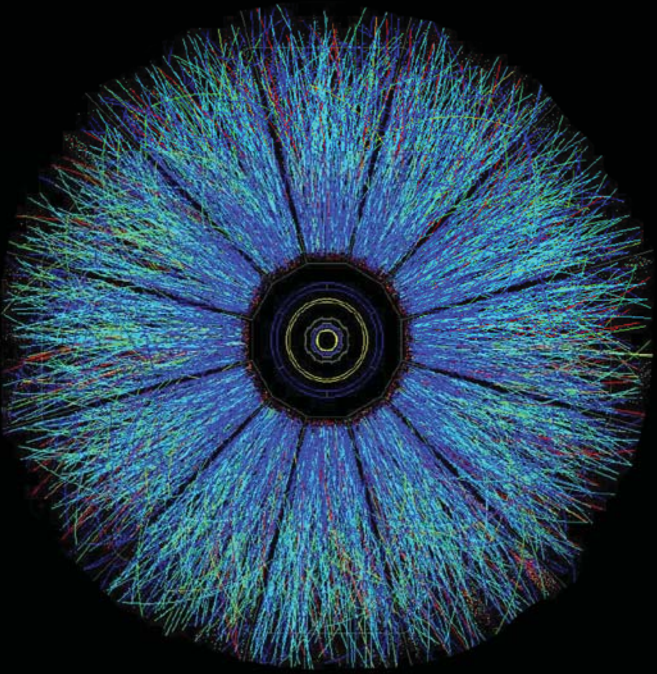
SUPERCONDUCTIVITY



Present and Future Applications

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 societal and economic benefits of superconductors are effectively realized and speedily implement 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 precommercial 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.

www.ccas-web.org

IEEE Council on Superconductivity (IEEE CSC)

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.

The IEEE Council on Superconductivity, CSC, promotes programs and activities that cover the science and technology of superconductors and their applications. Superconducting applications span the range from small scale analog and digital circuits and systems, to large scale applications of MRI, electrical power generation, storage, and transmission. Applications include the development and enhancement of the associated materials.

The IEEE CSC publishes the IEEE Transactions on Applied Superconductivity (TAS), with six issues per year. Any IEEE member can affiliate with the Council upon signing up for, or renewing, the IEEE Membership. Other activities of the IEEE CSC include conference and workshop sponsorships and organization, graduate student fellowships, preparation and distribution of digital archives, student travel support for conferences, development of standards in collaboration with other international organizations, IEEE Awards, Best Paper Awards, Entrepreneurial Awards, a Distinguished Lecturer program, and the highly successful Superconductivity News Forum in collaboration with ESAS, the European Society for Applied 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 and Energy Society, Reliability Society, and the Ultrasonics, Ferroelectrics and Frequency Control Society.

Awards

IEEE CSC has established multiple 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. The current awards include the IEEE Award for Continuing and Significant Contributions in the Field of Applied Superconductivity; the IEEE Max Swerdlow Award for Sustained Service to the Applied Superconductivity Community; the IEEE James Wong Award for Continuing and Significant Contributions to Applied Superconductor Materials Technology; and the IEEE CSC Carl H. Rosner Entrepreneurship Award. In addition IEEE CSC Graduate Study Fellowships are awarded annually to full-time graduate students pursuing a PhD (or equivalent) degree in the area of applied superconductivity, at an accredited college or university of recognized standing worldwide.

Distinguished Lecturers

For information about the current Distinguished Lecturers, to request a lecture, or to nominate someone to be a future Lecturer, please visit the IEEE CSC website at www.ieeecscc.org. You may

SUPERCONDUCTIVITY
Present and Future Applications

Superconductivity: Properties, History 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 23.2 K. 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 35 K. This was quickly followed in early 1987 by the announcement by C. W. Chu of a cuprate superconductor functioning above 77 K, 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 135 K. A superconducting material with a critical temperature above 23.2 K is known as a High Temperature Superconductor (HTS), despite the continuing need for cryogenic refrigeration for any application.

