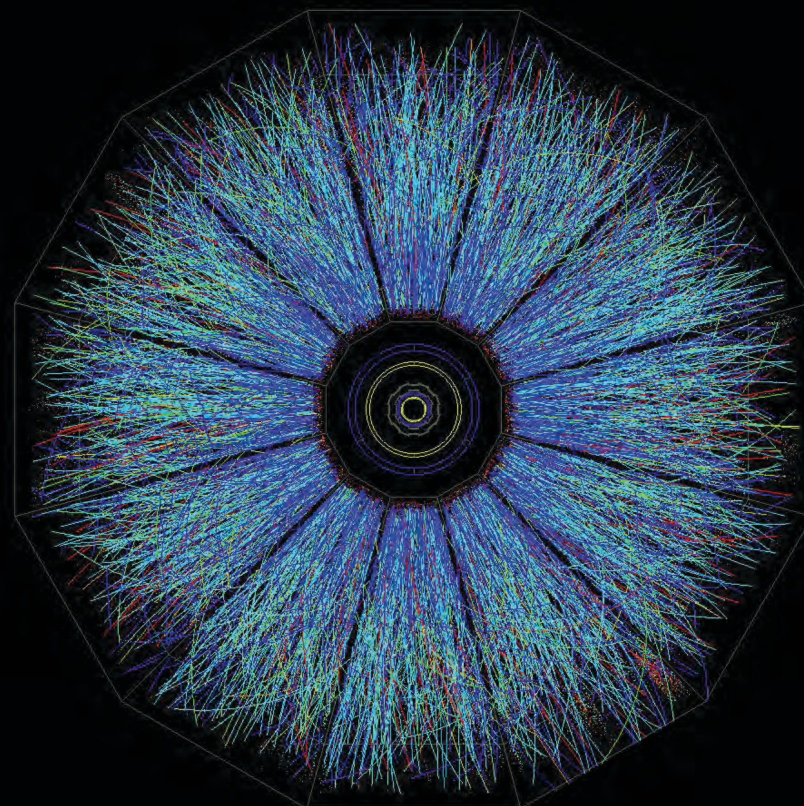
SUPERCONDUCTIVITY



CCAS
Coalition for the Commercial Application of Superconductors

IEEE CSC
Council on Superconductivity

Present and Future Applications

CCAS
Coalition for the
Commerical Application
of Superconductors

Coalition for the Commercial Application of Superconductors (CCAS)

CCAS is a member-driven, non-profit 501(c)6 organization, initially formed in 1987 to represent superconductivity stakeholders in the United States.

CCAS Vision

CCAS members believe that the commercialization of superconductors and related technologies will translate into significant benefits to the world economies across a broad range of endeavors. Superconductors offer the promise of important major advances in efficiency and performance in electric power generation, transmission and storage; medical instrumentation; wireless communications; computing; and transportation, that will result in societal advances that are cost effective and environmentally friendly.

CCAS Mission

The mission of CCAS is to provide broad dissemination of the applications and benefits of superconductivity and related technologies and to represent the industry by speaking with a united voice on public policy issues.

CCAS seeks to ensure that the societal and economic benefits of superconductors are effectively realized and speedily implemented by endorsing and supporting government programs and activities consistent with the CCAS vision.

CCAS seeks to enable members to communicate and collaborate, nationally and internationally, to collectively develop and demonstrate multi-disciplinary technology, to educate policy makers, and to advocate priorities for adequate government funding for superconductor based programs from research to pre-commercial demonstrations.

CCAS Membership

CCAS is a U.S. based organization with membership open to all stakeholders that share an interest in its vision and mission. CCAS members are involved in the end-use, manufacture, development and research of superconductor based systems, products and related technologies. Members comprise large and small corporations, research institutions, national laboratories and universities.

For more information contact Dr. Alan Lauder, Executive Director, CCAS, at alauder@comcast.net or by phone at 610-388-6901.

IEEE CSC
Council on Superconductivity

IEEE Council on Superconductivity (IEEE CSC)

The IEEE Council on Superconductivity promotes activities that cover the science and technology of superconductors and their applications. Areas of interest range from small scale applications, such as ultra-sensitive radiation detectors and sensors, and analog and digital circuits and systems, to large scale applications such as high field magnets, and electrical power generation, storage and transmission. The development and enhancement of the properties of superconductor materials suitable for use with these applications is also of great interest.

The IEEE CSC distributes technical information mainly through its publication of the IEEE Transactions on Applied Superconductivity.

The purpose of the Council is to advance and coordinate work in the field of superconductivity conducted throughout the IEEE, and as such is primarily technical and educational in character. To further these objectives, the Council may publish appropriate periodicals, sponsor IEEE superconductivity related conferences and conference sessions, sponsor IEEE Press publications, and engage in any other activity within its field of interest that is consistent with the Constitution, Bylaws, and Policies of the IEEE, and of the IEEE Council on Superconductivity.

Member Groups and Societies

IEEE Member Societies of the Council include the Communications Society, Components, Packaging and Manufacturing Society, Dielectrics and Electrical Insulation Society, Electron Devices Society, Instrumentation and Measurement Society, Magnetics Society, Microwave Theory and Techniques Society, Power Engineering Society, Reliability Society, and the Ultrasonics, Ferroelectrics and Frequency Control Society.

Awards

IEEE CSC has established two awards, approved by the IEEE, to recognize researchers, engineers and managers, who during their professional careers have made outstanding contributions to the field of applied superconductivity. Awardees receive a plaque, an inscribed medallion, and a cash honorarium. For information, contact Dr. Martin Nisenoff at <m.nisenoff@ieee.org>.

The IEEE Award for Continuing and Significant Contributions in the Field of Applied Superconductivity recognizes individuals for contributions in the field of applied superconductivity over a period of time based on novel and innovative concepts proposed by the individual, the authorship or co-authorship of a number of publications of major significance to the field of applied superconductivity and the presentation of a number of invited and plenary talks at major national and international conferences and meetings in applied superconductivity.

The IEEE Max Swerdlow Award for Sustained Service to the Applied Superconductivity Community recognizes sustained service to the applied superconductivity community that has had a lasting influence on the advancement of the technology either through the demonstration of exceptional service to and leadership within the community, the promotion of major programs in applied superconductivity or through management roles in major research organizations.

Distinguished Lecturers

For information about the current Distinguished Lecturer or to nominate someone to be a future Lecturer, please contact Dr. John Spargo, President, IEEE CSC, at <john.spargo@ngc.com>.

SUPERCONDUCTIVITY
Present and Future Applications

For brochure reprints contact: alauder@comcast.net

Superconductivity: Properties, History, Applications and Challenges

Superconductors differ fundamentally in quantum physics behavior from conventional materials in the manner by which electrons, or electric currents, move through the material. It is these differences that give rise to the unique properties and performance benefits that differentiate superconductors from all other known conductors.

Unique Properties

- Zero resistance to direct current
- Extremely high current carrying density
- Extremely low resistance at high frequencies
- Extremely low signal dispersion
- High sensitivity to magnetic field
- Exclusion of externally applied magnetic field
- Rapid single flux quantum transfer
- Close to speed of light signal transmission

Zero resistance and high current density have a major impact on electric power transmission and also enable much smaller or more powerful magnets for motors, generators, energy storage, medical equipment and industrial separations. Low resistance at high frequencies and extremely low signal dispersion are key aspects in microwave components, communications technology and several military applications. Low resistance at higher frequencies also reduces substantially the challenges inherent to miniaturization brought about by resistive, or I^2R, heating. The high sensitivity of superconductors to magnetic field provides a unique sensing capability, in many cases 1000x superior to today's best conventional measurement technology. Magnetic field exclusion is important in multi-layer electronic component miniaturization, provides a mechanism for magnetic levitation and enables magnetic field containment of charged particles. The final two properties form the basis for digital electronics and high speed computing well beyond the theoretical limits projected for semiconductors. All of these materials properties have been extensively demonstrated throughout the world.

History of Superconductor Materials

In 1911, H. K. Onnes, a Dutch physicist, discovered superconductivity by cooling mercury metal to extremely low temperature and observing that the metal exhibited zero resistance to electric current. Prior to 1973 many other metals and metal alloys were found to be superconductors at temperatures below 23.2K. These became known as Low Temperature Superconductor (LTS) materials. Since the 1960s a Niobium-Titanium (Ni-Ti) alloy has been the material of choice for commercial superconducting magnets. More recently, a brittle Niobium-Tin intermetallic material has emerged as an excellent alternative to achieve even higher magnetic field strength. In 1986, J. G. Bednorz and K. A. Müller discovered oxide based ceramic materials that demonstrated superconducting properties as high as 35K. This was quickly followed in early 1997 by the announcement by C. W. Chu of a cuprate superconductor functioning above 77K, the boiling point of liquid nitrogen. Since then, extensive research worldwide has uncovered many more oxide based superconductors with potential manufacturability benefits and critical temperatures as high as 135K. A superconducting material with a critical temperature above 23.2K is known as a High Temperature Superconductor (HTS), despite the continuing need for cryogenic refrigeration for any application.

