains that adhere to each other in accordance with the processing method used. The grain boundaries per se remain in a normal state even when the bulk of the material is superconducting. The J_c that can be achieved depends on how well the current can tunnel through each boundary from one grain to the next. The grain boundary barriers are referred to as "weak links," and the goal of high-T_c materials development is to make thin grain boundaries free of contamination — producing stronger links between the individual grains and hence higher J_c values. Weak links were not a major problem for the low-T_c niobium-based alloys due to their relatively thin grain boundaries.

FABRICATION

A variety of processing methods have and are continuing to be investigated to produce thin films, tapes, wires and castings or free-form shapes. Thins films are of primary interest for superconductor applications involving electronics and instrumentation. The bulk material applications (see Table 1) use solid rods, bars and other geometrical shapes. High field magnets and most large-scale superconductor applications require long thin strands of wire or tape flexible enough for winding. While considerable progress has been made in fabricating wire from high-T_c ceramic materials during the past five years, much more work is required to match the capabilities of the NbTi and NbSn low-T_c superconductors.

The real high-T_c challenge is in fabricating long lengths of wire with high current carrying capability. The first step in processing bulk high-T_c materials requires producing Y-Ba-Cu-O or other superconductor powder and then mixing it with various additives to assist in the forming and shaping processes. Fabrication techniques include: solidification of molten material, shape forming and consolidation through sintering, spinning to form thin filiments, powder-in-tube processing, and melt-texturing techniques.

Due to the anisotropic nature of high-T_C materials, the individual grains must be aligned in order to minimize the weak link problem. For the Y-Ba-Cu-O compound, the best success has been achieved with melt-texturing processes in which the material is solidified in a temperature gradient. Bi-Sr-Ca-Cu-O compounds have a layered micaceous structure a good plane alignment has been achieved with rolling or swaging methods such as associated with powder-in-tube processing.

APPLICATIONS

Superconductor applications range from small-scale electronics devices to large-scale power equipment. Table 1 summarizes some of the major applications of interest, which have been grouped (somewhat arbitrarily) into six categories that are discussed in the subsections below. Past development efforts for each of the application areas have involved LTSCs, with the current status ranging from moth-balled laboratory pre-prototypes to commercially available devices .

The question arises whether HTSCs can replace the materials used in the past, and if they can perhaps provide the enabling technology for those applications that haven't reached the market place. The first two categories in Table 1 represent near- or intermediate-term applications for high-T_C materials since they use, for the most part, either thin films or bulk forms of superconductor. The remaining categories rely primarily on wire windings and should be considered as intermediate-term and long-term HTSC application areas.

Table 1. Superconductor Applications

Electronics & Instrumentation	Bulk Material & Castings	Research Devices	Industrial & Commercial	Electric Power Systems	Transportation & Propulsion
Computers	Current Leads	SSC	MRI Devices	Motors & Generators	Maglev
Squids	Magnetic Bearings	Accelerators	Magnetic Separators	Transmission Cables	Ship Propulsion
IR & Microwave Sensors	Shielding	Laboratory Magnets	Magnetic Heat Pumps/Refrig.	Storage	EM Launchers
			EM Pumps		Aerospace

ELECTRONICS & INSTRUMENTATION

A number of electronic devices and instruments that utilize LTSCs are available commercially. This market can be expected to grow rapidly for those applications that can incorporate high-T_C materials because of the advantages of 77 K liquid nitrogen cooling relative to 4 K liquid helium.

Computers

The potential exists for very compact super computers because superconducting circuits do not generate heat and can be packed close together. Thin film high-T_C circuits could be used to interconnect semiconductors and enable higher speed computer operation. Josephson junctions, formed by thin layers of weakly coupled superconducting films, can be used to make electronic switches that operate ten times faster than semiconductor switches to further enhance computing speed.

SQUID Sensors

Superconducting quantum interference devices (SQUIDs) consist of one or two Josephson junctions and are very sensitive detectors of electromagnetic signals. SQUIDs are used in the construction of magnetometers, gradiometers, susceptometers and voltmeters. Superconductor sensor applications vary from geophysical exploration involving measurement of small variations in the earth's magnetic field, to highly sensitive magnetocardiograms and magnetoencephalograms for medical research.