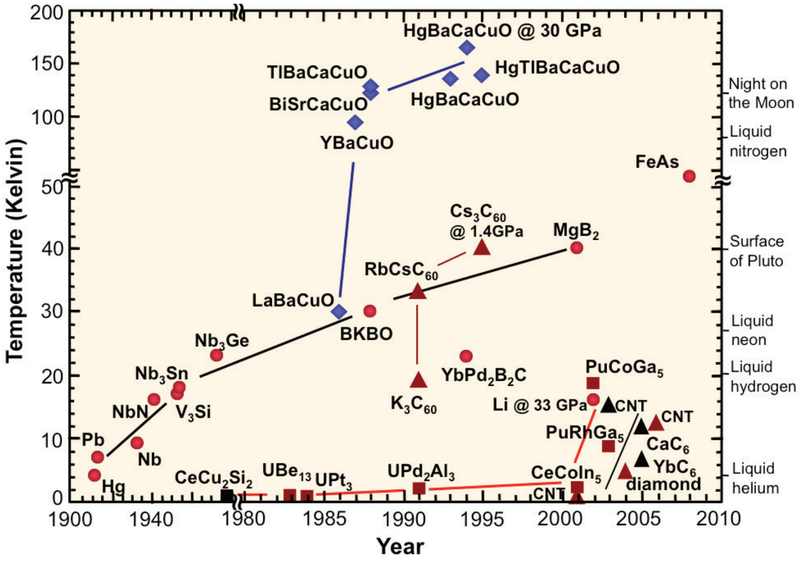


Image courtesy of Department of Energy - Basic Energy Sciences

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. During the 21st century, superconductivity is forming 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 Magnetoencephalography (MEG). The latter is based on Superconducting Quantum Interference Device (SQUID) technology that detects and measures the weak magnetic fields generated by the brain. Current 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, sea and air 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, railway traction transformers and reasearch on lightweight aircraft engines.

Medicine. Advances in HTS promise more compact and less costly Magnetic Resonance Imaging (MRI) systems with superior imaging capabilities. In addition, Magnetoencephalography (MEG), Magnetic Source Imaging (MSI) and Magnetocardiology (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; frequent major weather events; threats of terroristic activities 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, safety, reliability and efficiency of the nation's power system.

The U.S. 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. The frequency and impact of severe weather events such as hurricanes further impacts the grid. It has been estimated that $100 billion could be spent over the next 10 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 has become extremely difficult in the face of landowner and community opposition. This is especially the case in urbanized areas where power needs are concentrated and available land is scarce. 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. 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.

HTS technologies have undergone rapid development in the comparatively short time of two decades since the first HTS compounds were synthesized in research laboratories.. 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 than are available using traditional grid upgrade solutions, and yielding major environmental benefits.

HTS Wire. The foundation of these applications is a new kind 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 both first generation (1G) HTS wire that is multifilamentary in composition and, more recently, second generation (2G) HTS wire, using a coated conductor architecture and a variety of thin film manufacturing processes. 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. HTS wire enables the following power applications.

HTS Power Cables. Today's conventional power lines and cables are being operated closer to their thermal or stability limits, and new lines are becoming hard to site. Compact, high-capacity underground HTS cables offer an important new tool for boosting grid capacity and increasing grid reliability and resiliency. Today's advanced HTS cable designs enable controllable power flows and the complete suppression of stray electromagnetic field HTS power cables transmit 5-10 times more power than conventional copper cables of equivalent cross section, enabling more effective use of limited and costly rights-of-way, and in some cases, also provide fault current limiting.

There has been significant progress toward the commercialization of HTS cable. In the U.S., the world's first HTS power transmission cable system in a commercial power grid is capable of transmitting up to 574 megawatts (MW) of

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

electricity, enough to power 300,000 homes. Close to a dozen U.S. utility companies have either installed demonstration HTS cable projects or undertaken detailed feasibility evaluations. Utility sponsored, in-grid projects are also underway in Germany, Korea, Japan and China.

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, stand-alone "smart" fault current limiters (FCLs) and fault current limiting capability built into HTS cables which, in both cases, 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 states instantaneously, from 'super' conductors to resistors. Several demonstrations of this breakthrough technology have been completed, with others underway, and commercialization is expected to begin in 2015.

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 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 Generators 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 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.

Wind Turbine
Image courtesy of American Superconductor

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 superconductors, have been in use for many years. They have been applied to enhance the capacity and reliability of stability-constrained utility grids, as well as to improve reliability and power quality at large industrial user sites with sensitive, high-speed processes. 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, resiliency, 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 be proven in multiple demonstrations operating for many years. 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 inherently take a cautious and conservative approach to adopting new technology solutions. This is due to 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 1990s, 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 are facing unprecedented new challenges. Pressures on the systems and technologies that move people and goods will continue to intensify due to several factors: rising demand; changes in fuel market economics; emissions and evironmental issues; and the demand for improved system performance. In response, most modes 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 and lighter weight aircraft engines. The incorporation of superconductor technology into transportation system design can improve the efficiency and performance, reduce the size, 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 onpetroleum-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 U.S. 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.

36MW HTS Ship Drive Motor
Image courtesy of American Superconductor

This improved efficiency translates into a longer cruising range and greater fuel economy. Smaller motor assemblies could also enable electric ships to use more shallow ports, and could be incorporated directly into steerable pod-based assemblies, resulting in greater flexibility and improvedmaneuverability. 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 U.S. 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.

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 guide way, or track. Magnetically levitated trains have attained top speeds in excess of 500 kph. 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.

A landmark commercial application of superconducting maglev technology is underway in Japan that could transform mobility in modern societies. Japan has conducted research and development on superconducting maglev since the 1960s and has produced breakthrough designs and prototypes. Since 1997, the Central Japan Railway Company (JRC) has deployed and tested a superconducting maglev (SCMAGLEV) in Yamanashi prefecture.