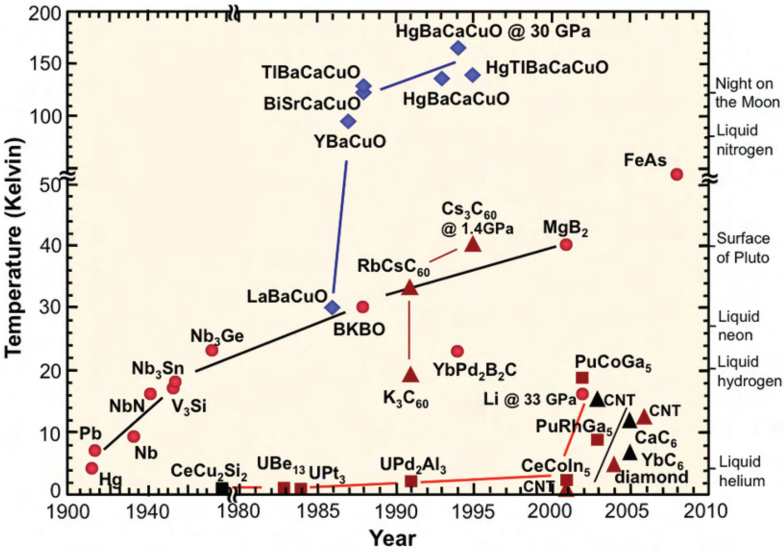


Image courtesy of Department of Energy - Basic Energy Sciences

Challenges

- Cost
- Refrigeration
- Reliability
- Acceptance

Forty years of development and commercialization of applications involving LTS materials have demonstrated that a superconductor approach works best when it represents a unique solution to the need. Alternatively, as the cost of the superconductor will always be substantially higher than that of a conventional conductor, it must bring overwhelming cost effectiveness to the system. The advent of HTS has changed the dynamic of refrigeration by permitting smaller and more efficient system cooling for some applications. Design, integration of superconducting and cryogenic technologies, demonstration of systems cost benefits and long term reliability must be met before superconductivity delivers on its current promise of major societal benefits and makes substantial commercial inroads into new applications.

Superconductivity: An Overview of Applications

Superconductivity is a unique and powerful phenomenon of nature. Nearly a century after its first discovery, its full commercial potential is just beginning to be exploited.

About Superconductivity

Superconductivity is widely regarded as one of the great scientific discoveries of the 20th Century. This miraculous property causes certain materials, at low temperatures, to lose all resistance to the flow of electricity. This state of "losslessness" enables a range of innovative technology applications. At the dawn of the 21st century, superconductivity forms the basis for new commercial products that are transforming our economy and daily life.

Current Commercial Applications

- Magnetic Resonance Imaging (MRI)
- Nuclear Magnetic Resonance (NMR)
- High-energy physics accelerators
- Plasma fusion reactors
- Industrial magnetic separation of kaolin clay

The major commercial applications of superconductivity in the medical diagnostic, science and industrial processing fields listed above all involve LTS materials and relatively high field magnets. Indeed, without superconducting technology most of these applications would not be viable. Several smaller applications utilizing LTS materials have also been commercialized, e.g. research magnets and Magneto-Encephalograhy (MEG). The latter is based on Superconducting Quantum Interference Device (SQUID) technology which detects and measures the weak magnetic fields generated by the brain. The only substantive commercial products incorporating HTS materials are electronic filters used in wireless base stations. About 10,000 units have been installed in wireless networks worldwide to date. More detail on these applications is presented in subsequent sections.

Emerging Applications

Superconductor-based products are extremely environmentally friendly compared to their conventional counterparts. They generate no greenhouse gases and are cooled by non-flammable liquid nitrogen (nitrogen comprises 80% of our atmosphere) as opposed to conventional oil coolants that are both flammable and toxic. They are also typically at least 50% smaller and lighter than equivalent conventional units which translates into economic incentives. These benefits have given rise to the ongoing development of many new applications in the following sectors:

Electric Power. Superconductors enable a variety of applications to aid our aging and heavily burdened electric power infrastructure - for example, in generators, transformers, underground cables, synchronous condensers and fault current limiters. The high power density and electrical efficiency of superconductor wire results in highly compact, powerful devices and systems that are more reliable, efficient, and environmentally benign.

Transportation. The rapid and efficient movement of people and goods, by land and by sea, poses important logistical, environmental, land use and other challenges. Superconductors are enabling a new generation of transport technologies including ship propulsion systems, magnetically levitated trains, and railway traction transformers.

Medicine. Advances in HTS promise more compact and less costly Magnetic Resonance Imaging (MRI) systems with superior imaging capabilities. In addition, Magneto-Encephalography (MEG), Magnetic Source Imaging (MSI) and Magneto-Cardiology (MCG) enable non-invasive diagnosis of brain and heart functionality.

Industry. Large motors rated at 1000 HP and above consume 25% of all electricity generated in the United States. They offer a prime target for the use of HTS in substantially reducing electrical losses. Powerful magnets for water remediation, materials purification, and industrial processing are also in the demonstration stages.

Communications. Over the past decade, HTS filters have come into widespread use in cellular communications systems. They enhance signal-to-noise ratios, enabling reliable service with fewer, more widely-spaced cell towers. As the world moves from analog to all digital communications, LTS chips offer dramatic performance improvements in many commercial and military applications.

Scientific Research. Using superconducting materials, today's leading-edge scientific research facilities are pushing the frontiers of human knowledge - and pursuing breakthroughs that could lead to new techniques ranging from the clean, abundant energy from nuclear fusion to computing at speeds much faster than the theoretical limit of silicon technology.

Issues and Recommendations

Recent progress in superconductivity follows a pattern that marked previous developments in new materials - for example, in transistors, semiconductors and optical fibers. Materials-based technology development entails high risk and uncertainty compared to more incremental innovations. It typically takes 20 years to move new materials from the laboratory to the commercial arena. Yet products using new materials often yield the most dramatic benefits for society in the long run.

The long lead times inherent in HTS technology development necessitates a sustained government role, and government-industry partnerships play a pivotal role in this process. These partnerships require stable and consistent funding and a tolerance for risk. Careful planning is required to ensure parallel progress in related fields, such as cryogenics, to assure broad commercial acceptance of new LTS and of HTS technology. Prospective customers such as electric utilities require a stable and symmetrical climate for investment in research, development and demonstration projects.

Superconductivity: Applications in Electric Power

Today's power grid operators face complex challenges that threaten their ability to provide reliable service: steady demand growth; aging infrastructure; mounting obstacles to siting new plants and lines; and new uncertainties brought on by structural and regulatory reforms. Advances in high temperature superconductivity (HTS) over the past two decades are yielding a new set of technology tools to renew this critical infrastructure, and to enhance the capacity, reliability and efficiency, of the nation's power system.

The US Power Grid Under Stress

Power industry experts in the United States are widely agreed that today's aging power grid must be strengthened and modernized. Utilities must cope with a growth in the underlying level of demand driven by our expanding, high technology-intensive economy. Consumers in the digital age have rising expectations and requirements for grid reliability and power quality. Competitive reforms have brought about new patterns of power flows. EPRI (the Electric Power Research Institute) has estimated that $100 billion must be spent over the next ten years to achieve and maintain acceptable levels of electric reliability.

At the same time, utility shareholders are insisting on strong financial performance and more intensive use of existing utility assets. Moreover, gaining approval to site new infrastructure - both generating plants as well as transmission lines - has become extremely difficult in the face of landowner and community opposition and the NIMBY ("not in my back yard") phenomenon. This is especially the case in urbanized areas where power needs are concentrated. As a result, utilities face lengthy and uncertain planning horizons, as well as a rising risk of costly blackouts and other reliability problems.

HTS power cable
Image courtesy of Sumitomo Electric / SuperPower

The existing grid is also becoming increasingly regionalized with more generation located remotely to be close to its particular source of fuel. The grid will therefore have to mitigate increasing inter-regional fault current transfers and the increasing number of parallel transmission paths that will be required to allow lowest cost electricity to flow to where it is needed and to allow a smarter grid to quickly respond to disruptions of sources, transmission or local generation paths. Distributed generation can help but is not always available when needed, and also must be redesigned, possibly with the help of fault current limiters, to ride through local faults and remain available.

Solving this complex set of problems will require a combination of new policies and technologies. Regulatory reforms are needed to foster stronger incentives for grid investment and to overcome the fragmentation that has impeded utilities' ability to raise the required investment capital. Beyond new rules, however, the physical nature of the challenge requires the adoption of advanced grid technologies, including those based on HTS.

These new HTS technologies have undergone rapid development in the comparatively short time of two decades. The first HTS compounds were synthesized in research laboratories in the late 1980s. Today, the HTS industry has advanced to full-scale power equipment prototypes and demonstration projects that are undergoing the rigors of in-grid evaluation. As these new technologies are incorporated into the existing power system, they will offer utilities new tools to ease the pressures that limit the performance and capacity of their systems - with much lower space and land use impacts and with major environmental benefits than are available using traditional grid upgrade solutions.