Most existing SQUID-based sensors use low-T_c materials, but strong progress has been made on high-T_c SQUIDs and they should soon be appearing in commercial sensors. For example, several laboratories have assembled prototype magnetometers using high-T_c materials that can sense fields below 10^{-12} tesla (T), corresponding to 10^{-8} of the earth's field (0.5 gauss).

Infrared and Microwave Sensors

Researchers feel that HTSC infrared detectors can be developed that are more sensitive than those using LTSC materials. This improved performance for HTSC sensors will provide better resolution for satellite detectors, along with the added benefits a lower weight cryogenic system. Josephson junctions made with HTSC thin films can be used to detect microwaves and millimeter waves, and future applications range from medical sensors that differentiate very small temperature differences between organs to low-noise antennas for space surveillance.

BULK MATERIAL/CASTINGS

This category encompasses bulk material applications that that do not require long lengths of tape or wire. Consequently, the lead time for high-T_c technology development is greatly reduced and applications such as level detectors for cryogenic fluids have already entered the marketplace.

Current Leads

Current leads used to connect superconducting magnets and other low-T_c devices to their power supplies represent a major source of heat leaking into the helium cryogen. High-T_c bar leads can be used as the interconnect between the 4.2 K magnet windings and the copper bus (operating between 300 K and 77 K) to the power supply.

Thermal advantages of high-T_c leads relative to an all copper system are the elimination of I^2R heating for the 4.2 K to 77 K section and reduced longitudinal heat conduction (due to the lower thermal conductivity of the superconductor relative to copper). Calculations indicate that properly designed leads can reduce helium boiloff by 50% or more. Prototype high-T_c current leads have been fabricated and further development is being actively pursued by Argonne National Laboratory, Westinghouse and others.

Cryogen Level Detectors

Long rods of Y-Ba-Cu-O or other high-T_c material can be inserted vertically into a container of liquid cryogen and used as a depth sensor provided that the liquid temperature is less than T_c of the superconductor and the region above is warmer than T_c. The section of the rod immersed in the liquid is superconducting while the upper portion is in the normal state. If a small current is passed through the rod, the voltage measured across it will be proportional to the length of normal state material above the liquid surface. Any form (solid rod as well as wire, thin films, etc.) of HTSC is acceptable provided the mechanical properties and support structure is adequate. Liquid-nitrogen level sensors incorporating high-T_c materials are currently being marketed by two companies.

Magnetic Bearings

One characteristic of superconductors is that they expel magnetic flux when cooled below their critical temperature T_c. This is often demonstrated by levitating a small permanent magnet over a chunk of high-T_c material submerged in liquid nitrogen. The flux pinning characteristics of superconductors allow stable levitation of a rotating bearing, without the position sensors and elaborate feedback control systems that are required to achieve stability for conventional electromagnetic bearings. It is not necessary to achieve high current transport between the grains of a superconductor to achieve good levitation characteristics, and the intergranular magnetization properties of melt-textured Y-Ba-Cu-O materials are already adequate for some bearing applications.

HTSCs may well be the enabling factor for this technology, since liquid helium cooling requirements make low-T_c magnetic bearings impractical. A number of research laboratories throughout the country are actively working on high-T_c magnetic bearings and measured friction losses for some small laboratory prototypes lower than for conventional bearings by more than an order of magnitude . Potential applications range from spacecraft gyroscopes to energy storage flywheels.

Shielding

The effects of long term exposure to various levels of magnetic field strength is the subject of much debate. However, it is clear that personnel working in the vicinity of high strength magnets and large-scale superconducting machinery must must be adequately shielded against adverse electromagnetic effects. Other shielding needs include security protection of computers and elimination of electromagnetic background effects when making sensitive measurements. The flux exclusion properties of a sheet of superconducting material, along with the modest liquid nitrogen cooling requirements for high-T_c materials, provides an ideal candidate for near-term shielding applications.

INDUSTRIAL & COMMERCIAL

The applications in this category utilize, for the most part, relatively large bore magnets. Low-T_c NbTi wire is used for the magnet windings for those applications being marketed. Replacement with high-T_c materials is considered a long-term goal that awaits fabrication technology for long lengths of high quality wire.