JRC L-zero series SCMAGLEV
Image © JR Central 2013

Using low temperature superconducting (LTS) magnets made of niobium-titanium alloys, the JRC SCMAGLEV is the fastest train in the world, achieving a speed record of 581 kph (361 mph) in 2003. On-board LTS magnets and ground coils embedded in the walls of a U-shaped guide-way provide levitation, propulsion and guidance. After traveling 850,000 kilometers at Yamanashi, the test site is now being expanded and will be part of a full revenue line. Superconductor magnets are the key enabling technology for this latest major advance in transportation systems. Also, there is now research underway on the application of HTS coils to maglev trains, which could result in lower cooling costs and higher stability.

Superconductivity: Applications in Medical Imaging and Diagnostics

MRI (Magnetic Resonance Imaging) has become the "gold standard" in diagnostic medical imaging, providing images of soft tissue not available from any other modality. 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 at lower cost. These include Ultra-Low-Field MRI, Magnetoencephalography (MEG) and Magneto-cardiography (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 or ultrasound. 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.

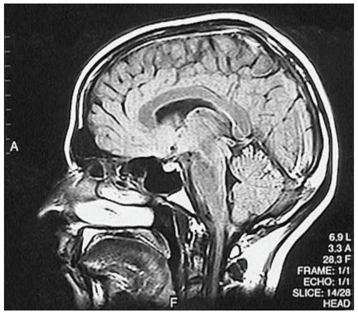

Superconducting MRI system in operation

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, the nuclear spin 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 nucleus, which can be measured as a signal that decays typically within several milliseconds. The timing of this signal decay, 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 approximately $4B/year in new equipment sales. There are now well over 30,000 MRI systems installed worldwide, and the number is growing by 10% annually.

Advantages of Superconductivity. The heart of the MRI system is a magnet. The typical field values required for the latest generation of 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. The use of superconducting magnets provides a unique solution to these requirements. This trend will continue as field strength continues to progress from the current mainstream 1.5 T (Tesla) and 3 T systems to ever higher strengths in order to improve the clarity of the signal generated and increase the speed of image acquisition.

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 or ion beam therapy to plan the approach and more precisely locate, remove or radiate tumors. Another new technique, Magnetic Resonance Spectroscopy, is used on a limited basis for evaluating brain tumors, neurological diseases and epilepsy.



An example of an MRI brain scan
Image courtesy of Scott Camazine, MD

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. Further advances in the design of MRI systems are also enhancing the ability to utilize smaller, more specialized units dedicated to imaging of the body extremities such as arms and legs. The smaller foot-print of these units makes them more space, energy and resource efficient and allows for the higher throughput at a medical facility when combined with a whole body system for more complicated or extensive scans.

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.
- Recent measurements on *ex vivo* prostate tissue demonstrate a significantly higher contrast between healthy and malignant tissue than at high fields. It is essential, however, to carry out studies to confirm that tumor imaging is viable *in vivo*. If ULF-MRI is successful in imaging cancer, it has a number of potential applications: diagnosing the severity of prostate cancer prior to biopsy, imaging of prostate cancer to guide biopsy, monitoring cancer progression during active surveillance or radiation therapy and imaging of other types of cancer, for example, brain and breast tumors.
- 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 viewed by some as "greener" than high-field MRI in that it consumes vastly less electrical power, though helium usage is not as efficient.

Magnetoencephalography (MEG) and Magnetic Source Imaging (MSI)

Clinical MEG System
Image courtesy of 4-D Neuroimaging

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. Major successes include:

- Pre-surgical mapping of brain tumors. By applying external stimuli (visual, audio, tactile), one can map out the function of the brain (which can be highly distorted by the presence of the tumor) prior to

surgical removal of the tumor. With the aid of an MRI, this enables one to construct a 3D model of the brain and tumor.
- Showing the least invasive way of performing the surgery. This technique has been successful in reducing the incidence of collateral damage to the brain resulting from the surgical removal of the tumor.
- Location and pre-surgical mapping of the source of focal epilepsy. The focus is located using MSI. Pre-surgical mapping is conducted as for tumor surgery.
- Monitoring recovery from stroke or brain trauma (e.g. severe blow to the head as in football players, motorcycle accidents). MSI is used to monitor the response of the brain to standardized external stimuli (visual, audio, tactile) over a period of time to quantify the rate of recovery.

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 database 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.

Non-invasive MCG System
Image courtesy of CardioMag Imaging (CMI)

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:

- 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; and
- 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 magnetic resonance 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. This is critical in the quest to realize the full potential of these advances in systems and applications. Secondly, further support for superconductor development is needed to help provide the required performance, costs and availability to support the increasing array of applications that are looking to operate either with low or no helium present in the system. Helium availability and cost could represent one of the key challenges to further growth of these applications as currently they all rely on this commodity for cooling. While it is clear that future designs will look to reduce or eliminate helium entirely, currently the cost, performance and design constraints make this a very challenging choice.