HTS Wire. The foundation of these applications is a new generation of wire, capable of carrying vastly (on the order of 100+ times) higher currents than conventional copper wires of the same dimension, with zero or negligible resistive losses. Today's prototype and demonstration technologies have made use of a proven, readily available and high-performance first generation HTS wire that is multifilamentary in composition. Second generation (2G) HTS wire, using a coated conductor architecture and a variety of thin film manufacturing processes, is rapidly making its way to market. 2G wire will greatly broaden the addressable market for existing HTS devices because of its predicted lower cost. It will also enable altogether new types of HTS applications due to its superior performance characteristics in certain modes of operation. 2G wire has been commercially available since 2006.

HTS wire, in short, brings the promise of a revolution in the way electricity is generated, delivered and consumed - much as the introduction of optical fiber led to a technological leap forward in the telecommunications industry. Among the power applications HTS wire enables are the following:

HTS Power Cables. Today's conventional power lines and cables are being operated closer to their thermal limits, and new lines are becoming hard to site. Compact, high-capacity underground HTS cables offer an important new tool for boosting grid capacity. Today's advanced HTS cable designs enable controllable power flows and the complete suppression of stray EMF. HTS power cables transmit 3-5 times more power than conventional copper cables of equivalent cross section, enabling more effective use of limited and costly rights-of-way. Significant progress toward the commercialization of HTS cable is underway. Three major in-grid

138kV HTS cable system installed in Long Island, NY
Image courtesy of American Superconductor

demonstrations have been completed in the US including the world's first HTS power transmission cable system in a commercial power grid which is capable of transmitting up to 574 megawatts (MW) of electricity, enough to power 300,000 homes. Two more demonstrations are in the planning stage in the US and another dozen projects are active around the world.

Fault Current Limiter
Image Courtesy of Zenergy Power

HTS Fault Current Limiters. As new generators are added to the network, many local grids face a rising risk of unacceptably high power surges that result from "faults" or short circuits. These occasional surges are induced by adverse weather, falling tree limbs, traffic accidents, animal interference and other random events. As fault current levels rise, they pose a mounting risk that such surges will exceed the rating of existing conventional circuit breakers, switchgear, bus, distribution transformers and other equipment and expose grids to much more costly damage. HTS technology enables a new solution: compact, "smart" fault current limiters (FCLs) that operate, passively and automatically, as power "safety valves" to ensure system reliability when individual circuits are disrupted. Taking advantage of the inherent properties of superconductors, they sense such dangerous overcurrents and reduce them to safe levels by changing state instantaneously, from from "super" conductors to resistors. Several demonstrations of this breakthrough technology are now underway, with an expected commercial horizon of 2010.

HTS Transformers for the Grid. Grid operators face a major challenge in moving power safely and efficiently, from generators to consumers, through several stages of voltage transformation. At each stage, valuable energy is lost in the form of waste heat. Moreover, while demands are continually rising, space for transformers and substations - especially in dense urban areas - is severely limited. Conventional oil-cooled transformers also pose a fire and environmental hazard. Compact, efficient HTS transformers, by contrast, are cooled by safe, abundant and environmentally benign liquid nitrogen. As an additional benefit, these actively-cooled devices will offer the capability of operating in overload, to twice the nameplate rating, without any loss of life to meet occasional utility peak load demands.

HTS Transformers for Wind Energy. The increasing demand for clean, carbon-free electric power, coupled with the global warming crisis, has fueled tremendous interest in and development of renewable energy technologies such as wind power. To break through the economic barrier and assure the future of this vast and critically important green energy source, new

Wind turbine
Image courtesy of American Superconductor

technologies are needed offering lower weight, higher efficiency, and significantly improved reliability. Direct drive wind generators are utilizing a new high-efficiency stator design and replacing copper with HTS wire on the rotor. Estimates are that a 10 MW drive utilizing HTS technology would weigh about one third the weight of a conventional direct drive generator with the same power rating. This reduction in weight would also allow an increase in blade size and greater power output. The net effect is expected to double the power capacity of conventional systems and lower the cost of wind generated energy.

Energy Storage. With power lines increasingly congested and prone to instability, strategic injection of brief bursts of real power can play a crucial role in maintaining grid reliability. Small-scale Superconducting Magnetic Energy Storage (SMES) systems, based on low-temperature superconductor, have been in use for many years. These have been applied to enhance the capacity and reliability of stability-constrained utility grids, as well as by large industrial user sites with sensitive, high-speed processes, to improve reliability and power quality. Larger systems, and systems employing HTS, are a focus of development. Flywheels, based on frictionless superconductor bearings, can transform electric energy into kinetic energy, store the energy in a rotating flywheel, and use the rotational kinetic energy to regenerate electricity as needed. Using bulk HTS self centering bearings allows levitation and rotation in a vacuum, thereby reducing friction losses. Conventional flywheels suffer energy losses of 3-5% per hour, whereas HTS based flywheels operate at <0.1% loss per hour. Large and small demonstration units are in operation and development.

HTS: An Enabler of the Electricity Revolution. The advent of HTS technology offers the opportunity for grid operators to move to a new level of power system performance. Since the dawn of the utility industry in the late 19th century, power networks have been based almost exclusively on components made of conventional materials such as copper, aluminum and iron. The performance and capacity of the grid has been improved and expanded over time. Yet grid performance is ultimately limited by the inherent properties and limitations of these materials.

HTS-based technology removes many of these operational and space constraints. It offers grid operators a new set of tools and strategies to improve the performance, reliability, safety, land use and environmental characteristics of a power system. The need for such new solutions is becoming acute with the relentless electrification of energy use - a trend that makes our aging, heavily burdened grid more critical than ever to the functioning of modern society.

Issues and Recommendations

In many ways, the electric power industry is at a crossroads. Within the past few years, electric power industry structural reform efforts have stalled perceptibly. The current gridlock in policy reforms and power flows is largely due to the mounting difficulty of expanding the power delivery network. Without a way to expand the "superhighway system" that supports power flows, recent competitive market reforms simply cannot succeed. HTS technology can play an important role in "breaking the gridlock" of power flows and policy reforms that threaten the power industry and our overall economy.

However, before HTS technology solutions can enjoy broad acceptance, they must undergo field trials. Such demonstrations play a crucial role in establishing a record of reliability and working out grid integration issues. Despite the acute needs facing the electricity sectors, it is widely observed that investor-owned utilities have taken a cautious and conservative approach to adopting new technology solutions in recent years. This has resulted from several factors including: a perception of asymmetric regulatory risks; disallowances resulting from past technology failures; and the loss of sites where experimental technologies can be tested without potentially adverse consequences for customers. Industry restructuring efforts underway since the early 1990's, moreover, have had the unfortunate effect of undermining investment in jointly-funded industry R&D.

There is an urgent need to reverse this trend. Government bodies - including legislatures, regulatory commissions and research-oriented agencies - can foster a more positive climate for HTS "early adopters." Comprehensive field trials of these advanced technologies require, by their nature, stable funding on a multi-year basis. There are several specific measures that government bodies can undertake to support the more rapid commercialization of these and other promising grid technologies:

- Encouragement of additional demonstration and pilot projects of advanced grid technologies.
- More favorable rate treatment for grid-related research and development expenditures, which have undergone a steep decline since the early 1990s.
- More thorough review of all feasible alternatives in the regional planning process - including low-impact grid upgrades along with other conventional and non-conventional solutions.
- Review of the criteria governing the use of "clean energy funds" and other state mechanisms to promote new technology development and deployment. For many emerging technologies, the "missing link" to market acceptance is a reliable pathway to market that could be provided or enhanced by innovative grid technologies enabled by HTS.

Superconductivity: Applications in Transportation

Around the world, transportation systems of all kinds are facing unprecedented new challenges. Pressures on the systems and technologies that move people and goods are expected to intensify due to several factors: rising demand; changes in fuels market economics; and the demand for improved system performance. In response, several types of transportation are being electrified. Superconductivity can leverage the advantages of electrified transportation of various types, ranging from high-speed trains to advanced ship propulsion systems. The incorporation of superconductor technology into transportation system design can improve the efficiency and performance, reduce the weight and fuel consumption, and extend the range of transportation systems of all types.

Transportation at a Crossroads

Around the world, today's transportation systems are facing an unfolding crisis. Nearly all of the dominant technologies that provide mobility today - including automobiles, trains, ships and aircraft - depend overwhelmingly on petroleum-based fuels. Yet world oil prices continue to rise, and low-cost oil supplies are dwindling. Modern societies, which depend on a high level of mobility, face the prospect of higher costs and concomitant slower economic growth if new solutions to assure the movement of passengers and goods are not available.

One of the most promising responses to this challenge lies in the electrification of transportation. Electrification allows for the powering of many transportation systems from the interconnected power grid and the inherent efficiency of electric drive systems can also result in significant cost savings.