Magnetic Resonance Imagers (MRI)

MRI systems represent a major commercial success story for LTSC technology, with several thousand units in place at hospitals throughout the world. Their operation is based on detecting nuclear magnetic resonance effects of hydrogen atoms in biological tissue material, such as the human brain, and image resolution is better than one millimeter.

The fabrication technology required for high precision MRI magnets is quite sophisticated and field strengths are in the 0.5 to 3 T range. Laboratory MRI systems are also available for imaging non-biological materials. The advent of high-T_c magnet windings and the accompanying liquid nitrogen cryostat would result in result in refrigeration economies that would further enhance the MRI market. The use of HTSC shielding to protect medical personnel from the stray fields of MRI systems is an additional innovation anticipated for the future.

Magnetic Separators

Magnetic separation devices are used to remove certain constituents from a mixture based on differences in their magnetic properties. For example, LTSC-based magnetic separation is currently used to remove impurities from kaolin clay in the paper manufacturing process. Due to their lower capital cost relative to LTSC units, strong electromagnets are generally employed for magnetic separation applications involving the removal of impurities from food and raw materials. The advent of HTSC magnets should increase the market potential for magnetic separation applications.

The most common separator design uses a ferritic mesh, situated inside a magnetic field, which attracts ferromagnetic particles and removes them from a flow stream passing through the mesh. An alternate design uses a magnetic field gradient to separate constituents of a mixture into different streams as they pass through a long field region. The capability of this design to remove sulfur bearing particles from pulverized coal has been demonstrated by Argonne National Laboratory using a helium-cooled superconducting quadrupole magnet. A variation on this design could also be used for separation and cleanup of gas streams based on slight variations of their magnetic properties.

Magnetic Heat Pumps/Refrigerators

Magnetic refrigerators have been used for many years in cryogenic research to achieve temperatures approaching absolute zero. Magnetic heat pumps and refrigerators utilize the magnetocaloric effect, wherein paramagnetic or ferromagnetic materials heat up when placed in a magnetic field and cool down when removed. A material such as gadolinium for example exhibits a 1 K/tesla change; consequently, use of a 10 T magnet is required for a 10 K temperature "lift" in a single stage unit. Multistage devices with a series of magnetic working materials can be used to cover any desired temperature range. Advantages include the potential for increased efficiency and the elimination of chlorofluorocarbon refrigerants. The Department of Energy is currently supporting development of a prototype LTSC magnetic refrigerator for hydrogen liquefaction. This is a long term application for HTSC since wire windings for high field strength magnets are required.

Electromagnetic Pumps

Electromagnetic (EM) devices have been used for many to pump liquid metals and other conducting fluids. EM pumps have been built based on a variety of design options which include: ac versus dc power, induction (J induced by the field coils) versus conduction (J supplied by an external electrical circuit) concepts, and stationary versus rotating magnets. Advantages relative to mechanical pumps include: no moving parts in the fluid, no bearings, no pump seals. and consequently higher reliability. The main disadvantage of EM pumps are their low efficiencies.

Pump types for which superconductors could improve performance include dc induction EM pumps with rotating field coils (e. g., centrifugal and helical-rotor designs) and dc conduction EM thruster devices. Superconductors and their associated high field capabilities are advantageous if the pumping application involves very large capacity flows or if the electrical conductivity of the fluid being pumped is relatively low. Potential application areas are pumps for future MHD power plants and for the movement of sea water (see also Ship Propulsion below).

ELECTRIC POWER SYSTEMS

This application category offers the greatest potential benefits for superconductors in the long term because of the potential energy savings in our electric economy.

Motors and Generators

The advantages of applying superconductors to rotating electrical machinery are higher power density and improved efficiency. Although conventional motors are 75 to 95 percent efficient and utility-size generators can reach 98 to 99 percent efficiency, even incremental increases in efficiency can result in substantial energy savings over time. Motor and generator designs that incorporate superconductors are generally limited to machines with dc field windings (e.g., dc and synchronous devices) to circumvent the high ac losses that can occur in superconducting devices.