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

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 and further refinements earned the 1952 Nobel Prize in Physics as well as the 1991 and 2002 Nobel prizes in Chemistry. 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 40 years. Using modern methods of NMR spectroscopy, an incredible range of science and technology is addressed on a daily basis.

A 1000 MHz NMR spectrometer
Image courtesy of Bruker

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 us to 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 over the past 25 years in superconducting materials, first with niobium-titanium, then with niobium-tin conductors and now with a variety of materials suitable for ultra-high field applications, 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 widely available superconducting materials will limit future NMR machines to the 1000 MHz (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.

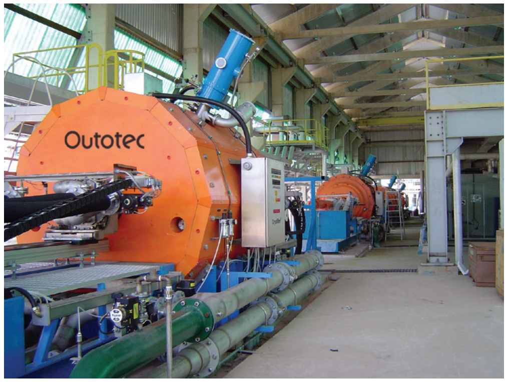
Kaolin Clay Processing

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.

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 1.8 T (1.8 Tesla) with a practical upper limit of about 2.0 T. Conversely, a superconductor based unit is typically designed to operate at 5 T. 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.

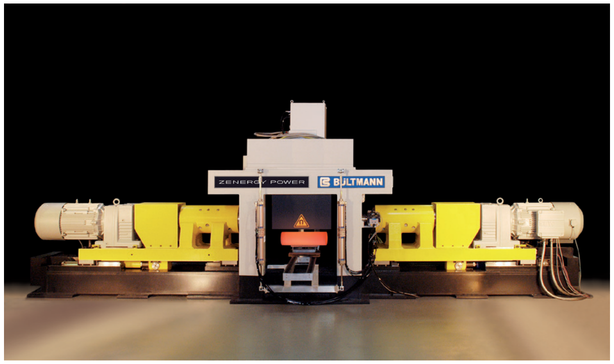


Industrial LTS Magnetic Separator
Image courtesy of Outotec (USA) Inc.

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 wastewater 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 K 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

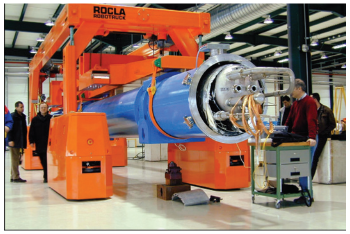
Superconductivity: Applications in High-Energy Physics and Other Areas of Research

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 50 years 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 physics theory in history, yet it leaves 95% of the mass in 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, which generate particles that only existed a few moments after the Big Bang that created the universe almost 14 billion years ago.


One of the first LHC Magnets ready for testing
Image courtesy of CERN, Geneva

The Large Hadron Collider, or LHC, is located near Geneva, Switzerland and began operation in September 2008. It is the largest and most powerful particle accelerator in the world, with a circumference of 27 kilometers. Protons with energies of up to 7 trillion electron volt are brought to collision inside giant detectors used to reconstruct the complex collisions needed to find new particles. This gargantuan “time machine and microscope” will generate conditions that existed approximately a billionth of a second after the Big Bang, and if nature is kind, will uncover phenomena never seen before.

Superconductivity Required

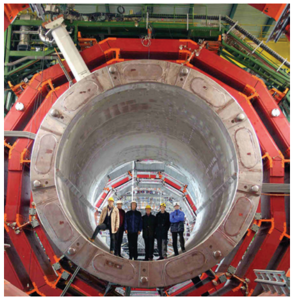
The storage rings in accelerators for the colliding protons are made of superconducting magnets, strung together like beads on a necklace. In the LHC, two concentric rings are made up of thousands of superconducting magnets. The colliding energy required could not be economically achieved without superconducting magnets. The largest are the main dipole magnets that steer the particles around the ring. These magnets contain over 1,200 tons of superconducting cable. Superconductivity also enables construction of giant magnets for the detectors at the LHC used to measure the properties of the particles produced in the collisions.


Accelerator Magnets fully operational in the LHC Tunnel
Image courtesy of CERN, Geneva

Fusion Energy

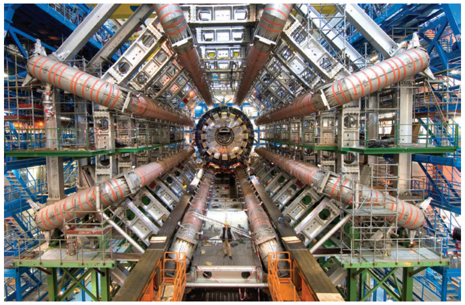
Bringing a Star to Earth

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 producing 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.


ATLAS Detector Magnet in an LHC Experiment - the largest operational superconducting magnet in the world
Image Courtesy of ATLAS Collaboration, CERN, Geneva

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 nature of superconductors make them ideal in such applications. These applications include magnetic actuators, magnetic refrigeration, magnetically assisted propulsion, superconducting magnets for radiation shielding and spaced based magnetic plasma confinement.