In many ways, the electrification of transportation is an old story. In the late 19th century, electric streetcar systems literally provided the incentive to electrify urban neighborhoods. Through the mid-20th century, many developed nations adopted high-speed electric trains. However, the rise of low-cost oil in the early 20th century encouraged the migration away from grid-based systems to the adoption of alternatives that offered greater convenience and flexibility.

In the 21st century, electricity is getting a new look as the basis for powering transportation systems. Factors driving interest in electrification of transportation include both the performance advantages of electric systems as well as the increasing cost and tightening supply of oil. Today's innovations are adapting electric technology in ways that combine the advantages of stand-alone transportation systems with the cleanliness, efficiency and convenience of electricity. Prominent land-based examples of today's cutting-edge mobility innovations include rechargeable, plug-in hybrid cars; super high-speed magnetically levitated trains; and intercity trains with more efficient traction transformers. All of these transportation systems could be powered by a wide range of energy sources through the power grid. Meanwhile, at sea, ship propulsion is also being electrified, employing self-contained systems for the efficient production and delivery of power on board large vessels.

The Role of Superconductivity

Superconductivity offers several ways to leverage the benefits of electrification in many of these transport applications. High-performance, lightweight superconductor technologies can make transportation propulsion systems more powerful yet smaller and lighter. The following capsule descriptions explain how superconductivity is being applied in a variety of transportation technologies to ensure that society continues to enjoy mobility in a resource-constrained world.

HTS Marine Ship Propulsion: A Revolution in Ship Design

Within the past 20 years, ship designers have begun to adopt electric propulsion systems. This shift has been characterized as the most important change in ship design since the adoption of diesel engines in the 1920s. Electric propulsion systems enable new, more flexible arrangements and the more efficient integration of a ship's energy-using systems, because they allow the same power plant to support propulsion as well as other requirements. As a result, ships can be redesigned to provide more space below deck, whether for passengers, cargo or, in the case of naval applications, weapons and weapon systems. Among large commercial ocean going vessels, nearly 100% of all new ships are electrically propelled, including many large cruise ships such as the Queen Mary 2. Electric propulsion offers other advantages for naval applications and in 2000, the US Navy announced that it would migrate toward an all-electric fleet.

Cruise Ship
Image courtesy of American Superconductor

The large size and heavy weight of conventional copper-based electrical propulsion motors and generators has been a barrier to broad adoption of electric propulsion. For these reasons, superconductors offer additional, important advantages for electrically propelled ships. HTS motors and generators are much smaller and lighter; operating prototypes are one-third the size and weight of their conventional copper-wound counterparts and quieter. The elimination of rotor losses results in much higher efficiency, especially under partial-load conditions, where many ships operate for the great majority of their operating hours. This improved efficiency translates into a longer cruising range and greater fuel economy. Smaller motor assemblies could also enable electric ships to use shallower ports, and could be incorporated directly into steerable pod-based assemblies, resulting in greater flexibility and improved maneuverability. Smaller propulsion motors translates into naval ships that can carry more powerful weapons such as high power combat radars and additional missiles. These advantages have garnered significant interest from the US Navy and other navies around the world. Apart from naval and cruise ship applications, other possible applications include many other ship types including LNG tankers, product tankers, ferries, research ships, cable layers and icebreakers.

36.5 MW HTS Ship Drive Motor
Image courtesy of American Superconductor

HTS Degaussing Coils

Another new demonstration of HTS capabilities is under way using specially designed HTS cables to replace the copper degaussing coils on military ships. The advantages of less weight and size, coupled with high current density, make HTS cables an ideal solution for protection of military vessels.

Magnetically Levitated Trains

Several countries in Europe and Asia rely heavily on rail transport to carry large numbers of passengers. For longer haul express routes, rail transportation has the advantage over air travel as it typically operates from a transportation hub in the city center. Magnetically levitated trains, employing superconducting magnets, offer a way to make trains literally "fly" to their destination by using powerful magnets to cause them to float above their guideway, or track. Magnetically levitated trains have attained top speeds in excess of 500 kmph. Some transportation experts believe that maglev transportation could revolutionize transportation in the 21st century in much the same way that airplanes revolutionized 20th century transport.

Superconductor magnets are essential to this application because of their dramatically lighter weight and lower power requirements. At present, maglev train lines operating in Japan, Germany and China make use of low temperature superconductor (LTS) technology. However, there is now research underway on the application of HTS coils to maglev trains, which could result in lower cooling costs and higher stability.

Other HTS Applications and Ramifications

Other transportation systems could, in time, be powered by systems using superconductor wire. The focus of these innovations however, is on large, bulk transport systems rather than individual passenger automobiles, which are used intermittently. The wider adoption of plug-in hybrid automobiles would result in increased total demand on the interconnected power grid and it is often noted that plug-in hybrid cars could provide a load-leveling function and lead to lower rates and more efficient grid asset utilization. If this concept becomes very commonplace, it will necessarily lead to an increase in total demand on the power grid, requiring upgrades to the general grid infrastructure. In certain locations, especially dense urban areas, this could necessitate the use of superconductor-based technologies in order to ensure the safe, reliable delivery of large amounts of power into dense urban areas.

The Foundation: Advances in HTS Wire

The basis for the performance advantages of these transportation technologies lies in high-performance superconductor wire. Electric shipboard motors employing superconductor wire can generate very powerful fields in a small fraction of the volume and weight of copper-wound motors. Otherwise, they make use of conventional, well-understood designs, employing the same century's worth of developments and refinements that apply to all AC synchronous electric motors. Maglev trains, likewise, make use of ultracompact, high-field coils that would be physically impossible to construct, absent the miraculous property of superconductivity.

With worldwide supplies of oil under increasing pressure, there is an urgent need to develop alternative solutions to ensure that economical means exist to move people and goods in the world of tomorrow. The phenomenon of superconductivity, which has found uses in applications ranging from research and medicine to electric power, could play a critical role in ensuring that these pressing needs can be met.

Superconductivity: Applications in Medical Imaging and Diagnostics

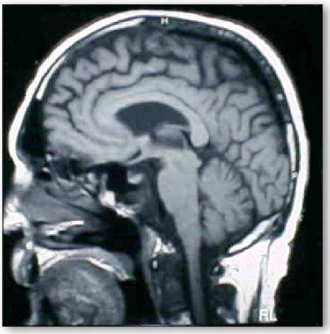
MRI (Magnetic Resonance Imaging) has become the "gold standard" in diagnostic medical imaging. It is not only safe and powerful, but thanks to superconducting magnets and their continued improvements, adds energy efficiency to its long list of benefits. In addition, advanced static and functional imaging techniques, using superconducting sensors, are emerging as complementary methods, enabling additional capabilities as well as lower cost. These include Ultra-Low-Field MRI, Magnetoencephalography (MEG), and Magnetocardiography (MCG). These advanced systems significantly improve the diagnostic tools available to healthcare providers and hold the promise of reducing lifetime healthcare costs.

Magnetic Resonance Imaging - MRI

Radiation-free Imaging. The introduction of MRI into the healthcare system has resulted in substantial benefits. MRI provides an enormous increase in diagnostic ability, clearly showing soft tissue features not visible using X-ray imaging. At the same time MRI can often eliminate the need for harmful X-ray examinations. These advantages have greatly reduced the need for exploratory surgery. The availability of very precise diagnostic and location information is contributing to the reduction in the level of intervention that is required, reducing the length of hospital stays and the degree of discomfort suffered by patients.

Superconducting MRI system in operation

The basic science of resonance imaging has been understood for many years. The nucleus of most atoms behaves like a small spinning magnet. When subjected to a magnetic field it tries to align, but the spin means that instead it rotates around the field direction with a characteristic frequency proportional to the field strength. When a pulse of exactly the right radio frequency is applied, some of the energy of the pulse is absorbed by the spinning nucleus, and then released several milliseconds later. The timing of this energy release, or relaxation, was discovered to depend critically on the chemical environment of the atom, and in particular was found to be different between healthy and diseased tissue in the human body. By rapidly switching on and off magnetic field gradients superimposed on the main field it is possible to determine very accurate position information from these signals. The signals are processed by a computer to produce the now-familiar images from within the human body. Since the first crude MRI images were made in the 1970s, the industry has grown to a turnover of $2B/year. There are now well over 20,000 MRI systems installed worldwide, and the number is growing by 10% annually.



An example of an MRI brain scan

Advantages of Superconductivity. The heart of the MRI system is a superconducting magnet. The typical field values required for MRI cannot be achieved using conventional magnets. Just as importantly, high homogeneity and stability of the magnetic field are essential to achieve the resolution, precision and speed required for economical clinical imaging, and superconductors provide a unique solution to these requirements.

Expanding Applications of MRI. Functional Magnetic Resonance Imaging (FMRI), a rapidly growing extension of MRI techniques, uses a sequence of fast images to study dynamic changes, primarily blood flow rates. This has proved to be a powerful tool for imaging the activation of local regions in the brain. It is used to evaluate which areas of the brain are responsible for different functions, such as speaking, comprehension, moving fingers and toes and vision. An even newer technique, MRI guidance imaging, is used to assist physicians during surgery to plan the approach and more precisely locate and remove tumors. Another new technique, Magnetic Resonance Spectroscopy, is used on a limited basis for evaluating brain tumors, neurological diseases and epilepsy. Spectroscopy gives information on the chemical composition and metabolic activity of brain tissue. This information is used to assist in making diagnoses, monitoring changes and evaluating seizure activity.