A number of prototype LTSC motors and generators have been built in the past, but have not reached the marketplace due largely to the economics associated with liquid helium cryogenic cooling equipment. For example, experimental superconducting generators in the 20 to 50 MVA range were built in the USA, USSR and Japan in the early 1980s. Future HTSC electrical machinery will have the advantage of reduced heat losses and improved economics associated liquid nitrogen refrigeration.

Transmission Cables

LTSC transmission cables have been studied since the early 1970s for both ac and dc systems. Brookhaven National Laboratory, for example, tested a prototype ac transmission line using helically wound LTSC tapes in the cable. Inefficiencies associated with the poor dielectric properties of helium and the refrigeration requirements to counteract heat in-leak through the cryogenic cable limits the ability of LTSC systems to compete with conventional transmission lines.

The outlook for HTSC cables shows some significant advantages, particularly with regard to refrigeration energy consumption. HTSC transmission cables using liquid nitrogen coolant require less than 10 watts of power to remove 1 watt of heat in-leak, compared to 200 watts of power per watt in-leak for LTSC cables. Relaxation of refrigeration constraints in HTSC systems allows greater flexibility in cable design options with further potential for cost reduction. Initial applications of HTSC cables, assuming that sufficiently long high-T_c tapes/wires will be fabricated, are anticipated for high power underground transmission lines leading into major metropolitan area.

Energy Storage

SMES. Superconducting magnetic energy storage (SMES) devices use coils of superconducting wire to store electromagnetic energy in the form of a persistent dc current. There has been a strong interest in SMES technology ever since superconductors were discovered, and the first non-laboratory unit was a 30 MJ system energized in 1983 using NbTi coils. This prototype SMES system was used to damp power oscillations in the Bonneville Power Administration electrical grid, and was decommissioned in 1987 mainly due to unreliability of the cryogenic system.

SMES applications can be categorized according to their size scale:

- Small-scale devices (~1 MJ or smaller) used for power conditioning and stabilization of critical manufacturing equipment and computer facilities. A transportable low-T_c SMES unit with several megawatts of power capacity is currently being test marketed by Superconductivity, Inc.

- Medium-scale SMES units (1 MJ to 10^4 MJ range) can be built with a self-supporting containment structures. This size category encompasses load leveling for electric transmission lines and Maglev trains, and pulse power applications.

- Large-scale diurnal energy storage systems (> 10^4 MJ) would be used by electric utilities for load leveling in regions where large hydro-pumped storage is not feasible. Large-scale SMES systems require earth support to counteract the magnetic forces acting on the coils, and would be constructed below grade in bedrock.

Recent efforts in the U. S. have focused on design of the Engineering Test Model (ETM) SMES pilot plant, with a storage capacity of ~7×10^4 MJ, that serves as a LTSC prototype for future systems ranging up to 10^9 MJ capacity. The ETM discharge capability covers the power range from 10 MW/2-hour capacity to 400 MW/100-second capacity, and the Phase II effort (detailed design and plant construction) is scheduled to begin this year. Conceptual design studies have completed for HTSC-based SMES units in all size categories.

Flywheels. Energy storage using flywheels and superconducting bearings represents an alternative to SMES plants in the small and medium-size categories. Flywheel storage units using state-of-the-art gas cooled or electromagnetic bearings lose approximately one percent of their energy per hour, which makes them uneconomical for diurnal applications. Recent experiments indicate that implementation of superconductor bearings could reduce these loses below one-tenth of a percent per hour using the best high-T_c materials that are currently available. Development efforts for near-term HTSC bearing/flywheel applications are being actively pursued by a number of laboratories in the U. S. and Japan.

TRANSPORTATION & PROPULSION

The applications in this category require either high-strength magnets or superconducting motor/generator systems. LTSC materials are currently being used for prototype development, with HTSC technology envisioned as a replacement in the future.