The ITER reactor will use 800 tons of superconductors in more than 40 individual magnets sections.
Image courtesy of ITER Organization, Cadarache, France

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

Superconductor devices, both analog and digital, offer unique advantages for RF (wireless) applications due to ultra-low dissipation and distortion as well as intrinsic (quantum) accuracy. The U.S. Army called their new receiver chip the "most significant change to satellite communications worldwide in 30 years." Superconductor RF filters with superior interference cancellation have been employed in cellular base stations, enabling wider range and fewer dropped calls. Fourth generation All-Digital Receivers (ADRs) for U.S. defense deliver dramatic improvements in performance, cost and efficiency for SIGINT, EW and SATCOM systems. ADRs are deployed in several government programs, addressing the most difficult national RF challenges.

HTS Filters

Cellular base stations receive relatively weak mobile signals with very sensitive antennas and receivers on many channels simultaneously. To perform this task and deal with the tremendous RF interference in the environment some systems employ superconductor RF filters that cancel much of this interference. These filters increase the range of handset due to the superior performance of these ultra-sharp filters. This technology has been commercially deployed in more than 10,000 base stations with over 400 million hours of run time. The cryogenically cooled filters have been exposed to the worse elements and proven very reliable, with Mean-Time-Between-Failure (MTBF) greater than 1 million hours. In an industry where reliability and uptime are the number one goal, these HTS filters have proven that superconductors improve our everyday life.

All-Digital Receivers

While HTS filters have demonstrated unique capabilities in analog (non-digital) RF applications, the true revolution is one that takes advantage of the intrinsic linearity and quantum accuracy of digital superconductor devices (chips) to produce the world's highest performing analog-to-digital converters.

Much like digital CDs and digital television provide superior performance, All-Digital Receivers deliver superior performance to all wireless applications. The crux of the improvement is in the unique ability of superconducting analog-to-digital converters to digitize a wide swath of spectrum without the need for analog pre-processing. As a result, significant portions of the conventional RF system are completely eliminated, reducing size and power while significantly improving receiver sensitivity performance. In addition, the manipulation of the digital data enables unparalled flexibility in the signal processing that detects, characterizes and decodes incoming RF signals. These all-digital superconductor receivers have been successfully integrated into legacy wireless systems with the latest cryogenic cooling and systems engineering innovations. From radio astronomy to the latest electronic warfare systems, digital superconductor RF has significantly pushed the state-of-the-art.

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

An early demonstration of the capability if superconducting All-Digital Receivers was carried out by the U.S. Army, where an X-Band satellite downlink was accomplished with a single ADR system that replaced many racks of legacy receiver components. The ability to directly digitize wideband X-Band SATCOM signals (an important military band) proved so impressive it led to the proclamation that the "most significant change to satellite communications worldwide in 30 years" had been achieved.

Today's All-Digital Receivers are packaged in ½ of a 19-inch electronics rack, completely free of liquid cryogen and capable of being equipped to digitize multiple GHz of instantaneous bandwidth virtually anywhere from DC to "W" Band. The modular design can be customized for a variety of applications and is upgradable and programmable with relative ease.

To complement the All-Digital Receiver and address certain applications, a Cryogenic Analog RF Module (CARM) has been recently developed to provide RF amplification with extremely low noise. Initially designed for Ka-Band, the module features a compact cryogenic cooler and can be modified for a wide range of RF bands.

The heart of the All-Digital Receiver system is the superconducting integrated circuit (IC). This chip circuit is made similarly to semiconductors, but the key material is Low Temperature Superconductor (LTS) niobium vs. silicon. The chip - less than half the size of a penny - employs Josephson junctions that make up Rapid Single Flux Quantum(RSFQ) logic circuits that move picosecond-duration magnetic pulses vs. electrons. These LTS ICs need to be cooled to approximately 4 degrees Kelvin compared to 70 degrees Kelvin for analog HTS materials. New innovations in small, off-the-shelf, cryogen-free cryocoolers provide compact cooling platforms for packaging and deploying All-Digital Receivers.

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

Issues and Recommendations

All-Digital Receivers (and accompanying Transmitters and Transceivers) have been largely developed by and for defense and other government programs with the most difficult RF challenges. Continued government program support is needed to fully exploit the performance capabilities of this technology. Most commercial RF applications are highly commoditized with very large volumes and digital superconductors are still not cost competitive for many applications that otherwise would benefit from significantly improved performance.

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 radio astronomy 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
Image Courtesy of Jack Freer, Overland Photography

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 as 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 U.S. 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 of 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.
"USS McCampbell and USS Curtis Wilbur transit Pacific Ocean," by official U.S. Navy Imagery, is licensed under CC BY 4.0

Issues and Recommendations

Besides continued support for the R&D required to advance these devices and their 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 along with increased support for manufacturing would be of great benefit to industrial superconducting applications as we move from research and development to commercial deployments.