The Future of MRI. The number of MRI installations worldwide continues to grow at a rapid pace, providing ever more access to this powerful tool. MRI systems continue to advance in speed and resolution as the technologies of superconducting materials and superconducting magnets continue to advance. Exciting new methods that build on MRI are enabling new tools for both diagnosis and treatment of disease. It is clear that there are enormous potential benefits of continued support for R&D in superconducting materials and magnets.

Ultra-Low Field Magnetic Resonance Imaging (ULF-MRI)

Conventional Magnetic Resonance Imaging, discussed above, created a revolution in non-invasive imaging procedures, and the technique is used worldwide for many diagnoses. MRI is enabled by the high magnetic fields that only superconducting magnets can produce. Incremental improvements in the performance and cost of this established technology continue, but today researchers are also developing a complementary technique, Ultra-Low-Field MRI. In this new approach, instead of a high magnetic field from a superconducting magnet, a very low field - 10,000 times lower - is used. This low magnetic field is produced by simple, low cost, magnets made with room temperature copper wire. To compensate for the loss of the high magnetic field, the extreme sensitivity of a superconducting detector is required.

This detector, a "SQUID" (Superconducting QUantum Interference Device), enables the following benefits at low field:

- Significantly lower system cost, which could enable the new system to be much more widely available and used as an initial screening.
- In certain tissues, for example in breast and prostate tumors, ULF-MRI offers significantly better contrast between different tissue types, leading to more definitive diagnoses.

These two benefits combine to make ULF-MRI an important advance geared towards reducing the cost of healthcare on the one hand and enhancing the diagnostic ability of certain conditions on the other. The effort is slowly advancing from research to *in vivo* imaging; it holds also the promise of combining ULF-MRI with magnetoencephalography (MEG). ULF-MRI is much "greener" than high-field MRI in that it consumes vastly less electrical power.

Magnetoencephalography (MEG) and Magnetic Source Imaging (MSI)

The same extreme sensitivity of SQUIDs that enables ULF-MRI has already enabled the development and use of magnetoencephalography (MEG), sometimes referred to as magnetic source imaging (MSI). In these systems, which are available commercially, an array of SQUID sensors detects magnetic signals from the brain in a totally non-invasive manner. One of their major successes has been pre-surgical mapping of:

- eloquent brain areas (sensory, motor, language, etc.). Accurate knowledge of these locations assures that they are not inadvertently removed during brain surgeries.
- brain tumors, a procedure that has significantly reduced collateral damage to the brain that may accompany surgical removal of the tumor.
- accurate noninvasive location in the brain of sources of epileptic seizures. As a result, surgery to excise the defective area can be performed with much greater precision, significantly decreasing the danger of excising normal brain tissue during the procedure and eliminating the need for potentially fatal pre-operative surgery to determine the precise location of the epilepsy source.

Clinical MEG system
Image courtesy 4-D Neuroimaging

The use of MEG has been also extended to studies of unborn fetuses (fMEG). This technique has the potential to provide assessment of fetal neurological status and to assist physicians during high-risk pregnancies and diagnostics associated with infections, toxic insult, hypoxia, ischemia, and hemorrhage. There are presently no other techniques for noninvasive assessment of fetal brain status.

The major challenge for the wider deployment of MEG systems is the initial cost of the system and the large data base required to demonstrate excellent correlation of MSI with subsequent surgery. This effort involves system installation and data collection at research hospitals, an activity that is currently sparsely supported. The current initial diagnostic technique is low cost, electroencephalography (EEG). The major advantage of MEG over EEG is that the former does not require any contact with the patient's skin. In EEG, since electric currents travel the path of least resistance, moisture on the patient's scalp and variations in skull thickness can distort the mapping of the epilepsy source. Conversely, the magnetic field detected in MEG passes undistorted from the source to the SQUID detectors in the helmet worn by the patient.

Since the interpretation of MSI inevitably requires an MR image, the combination of ULF-MRI with MSI into a single system would both reduce the cost of the combined procedures and improve their co-registration accuracy.

Magnetocardiography (MCG)

Sensitive SQUIDs are also the basis of functional imaging of the heart in magnetocardiography (MCG or MFI - heart magnetic field imaging) systems. MCG systems detect, non-invasively and with unprecedented accuracy, the net flows of cardiac electric currents that drive the muscles in the heart. In many clinical locations around the world both scientists and physicians are independently validating the benefits of utilizing MCG for the detection and diagnosis of many forms of heart disease, especially cardiac ischemia and coronary artery disease. Sensitivity for the detection of ischemia has been reported as high as 100% in recent studies, and with such diagnostic accuracy it is not unreasonable to predict that MCG systems will find a home not only in hospitals, and especially emergency departments, but also in outpatient imaging centers and cardiology clinics, where the rapid evaluation of patients with suspicion of a life-threatening heart attack is absolutely critical to save lives. Significant economic benefits can also be projected. Compared with electrocardiography (EKG), MCG has a number of distinct advantages:

Non-invasive MCG system
Courtesy CardioMag Imaging (CMI)

- completely non-invasive, requiring no electrode contact with the skin.
- provides wide-ranging information about the electrophysiological activity of the heart, including the detection of coronary artery disease.
- signal strength depends on the distance between the heart and the detector, enabling the accurate measurement of the MCG of a fetus without saturating the detector with the signal from the mother's heart (fetal-MCG or fMCG).

While commercial systems do exist, the challenge for MCG, as in the case for MEG, is the development of a large enough database of clinical diagnostic correlations to convince insurers, such as Medicare, of the economic and healthcare benefits of MCG. Because it is radiation-free and risk-free MCG can be used often during routine follow-up after an operation or during cardiac rehabilitation. The efficacy of a drug regimen can be tracked with MCG or even the recurrence of blockages after invasive treatment of a coronary artery. With the safety of a blood pressure reading and being equivalent to the diagnostic power of a nuclear imaging procedure, MCG should be poised to revolutionize cardiac care.

Issues and Recommendations

The most pressing need in the quest to realize the full potential of these advances is the support for medical research aimed at correlating the data collected by ULF-MRI, MEG, and MCG, with actual clinical outcomes. As the pressure continues towards decreasing healthcare costs, this is an example where the investment in supporting research would inevitably lead to long term benefits and savings far exceeding the initial cost of development.

Superconductivity: Applications of NMR in Pharmaceuticals, Biotechnology, Genomics and Materials Science

NMR (Nuclear Magnetic Resonance) is a critical tool for genomics, drug discovery, biotechnology and materials science. Low Temperature Superconductor (LTS) materials enable the stable and homogeneous magnets required for precision NMR spectroscopy. Continued advances in superconducting materials have been repeatedly used to advance the performance of NMR systems, and thus benefit a wide range of science and technology applications.

A Versatile Enabling Tool

A 900 MHz NMR spectrometer
Image courtesy of Oxford Instruments

NMR is considered the most versatile spectroscopic tool in science today. In a 2003 report to the National Academies of Science, Robert Tycko of NIH stated that "NMR is one of the most important techniques in modern science, with applications in physics, chemistry, materials science, biology and medicine." The discovery of NMR as an analytical technique earned the 1952 Nobel Prize in Physics, and the methods of Magnetic Resonance Imaging, which are based on NMR, earned the 2003 Nobel Prize in Medicine.

NMR techniques have provided a fundamental tool for the study of materials in chemistry and physics laboratories for more than forty years. Using modern methods of NMR spectroscopy, an incredible range of science and technology is addressed on a daily basis. Some examples in materials science include the study of the chemistry of the fungal degradation of wood (a crucial recycling element in the global carbon cycle), the determination of the chemical structure of extraterrestrial matter in meteorites and the effects of various trace element additions on melt chemistry and matter flow in a variety of materials. In the life sciences, new methods use NMR as a diagnostic tool to identify people at greatest risk for developing heart disease, by analyzing the size and concentration of lipoproteins, the small spheres that carry cholesterol around the body and deposit it in various locations. More importantly, by evaluating specific medications using NMR technology, physicians are better able to select cholesterol medications that will have optimal results for a patient depending on his or her lipoprotein size and concentration.

Proteomics and Drug Discovery

Proteins serve vital functions for sustaining life - from absorbing the oxygen we breathe, to digesting the food we eat, to producing the electrochemical signals that enable to us think. The structure and function of proteins remain at the frontier of life science. A typical protein is a chain of hundreds of amino acids combined in any of tens of thousands of patterns. While scientists have long been able to determine the sequences of many protein chains, the challenge is in the way this chain folds into a unique structure. It is this structure that determines the protein's biochemical functions and properties; determining the structure is key to understanding the way it works. Knowing these structures has allowed drug companies to revolutionize drug-making processes, enabling them to develop drugs that specifically target certain proteins. In fact, finding the structure of a protein is such an achievement that many Nobel prizes have been given to those who have solved them. NMR has provided a powerful tool for protein structure determination and drug discovery.