Maglev

Magnetic levitated (maglev) trains have been investigated extensively starting in the 1970s, and experimental maglev vehicles are currently operational in Japan and Germany. Current maglev design practice uses one of two approaches:
(1) electrodynamic "repulsive" systems employ superconducting magnets on board the vehicle for the levitating and guidance forces along the guideway, and (2) electromagnetic "attractive" systems which use strong electromagnets and feedback circuits for levitation and control. Electrodynamic maglev systems are generally favored in the U. S and Japan, while an electromagnetic prototype is under development in Germany.

Speeds in excess of 300 miles/hour have been achieved with a LTSC maglev test vehicle in Japan's program. The National Maglev Initiative program in the U. S. is currently supporting a number of studies to evaluate critical design issues involving the vehicle, guideway, levitating magnets, propulsion/braking systems, control alternatives, and system integration of these factors. The results of these studies will be used to establish guidelines for development of a commercial Maglev prototype.

A low-speed maglev system is being planned for the Disney World/Orlando area, and a number of metropolitan areas are assessing maglev systems. LTSC technology will play the major role for near-term electrodynamic maglev development, while future systems will undoubtedly incorporate HTSC magnets due to the advantages of liquid nitrogen relative to helium refrigeration systems. A mature maglev transportation system can be expected to replace short-haul (a few hundred miles) airline travel, thus freeing airports congestion.

Ship Propulsion

The U. S. Navy has actively pursued LTSC technology for many years because of the significant weight and size advantages that superconducting motors/generator sets offer. The engine on a ship is mechanically coupled to the propeller with a bulky gearbox system, and this could be replaced by a compact superconducting electric drive system. A prototype LTSC electric drive was first tested on a ship in 1980, and the major problem was that the liquid helium liquefaction system could not satisfy shock and vibration requirements for shipboard use.

Electromagnetic (EM) thruster systems represent an alternative ship propulsion system in which an electrical current is passed directly through the sea water, and the current interacts with an applied magnetic field to propel the ship forward. Superconducting magnets are required to generate the large magnetic fields (10 to 20 tesla) needed to achieve reasonable efficiencies. Japan has recently announce the launching of Yamato I, a 280 metric ton experimental ship powered by an EM thruster.

EM Launchers

Electromagnetic launchers operate on the railgun principle, and have been proposed for launching payloads from the earth and the moon, as well as for orbital transfers. On a smaller scale, EM launchers could be used to replace the noisy steam catapult systems used to launch aircraft from Naval carriers. Superconductors are required to provide the large magnetic forces required for most launch applications.

CONCLUSIONS

Electronic devices, such as those based on SQUID sensors and other HTSC thin-film technology, have been developed and are transferring to the commercial market. Liquid nitrogen level detectors are currently being marketed using Y-Ba-Cu-O superconductors. HTSC materials are currently being used to shield of magnetic fields in a number of laboratory situations. Development of high-T_c current leads for magnet cryostats has progressed to a stage that is adequate for field testing. Laboratory results for HTSC superconducting bearings have been very incouraging, and they could provide the enabling technology for flywheel energy storage.

Intermediate-term HTSC applications include short transmission lines, small motors, fault current limiters, and other devices that can be fabricated from moderate lengths of wire and tape. The excitement associated with high-T_c materials has inspired renewed interest in the application of low-T_c superconductors to motor/generator systems, SMES, maglev trains, and EM thrusters. Nationally based programs are in place to develop improved LTSC prototypes in each of these application areas.

Significant improvements have been made in the current carrying capacity of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O tapes and wires. In particular, current denities of 10^5 A/cm^2 have been measured in prototype Bi-Sr-Ca-Cu-O conductors at liquid helium temperatures, and of $4x10^4$ at liquid hydrogen temperatures. However, further development is necessary to fabricate coil windings suitable for high-field magnets and other large-scale applications at liquid nitrogen temperatures.

The fact that the performance of high-T_c superconductors improves significantly with decreasing temperature raises the possibility for applications operating at temperatures intermediate between the 4 K and 77 K levels of liquid helium and nitrogen. Possible cryogens are liquid hydrogen at 20 K and gaseous helium at any intermediate temperature. The ability to cool superconducting magnets with commercial refrigerators operating in the 10 to 30 K range, without the Joule-Thompson expansion valves required for liquid helium liquefiers, would be a major economic advantage for future HTSC application development.

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