Superconductivity: Applications in Large-Scale Computing

Low temperature superconductor technology makes possible computers with operating speed, energy efficiency and physical compactness far beyond the limits of conventional semiconductor technologies. While highly challenging, the path forward is clear. Success will enable large-scale computing to continue growing at a price we can afford.

Superconductivity has long held promise for computing due to some of its unique capabilities. Semiconductor technologies won out in the past, but seem to be hitting the wall, especially when it comes to energy usage and speed.

Transistors, the switching elements in present-day computers, are made of semiconducting materials. The problem is that a small but still significant amount of energy is dissipated when a transistor switches. Additional energy is required to transmit signals through the tiny wires that connect transistors and other circuit elements. The faster the transistors switch, the greater the power loss. Processor chips recently hit cooling limits, causing computer engineers to stop increasing the operating frequency as had been planned. The number of processors working in parallel has been increased in attempt to make up the shortfall, but this approach makes programs harder to develop and often results in poor processor utilization.

Energy cost is now a significant and growing portion of life-cycle cost for large computing systems such as server farms, data centers and supercomputers. Drivers for the increase include increased internet traffic, movement to cloud computing supported by large computers, and the increasing demands for capability computing in the scientific, technical and financial areas. How big is the problem? As an example, Facebook's data center in Prineville, Oregon used in 2013 the electrical energy required by about 20,000 U.S. homes. Building such large data centers and supercomputers is already challenging and yet the demand for data and computing continues to grow.

Superconducting computing offers a solution, but requires development.

The Josephson Junction is a type of switch unique to superconductors. A weak link between two superconductors allows a small current to pass with no voltage drop or energy dissipation. Increasing the current above the critical current causes the junction to switch and output a single flux quantum (SFQ). The switching speed is on the order of a picosecond, much faster than semiconductor transistors. The switching energy is also thousands of times smaller. Clock speeds of hundreds of gigahertz have been demonstrated in superconducting logic circuits. New types of SFQ logic circuits have greatly decreased the energy required per computation.

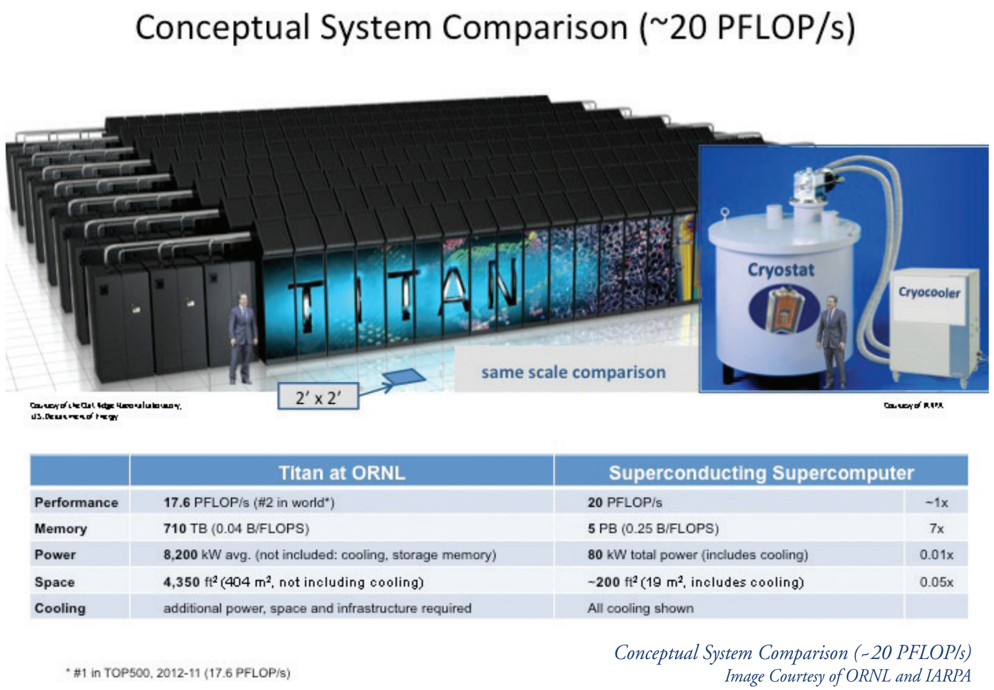
Interconnects between superconducting circuit elements can be provided by superconducting passive transmission lines, which dissipate almost no energy. These connections are also quite fast—pulses made up of single or multiple flux quanta propagate along the transmission lines at about one third the speed of light in a vacuum.

Memory is also required in computers. A small loop of superconductor can contain only an integer number of flux quanta. No flux quanta within the loop is commonly taken as a '0' in digital logic. Making small loops with sufficient inductance has been a challenge that might be overcome by adapting technologies already developed for producing semiconductor circuits with smaller sizes. Other memory or inductive elements uniquely enabled by superconductivity are also in development and may provide greater physical density.