Superconductivity: The Enabling Factor

The heart of the NMR spectrometer is a superconducting magnet. High field values and high homogeneity and stability of the magnetic field are essential to achieve the resolution and precision required for protein structure determination and other NMR analysis. With each advance made in superconducting materials over the past 25 years, ever-higher field NMR spectrometers have been built and used to analyze increasingly complex molecules.

The Future of NMR

A recent report from the National Academies of Science on future opportunities in high magnetic field science states that present limitations on superconducting materials will limit future NMR machines to the 1 GHz level. This report further recommends expanded development efforts aimed at higher field superconductors to enable further advances in NMR and other applications of high fields, and points out enormous potential benefits of continued support for R&D in superconducting materials/magnets.

Superconductivity: Applications in Industrial Processing

Low Temperature Superconductor (LTS) magnets enable the large magnetic separators used in the kaolin clay industry. Copper magnet technology was displaced beginning in 1986 as already installed systems were retrofitted and new systems were based on superconducting technology. The fundamental properties of superconducting materials impart performance properties to the magnet that cannot otherwise be achieved.

Kaolin Clay Processing

Kaolin is a white filler used extensively in paper and ceramic products. Annual production value is more than $3 billion. The United States is the largest manufacturer and exporter, with most of the production located in Georgia. Kaolin clay, as mined, contains low levels of ferromagnetic and paramagnetic impurities which act as color centers and must be removed to achieve the required "brightness." This was accomplished using environmentally unfriendly bleaching agents until 1973, at which time high gradient magnetic separators (HGMS) were introduced, based on wide-bore (84-120 inches diameter) copper magnets. In this process a kaolin clay slurry is passed through a tube packed with stainless steel wool that becomes magnetized when the field is turned on. Impurities adhere to the steel wool and are removed by back flushing with the field off. Throughput is directly related to field strength and continuous operation at maximum throughput is the economically desired mode.

Industrial LTS Magnetic Separator
Image courtesy of Outotec (USA) Inc.

Advantages of Superconductor Based Separators

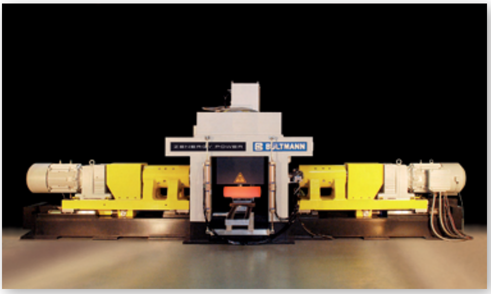
The overwhelming benefit realized by replacing copper by superconductor in magnets for kaolin clay processing is derived from the fundamental properties of the superconducting material. Copper separators typically operate at a field strength of 1.8T (1.8 Tesla) with a practical upper limit of about 2.0T. Conversely, a superconductor-based unit is typically designed to operate at 5T. As kaolin throughput is linearly related to field strength, superconductor units have a clear advantage in productivity.

Furthermore, large, copper-based magnetic separators require about 400kW per hour. When the copper coils are replaced with superconductor, the energy needed for the same kaolin throughput drops to 200W, and overall energy consumption is reduced by >95%. The continuing rise in energy costs further favors superconductor systems and more than offsets the modest capital investment premium.

Emerging HTS Systems

Several industrial applications have been identified as ideally suited for high field HTS based magnets and are being pursued. These applications include pre-treatment of water to prevent scale formation in boilers and heat exchangers, treatment of waste water streams, remediation of solid wastes and clean up of radioactive waste. Other opportunities are in materials manufacturing such as semiconductor production in high magnetic field and induction heating.

HTS Induction Heater. A new generation of non-ferrous induction heaters with shorter heating times and nearly double the efficiency of conventional induction heaters is now commercially available. A key element of these unique machines is the rotation of the work piece. HTS induction heaters, available in sizes between 0.25 MW and 2 MW of thermal rating, revolutionize aluminum, copper and brass billet heating prior to extrusion, cutting energy demand and operating costs to almost half, since there are virtually no electric losses. The induction coils are manufactured from advanced HTS material, chilled with compact machine-mounted chillers to 30 Kelvin and carry high direct current, with virtually no losses. To create the induction heating effect, the billet is rotated in a powerful electromagnetic field - the speed profile being determined by the size of billet and type of material. As well as doubling operating efficiency, the HTS induction heater requires less maintenance and is expected to have a longer working life, because of no conventional thermal loads. For the same reason, tool changing is faster and safer. The bottom line is improvement in productivity, flexibility, and operating costs.



HTS Induction Heater
Image courtesy of Zenergy Power

Superconductivity: Applications in High-Energy Physics and Other Areas of Research

Superconductivity has played a key role throughout the past century in expanding the frontiers of human knowledge. Today, these materials continue to offer important new tools to expand our understanding of the natural world and potentially foster new energy technologies.

Discovering The Nature Of Matter And Energy

Scientists spent the last half of the century putting together what is called the Standard Model of particle physics. The Standard Model, which explains the basic interactions of fundamental particles that make up everything we see is the most complete physical theory in history, yet it leaves 95% of the universe unexplained! Particle physicists use accelerators to recreate the conditions of the early universe in an attempt to piece together the complex puzzle of how we got to where we are today. These huge machines are used to accelerate particles to very high energies where they are brought together in collisions that generate particles that only existed a few moments after the Big Bang that created the universe 15 billion years ago.

LHC Magnet ready for testing

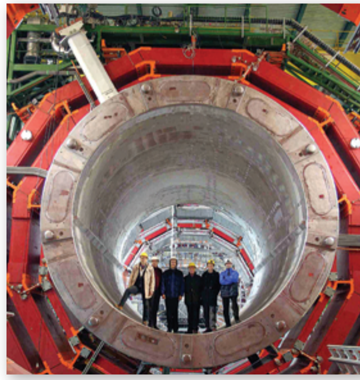
The Large Hadron Collider, or LHC, is located near Geneva, Switzerland and is scheduled to begin operation in late summer of 2008. It will be the largest and most powerful particle accelerator in the world with a circumference of 27 kilometers. Protons with energies of 7 trillion electron volts will be brought to collision inside giant detectors used to reconstruct the complex collisions that consist of hundreds of particles. This gargantuan "time machine" will generate conditions that existed approximately 20 billionths of a second after the Big Bang, and if nature is kind, will uncover phenomena never seen before.

Superconductivity Required

The rings of particle accelerators are made of superconducting magnets, strung together like beads on a necklace. In the LHC, two concentric rings are made up of thousands of superconducting magnets. The high energies required could not be economically achieved without superconducting magnets. The largest are the main dipoles that steer the particles around the ring. These magnets contain over 1,500 tons of superconducting cable. Superconductivity also enables

Accelerator Magnets in the LHC Tunnel

construction of giant magnets for the detectors at the LHC used to measure the properties of the particles produced in the collisions.



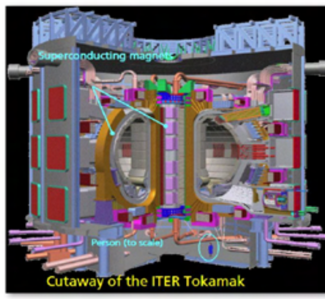
Detector Magnet for one of the LHC experiments

Fusion Energy

Bringing A Star To Earth

One of the biggest and potentially most significant scientific research projects now underway worldwide is the International Thermonuclear Experimental Reactor (ITER). This global project represents one of the biggest collaborations in energy research and is aimed at demonstrating the scientific and technological feasibility of fusion energy for peaceful purposes. ITER aims to provide the know-how to later build the first electricity-generating power station based on magnetic confinement of high temperature plasma - in other words, to capture and use the power of the sun on earth.

Superconductors play a critical enabling role in this important project by generating the high magnetic fields needed to confine and shape the high temperature plasma.



The ITER reactor will use 900 tons of superconductors in more than 20 Individual magnet sections

Space Exploration

Superconductors are under development for a range of space-related applications. Space telescopes and other space-based instruments require absolute minimal power budgets, and the low-loss natures of superconductors make them ideal in such applications. These applications include magnetic actuators, magnetic refrigeration, magnetically assisted propulsion and spaced based magnetic plasma confinement.

Issues and Recommendations

Such significant achievements can continue only with sustained support for the superconductor industry, including managing swings in demand that such large projects require, continuing research on new superconducting materials and maintaining a robust university infrastructure of programs in materials and device research.

Superconductivity: Applications in Wireless Communications

Superconductors offer the unique advantages of ultra-low dissipation and distortion as well as intrinsic (quantum) accuracy. These advantages combine to enable what researchers with the US Army have called the "most significant change to satellite communications worldwide in 30 years." Advanced filters are already deployed in commercial wireless base stations, enabling wider range and fewer dropped calls. A more significant development involves a complete transition to all-digital receivers and transmitters, a migration currently in the prototype phase which promises dramatic improvements in efficiency and cost for both military and commercial wireless communication systems.