New logic, interconnects, and memory with capabilities very different from conventional technologies will allow new computer architectures and capabilities. Development of superconducting computers is already underway. An example is the IARPA Cryogenic Computing Complexity (C3) program which seeks to develop the required technologies and then integrate those new technologies into a superconducting computer. The picture shows how a concept superconducting computer would compare to a conventional supercomputer.

Quantum computing is another potential application of superconductivity, although further in the future. Unlike conventional digital data bits which exist in only two states—either '1' or '0'—quantum bits can hold a mix of states and can be used to solve some problems much faster than conventional digital computers.

Developing superconducting computing technology will require people with both new ideas and the ability to make them work.



Conceptual System Comparison (~20 PFLOP/s)

	Titan at ORNL	Superconducting Supercomputer	
Performance	**17.6** PFLOP/s (#2 in world*)	**20** PFLOP/s	~1x
Memory	**710** TB (0.04 B/FLOPS)	**5** PB (0.25 B/FLOPS)	7x
Power	**8,200** kW avg. (not included: cooling, storage memory)	**80** kW total power (includes cooling)	0.01x
Space	**4,350** ft² (404 m², not including cooling)	~**200** ft² (19 m², includes cooling)	0.05x
Cooling	additional power, space and infrastructure required	All cooling shown	

* #1 in TOP500, 2012-11 (17.6 PFLOP/s)

Conceptual System Comparison (~20 PFLOP/s)
Image Courtesy of ORNL and IARPA

Superconductivity: Applications in Renewable Energy

Global concern about the environmental effect of greenhouse gas emissions from the continued use of fossil fuels for power generation has led to an increased interest in clean, green and non-polluting sources of renewable energy, such as solar, hydropower, geothermal, biomass and wind. Integration of renewables into the grid does, however, pose a number of challenges such as intermittency of the resources, connection to grid interconnects from remote generation locations, and comparative cost vs. fossil fuel generation. High temperature superconductivity (HTS) solutions offer a number of advantages that are expected to address some of these concerns.

Concern about Protecting Our Environment

Renewables don't answer all our energy needs, but they do safeguard our environment while generating a significant amount of useful energy. Renewables today account for some 25% of our energy usage worldwide and are expected to continue to gain more of a foothold, as concern about the environment and interest in renewable energy increases.

In fact, in order to address the steadily increasing demand for more clean and non-polluting power, a number of countries in Europe, Asia and South America plus Australia and 30 of the United States and the District of Columbia have established Renewable Portfolio Standards (RPS), regulations that require the increased production of energy from renewable energy sources such as solar, wind, hydropower, geothermal and biomass. New York, for example, has set a goal of generating 30% of its electricity from renewable energy sources by 2015.

Germany, setting perhaps the world's most aggressive goal, is aiming for 100% renewables by 2050. The goal is the steady elimination of greenhouse gases that come from fossil fuel generation of electricity. It is felt that market implementation of renewables will result in competition, efficiency and innovation that will deliver renewable energy at the lowest possible cost, allowing it to compete with cheaper fossil fuel energy sources.

Although wind and solar are attractive sources of renewable energy because they do not produce greenhouse gases, they also pose difficulties because of their inherent variability. Wind is not a steady resource available everywhere, and the sun rises and sets and is frequently shaded by clouds.

Wind Energy. Wind is a clean source of renewable energy that produces no air or water pollution. Today it represents the most mature and fastest growing source of renewable energy production. Currently wind accounts for ca. 1-2% of the total electricity produced worldwide, and this contribution continues to increase steadily. Germany has the most installed wind energy capacity, followed by Spain, the United States, India and Denmark, with fast growing development in France and China. According to the U.S. Department of Energy, offshore wind farms could provide enough energy to power our entire nation. To date we have barely touched the amazing capabilities of wind power and can expect to see it become a massive source of renewable energy in the U.S. and around the globe.

Wind energy is costly to set up, so it requires significant amounts of capital to establish wind farms. After the initial investment and start-up costs, however, wind is one of the cheapest forms of electricity generation to maintain. The extraordinary electrical efficiency and power density characteristics of HTS offer clear benefits for wind energy generation. HTS generators can be more powerful and much smaller than conventional devices. This is expected to contribute to the increase in offshore wind energy generation, particularly units of up to 10 MW.

Use of superconducting wire in the windings allows for very slow speed generators, and high currents without losses, and precludes the need for a gearbox, one of the turbine's heaviest components, thereby enabling smaller turbines – one third the size and a quarter of the weight to generate as much power as larger units. Eliminating the gearbox also reduces the number of bearings and other major failure-prone components, thereby reducing wind turbine maintenance needs and operating costs. Incorporating zero-resistance, HTS wire will boost efficiency and lead to smaller, lighter turbines which are also easier to transport, install and maintain.