HTS Filters

Cellular telephone base stations process signals by first detecting them with the antennas mounted at the top of the tower and then dividing those signals into channels dedicated to specific conversations. This division, when implemented with conventional technology, reduces the range of communication because of dissipation or loss of signal strength in the signal processing, and imposes limits on the number of channels due to lack of sharp filters and the resulting necessity to avoid overlap between the filtered outputs of different conversations handled. By using High Temperature Superconducting (HTS) filters, both limitations are addressed, and the service providers can increase the range of the base stations as well as enable a much larger number of simultaneous channels. This technology is now commercially deployed, with over 10,000 such systems in use in commercial systems and a total of over 200 million hours of run time. In an industry where reliability and uptime are the number one goal, these HTS filters have proven to be highly advantageous to the system.

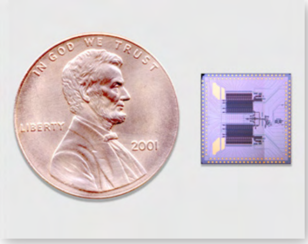
All-Digital Receivers

While HTS filters have demonstrated the unique positive impact of superconductors on the analog (non-digital) elements in wireless communications, the true revolution under development is one that takes advantage of the intrinsic linearity and quantum accuracy of superconductors to produce the world's best analog-to-digital converters. Much like digital CDs and digital television provide a superior experience as well as improved efficiency, all-digital receivers carry the same benefits to wireless communications. The crux of the improvement is in the unique ability of superconducting analog-to-digital converters to digitize a wide band of signal without the need for analog pre-processing. As a result, significant portions of the system, which usually add weight, volume, cost, and distortion, are completely eliminated. In addition, the manipulation of the digital data enables full flexibility in accommodating any protocol through the use of software, thus leading to an effectively universal system where the same hardware is adapted, by software, - to "translate" and decode any incoming signal from any other system.

Compatibility with legacy systems as well as "future-proofing" are ensured. While this technology is not yet commercially available, its development is proceeding at an impressive pace, supported in part by the US Government and in part by commercial ventures.

"Most Significant Change to Satellite Communications Worldwide in 30 years"

Recently, a demonstration of the capability of superconducting All-Digital Receivers was carried out by the US Army, in which an x-band satellite communications link was closed using such a receiver. The ability to directly digitize the x-band RF signal was proven and led to the proclamation that the "most significant change to satellite communications worldwide in 30 years" had been achieved. The heart of the system is the superconducting integrated circuit (IC) shown in the figure to the right. This circuit is made similarly to semiconductor ICs, but the key material here, instead of being Silicon, is the low temperature superconductor Niobium. The chip - less than half the size of a penny - contains about 11,000 Josephson junctions laid out to form superconducting Rapid Single Flux Quantum (RSFQ) circuits that move picosecond-duration magnetic pulses. After many years of research, the superconductivity community worldwide has determined that such digital applications can only be harnessed using low temperature superconductors, a fact that simplifies design and fabrication of the circuits but adds the more difficult constraint of cooling the IC to 4 degrees Kelvin (by contrast to the more easily reachable 70 degrees Kelvin for HTS materials). Nevertheless, advances in cryogenics, including recent breakthroughs in pulse-tube technology, fully provide the enabling cooling platform for packaging and deploying All-Digital Receivers. In addition, the same technology can be applied to All-Digital Transmitters (and hence, All-Digital Transceivers), resulting in similar gains in performance, cost, and efficiency.



All-Digital Receiver on a One-Centimeter Superconducting Niobium Chip
Image courtesy of Hypres, Inc.

Issues and Recommendations

Both military and commercial applications stand to benefit from the use of superconducting All-Digital Receivers (and Transmitters and Transceivers). The more difficult technical problems to address are in military applications, due to the much wider spectrum of frequencies, protocols, and applications involved. On the commercial front, commodity-level cost is such a competitive factor that initially, the better performance afforded by superconducting All-Digital technology is relegated to future plans pending its further evolution into a fully developed low-cost alternative. The much needed exploitation of supercomputing All-Digital technology will be enabled, perhaps uniquely, by a dedicated Governmental support to produce and demonstrate field prototypes with full performance. These demonstrations will be the needed catalyst to engage procurement plans from the Government and to place this technology on the roadmap for commercial wireless communications companies.

Superconductivity: Applications in Instrumentation, Sensors, Standards and Radar

Superconducting devices are so accurate they define the "Volt," goes the saying. The true testament to the intrinsic accuracy that results from the properties of superconductors is that the metrology standard for realizing the electrical unit of "Volt" is indeed a superconducting circuit. In addition to accuracy, superconductors enable the most sensitive detectors of electromagnetic radiation and are used in scientific research both at ground-based astronomy observatories as well as in space-based NASA missions.

Instrumentation

The earliest applications of superconducting electronics were, and continue to be, custom instruments based primarily on superb sensitivity in detecting magnetic fields. These instruments are based on various designs of SQUIDs and find applications in research laboratories for physics, chemistry, and materials science research as well as in field geological expeditions such as airborne detection of salt domes, a frequent indicator of potential new oil fields.

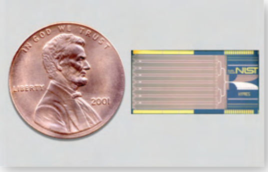
Sensors

Besides being ultrasensitive detectors of magnetic fields, superconductors also excel in the detection of extremely faint electromagnetic signals, for example signals originating in outer space. SQUID detectors hold the record in sensitivity and are used in many a radioastronomy observatory worldwide. The detectors are used in several modes, including as discriminators of the various frequencies of the incoming signals, as in the Radio Observatory featured in the figure, as well as in camera mode providing infrared images of astronomical objects, an example being the SCUB-2 infrared camera on the James Clerk Maxwell telescope in Hawaii.

The NASA Radio Observatory in Owens Valley, CA, relies on superconducting detectors

Standards

It took several decades of research and international collaboration to realize that superconducting devices can be the basis for a metrology standard for the electrical unit of the Volt. This is due to a fundamental property of a key superconducting element, the "Josephson Junction," which acts a frequency-to-voltage converter. Primary voltage standard systems, based on this principle, are now in virtually every national metrology laboratory, as well as in many advanced industrial research laboratories. The systems are available commercially for generating and calibrating any static voltage up to 10 Volts with accuracy up to 5 parts per billion. Continuing research by the National Institute of Science and Technology (NIST) in the US and similar institutions worldwide is focused on developing AC-voltage standards as well as arbitrary signal generators with the precision and accuracy of the existing DC-standards.



Primary Voltage Standard used to define the "Volt"
Image Courtesy NIST and Hypres, Inc.

Radar

Superconductive electronics can dramatically enhance anti-ship missile defense radars. Emerging threats include sea-skimming missiles that reflect very small fractions of the total radar signal. The challenges to the radar receivers are that they must distinguish these small echoes from the huge background clutter of waves, rain, jammers, and mountains on the shore in real time. Superconductivity enables the highest dynamic range digitizers and the smallest digits are meaningful to detect the most elusive threats. High dynamic range superconductive electronics provide the most advanced technology and simplify the receiver, thereby making these life-saving sensors affordable for a wide variety of Navy ships.

Superconductive digitizers enable ship self-defense radars to sense the small echoes from sea-skimming missile threats

Issues and Recommendations

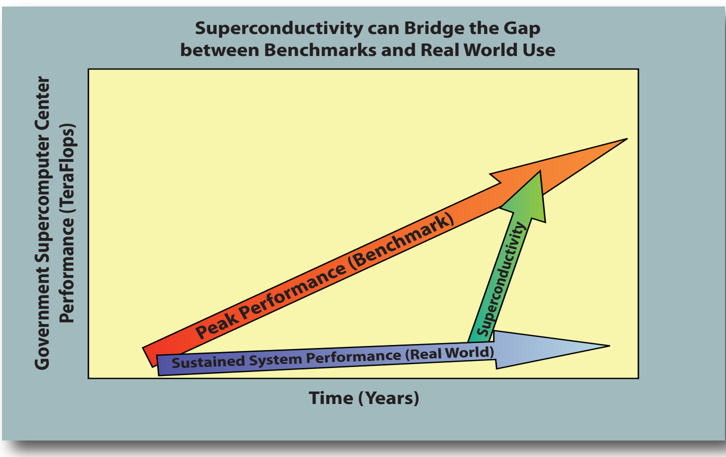
Besides continued support for the R&D required to advance these devices and applications, an enabling technology important in facilitating the adoption of these applications, and the concomitant improvement in performance of the systems they support, is a more efficient and reliable cryocooling system that is transparent to the end user. Advances are indeed occurring in this area but at a slow pace. Acceleration of this development would be of great benefit, enhancing the scientific and industrial applications of these instruments as sensors and standards as well as benefiting superconductor-based applications in communications.

Superconductivity: Applications in High-End Computing

Low temperature superconductor technology can take computing speed far beyond the theoretical limits of silicon while simultaneously effecting major reductions in both size and power requirements. While highly challenging, the path forward is clear and success will enable the most complex and interactive tasks to be performed that cannot be addressed in any other way.

Computers have increased exponentially in performance each year for more than 30 years, sustained by exponential increases in processor gate count and chip speed. In recent years, Moore's Law advances have slowed due to unsustainable chip heating required to simultaneously support more gates and faster clocks. The consequence is a limit in processor speeds to about 3 to 4 GHz, but ever-increasing gate count allows more processors on a single chip.

This new direction maintains performance growth for games, home and business computing, and even supercomputing for problems which can be made parallel or otherwise broken up. It is proving inadequate for problems that cannot be broken into small computational pieces. Unfortunately, many important national security problems cannot be easily broken up and separately managed. These problems require use of the sustained, full capability of a supercomputer.



Superconducting Electronics closes the gap between Peak Performance and Sustained System Performance

Superconducting electronics lead to both low gate power and ultra-high speed, with a theoretical limit estimated to be potentially 100 times faster than silicon. Already, superconductor-based Rapid Single Flux Quantum (RSFQ) circuitry has easily broken the 20 GHz speed barrier and speeds of 100 GHz are predicted within the next five years. Extremely fast switching time, operation at very low voltages, and very little power consumed or dissipated could provide a breakthrough for supercomputing for critical national needs.

In 2004, the Federal Plan for High-End Computing recognized the need to develop new technologies to meet emerging security threats and identified superconductor electronics as the fastest digital processors of any electronic technology. Subsequently, an extensive detailed technical and needs analysis by the National Security Agency's Office of Corporate Assessments, the Superconducting Technology Assessment, concluded that superconductive technology is an excellent candidate for computing at petaflops (one million billion operations per second) and beyond. The report points out that while there is considerable development and demonstration to be done, no new research breakthroughs are required. Superconductor electronics can help to close the growing gap between peak performance and sustained system performance in high end computers and a major US Government push to mature this technology is needed.

Superconductivity and Cryogenics: The Enabling Technology

Refrigeration plays an indispensable, enabling role in the emerging industry of high temperature superconductivity. New advances are being made in technologies and business models to enable a broad range of superconducting applications. On-site cryogenic refrigeration systems, designed for economical and reliable long-term operation, are under development that can greatly expand the market opportunity for HTS technology. The industrial gas industry, with its cryogenic expertise and infrastructure, is poised to play a critical role in accelerating HTS technology development and deployment.

The Role of the Industrial Gases Industry in Superconductivity

Large scale air separation unit in Nanjing Chemical Industrial Park (NCIP), Eastern China
Image courtesy of Air Products and Chemicals, Inc.

The emergence of high-temperature superconductivity (HTS) has tremendous potential for consumers and the entire US economy to benefit because of its expected high-impact in applications ranging from electric power to transportation. Many HTS applications operate in the temperature range of liquid nitrogen (77 K or -196 °C). This fact necessitates extremely reliable and cost effective onsite cryogenic refrigeration systems, as well as an overall system approach that takes into account both the equipment requirements and the need for an infrastructure to provide long term support.

For over a hundred years the industrial gas industry has been supplying the cryogenic refrigeration needs for US industry in such diverse areas as chemicals, low temperature superconductivity (LTS), and food products. Refrigeration is a core technology for the industrial gas industry. Some salient facts about this industry include the following:

- Over 85% of all atmospheric gases (oxygen, nitrogen and argon) are produced by cryogenic distillation.
- The majority of the cryogenic refrigeration provided to US industry comes from the industrial gas industry.
- Current and ongoing development activity offers a benefit for all aspects of cryogenic refrigeration equipment, including cryogenic distillation, pulse tube refrigerators, hydrogen and LNG onsite systems.

A core element of the cryogenic refrigeration system for HTS is expected to be mechanical refrigeration units (cryocoolers), which will typically be supported by on-site liquid nitrogen for back-up. The industrial gas industry has a broad range of such on-site systems in industries ranging from electronics to pharmaceuticals. These types of onsite systems are routinely monitored and controlled from remote operations centers.

Cooling as a Utility Science

The industrial gas industry stands ready to meet the needs for HTS commercialization by providing cryogenic cooling equipment and services on a highly reliable "utility" basis suitable for many applications. The industry is already based on several key principles that support such a business model, including the following:

Customer onsite system
Image courtesy of Air Products and Chemicals, Inc.

- Service orientation: The industry has a traditional focus on service and long-term customer relations. Equipment and technology are developed internally or otherwise sourced to meet application requirements.
- Continuous monitoring capabilities: A large fraction of the industrial gas used in the US is produced in plants that are monitored and controlled remotely "24/7" by centralized remote operations centers, not unlike those used by the utility industry.
- Size: With millions of customers, thousands of trucks, and a broad service and support staff, the industrial gas companies are well positioned to support customers of all sizes.
- Specialized expertise: Cryogenic equipment and systems are a core competency, both in terms of cryogenic fluid handling and cold production.
- Expandability: Both the cryogenic refrigeration expertise and operations, maintenance, safety and service infrastructure already exists. Even relatively large-scale markets, which might include long-length power cables, would require only an incremental expansion in the capacity of this industry.

Projects currently underway are demonstrating how the capabilities of the industrial gas industry can be matched to the commercial requirements for cryogenic refrigeration in HTS. For example, three HTS cable demonstration projects have an industrial gas company partner providing both the refrigeration system and ongoing service and support.

Commercially viable cryogenic systems for HTS must meet both reliability and cost requirements. There is no single cooling solution for all HTS technologies. Rather, there is a broad range of potential HTS applications that will require flexibility in how technology is applied. The business model of cryogenic cooling being provided as a "utility" is being demonstrated and will further evolve. Methods of implementation will vary depending on circumstances, for example, in remote locations such as on board ships.

When produced on an industrial scale, liquid nitrogen can be the most energy efficient, simple and reliable means of producing refrigeration for the larger HTS application such as cable. Electrical power is required by all industry, many of whom also require industrial gasses. With regular pump boost and temperature regulation stations along the cable, it is envisaged that the cable could actually act as a delivery pipeline to the other industrial users of liquid nitrogen and make a substantial reduction in truck delivery miles.

Generally, the process of determining the lowest life cycle cost for any system regardless of reliability requirements requires a combined assessment of equipment, system engineering, monitoring and maintenance. There may be numerous sources for particular pieces of cryogenic equipment. The key objective is to engineer the overall system to achieve the lowest life cycle cost that can be achieved within reliability constraints.

Pulse tube refrigeration system schematic
Image courtesy of Praxair, Inc.

Technology Development

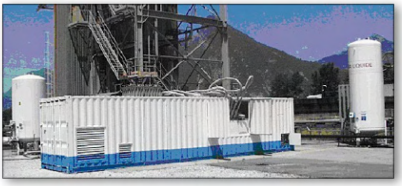
A key element of HTS cryogenic refrigeration systems is the mechanical refrigeration unit or cryocooler. The basic technology for very large and small-scale applications is in many respects well developed, based on considerable industrial experience in cryogenic distillation, as well as the years of experience of many manufacturers of small-scale cryocoolers. However, there is a need for ongoing research and development to meet the large-scale refrigeration needs, cost targets and rigorous reliability requirements for the full range of HTS application opportunities.

One of the most promising technology developments in cryocooler cycles is in the area of pulse tubes. Orifice pulse tube refrigerators operate in a closed cycle, using helium as a working fluid. The cold is generated by the use of acoustic (sound) waves that substitute for the typical pistons or rotating equipment found in other cryocoolers. This technology promises major advantages for HTS applications. These include the absence of cold moving parts, leading to extremely high reliability; and a theoretically high cycle efficiency, which is expected to translate into low operating costs.The development challenge is to fully achieve the high reliability and efficiency, while simultaneously reducing manufacturing costs. The focus of current development efforts is to achieve these goals, as well as to produce increasingly larger units with cooling capacities in excess of 1,500 watts at 77 K. Currently available units are capable of producing up to 1,100 watts at 77 K.

Two 1kW pulse tube cryocoolers installed at HTS cable site
Image courtesy of Praxair, Inc.

Issues and Recommendations

In conclusion, the basic equipment and infrastructure already exists to support HTS cryogenic refrigeration systems. To optimize the HTS opportunity, however, there is a continuing need to improve overall system designs with an eye toward commercial operation. The industrial gas industry is well positioned to provide refrigeration in the form of a cooling service.



Small containerized cooling facility suitable for HTS cable
Image courtesy of Air Liquide

As HTS applications begin to move towards commercial reality, it becomes increasingly necessary to demonstrate cryogenic refrigeration systems that are cost effective and reliable, and that can be serviced and supported by a proven infrastructure.

The following areas require specific focus:

- Continued support for cryocooler development, such as pulse tube and equivalent technologies, with a focus on reliability and overall life cycle cost reduction.
- Demonstration of complete, integrated cryogenic systems that incorporate both the equipment and support infrastructure required for long-term, reliable operation.
- Education and outreach to targeted customer industries about the implications of HTS cryogenic systems and the options for their long-term operation.