AMSC SeaTitan Wind Turbine Generator
Image courtesy of American Superconductor

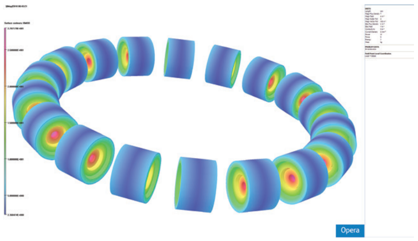
Energy Storage. Today's electricity grid has insufficient storage capability. Power must be generated when it is needed, making renewable energy an often unreliable source due to the unpredictability of sources for wind and solar power.

Superconducting Magnetic Energy Storage (SMES) is a solution for storage of electrical energy in a powerful magnetic field. SMES systems have been in development for about three decades. Past devices that used low temperature superconductors however, were designed to supply power only for short durations, generally less than a few minutes. The recent development of HTS wire that enables enhanced performance at high magnetic fields is expected to reduce the cost of storing energy in a SMES device and thereby extend the duration during which power is available.

In order to help manage electricity supply load variability, SMES technology for longer term (hours) storage with quick charge and discharge capability is being explored.

Storing electricity generated during periods of low demand, such as when the wind blows at night, allows that energy to be released for use during periods of high demand, such as when production plants are in full operation during the daytime. The energy stored in the magnetic field of the SMES coil is charged or discharged by increasing or decreasing the current in the coil. Scaling up the size of the coil, or adding additional coils to an array of coils, increases the storage capacity. SMES systems can be cycled indefinitely and provide instantaneous power, making them an attractive solution for load leveling in power plants.

With a life expectancy of 20+ years, SMES systems are expected to have a substantially longer life than batteries (1-10 years) and flywheels (8-12 years). Further, unlike pumped hydro and compressed air, other forms of renewable energy storage, SMES can be deployed almost anywhere.



25T, 2.5MJ Coil SMES Configuration ABB-SuperPower-Brookhaven-U. Houston
Image courtesy of SuperPower Inc.

Integration with the Grid. Renewable energy sources such as wind farms and large solar arrays are most often located inland or offshore, remote from population centers where the power is used, thus requiring transmission of this green power to the distant users. Long distance transmission of power by conventional ac or dc transmission lines can be difficult to install because of right of way requirements and community objections over aesthetics or perceived safety. Placing conventional conductors underground has limited applicability due to resistive or reactive power losses in the cables.

Superconductor cables have 5-10 times the current carrying capacity of conventional copper cables of the same size. They have no dc losses and only small ac losses and power can, therefore, be transmitted at lower voltage and higher currents, offering the possibility of creating a fully green grid that connects the remote renewable generation sources with the consumers via these “green power superhighways.” A dc HTS transmission cable will have losses (including refrigeration) that are less than half that of conventional ac overhead transmission lines. Also, with distributed generation, and many more locations of generation with solar and wind farms, superconductors solve congestion problems with high reliability through the use of superconductor based Fault Current Limiters and current limiting cables.

A number of demonstrations of HTS cable technology have been completed and are ongoing in the U.S., including the AEP HTS cable in Bixby, Ohio; the National Grid HTS cable in Albany, NY; the LIPA HTS Cable in Holbrook, NY; and project “Hydra” in NYC. Other demonstrations have been completed or are underway in other areas of the world as well, including Japan, South Korea, China and Germany. Though successfully demonstrating the technology in each case, these cables have not yet been generally adopted to due the huge initial capital costs and the lack of a broad track record of performance. If HTS superconductor cables can live up to their promise of cutting grid transmission losses at acceptable expense, this will help the viability of wind and solar farms that must transmit their power over long distances to established distribution networks.

Type test of Project Hydra Fault Current Limiting 15 kV HTS TriaxTM Cable by Southwire, AMSC, ORNL, Con Edison, DHS
Image courtesy of Southwire

Issues and Recommendations

In order for the renewable energy industry to take full advantage of the earth’s resources, it is essential that superconductivity solutions such as wind turbine generators, SMES, current limiters and long distance transmission lines be fully developed, demonstrated and deployed into the grid. This will require further development of HTS wire capabilities, cryogenic systems, and power electronics. Much of this work is underway, but would be significantly accelerated with a period of additional government support for these activities and demonstration of the devices.

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 U.S. 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 U.S. 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 U.S. 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:

- 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 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 larger HTS applications such as cable. Electrical power is required by all industries, 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.

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 for large cryocoolers 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.

Free piston Stirling cycle cryocoolers have been available in commercial volumes for HTS electrical devices since 2000. The Stirling cryocooler employs gas bearings, a single piston and displacer, a combination of gas and mechanical springs, efficient heat exchangers and a passive balancer used to minimize casing vibration. The compact, high performance and extremely reliable cryocooler is field-proven with Mean Time Between Failure (MTBF) of well over one million hours, with over 6,000 units deployed, logging over 400 million cumulative run-time hours. The utilization of this proven technology will be critical in scaling cryocooler size to meet the needs of new HTS applications.

Sterling Cryocooler
Image courtesy of Superconductor Technologies 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.

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, free Stirling cycle 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.

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