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REVIEW ARTICLE

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RECENT DEVELOPMENTS OF HIGH TEMPERATURE SUPERCONDUCTIVITY

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ABSTRACT

This paper deals with the multidimensional representation of chronological development of superconductivity. The decade following the discovery of high-temperature superconductors (HTSs) in 1986, extensive international research led to the fabrication of HTS materials with a range of critical transition temperatures (T_c's) above the boiling point of liquid nitrogen, as well as to broad phenomenological understanding of their properties. These materials have been pursued for a variety of technologies, but the strongest driver has been the electric power utility sector. Electric power transmission through HTS power cables offers the chance to reclaim some of the power lost in the grid, while also increasing capacity by several times. Use of HTS conductors could also improve high-current devices, especially in terms of efficiency, capacity, and reliability. By the mid-1990s, despite many formidable technical problems, researchers had begun to realize viable first-generation (1G) HTS conductor technologies based on $Bi_2Sr_2Ca_2Cu_3O_{14}$ (BSCCO), which make available conductors that are suitable for engineering demonstration projects and for first-level applications in real power systems. Second-generation (2G) HTS conductors based on $YBa_2Cu_3O_7$ (YBCO) are currently poised to replace BSCCO,

INTRODUCTION

This is followed by brief literature review concerning the research work.

1. 1911- Superconductivity was discovered by Heike KamerlinghOnnes in mercury at the boiling point of liquid helium [1].
2. 1931- Superconductivity in alloys was discovered by W.J. de Haas and W.H. Keesom [2].
3. 1933- The expulsion of a magnetic flux from the interior of a metal cooled below its superconducting transition temperature - Meissner effect was demonstrated by Walther Meissner and his colleague Robert Ochenfeld [3].
4. 1934- CorneliusGorter and H.B.G. Casmir proposed the two fluid models [4].
5. 1935- Famous London theory was developed by London brothers: Fritz London and Heinz London [5].
6. 1950- VitalyGinzburg and Lev Landau developed a theory of superconductivity based on electrodynamics [6]. The role of phonon in superconductivity was

discovered by Herbert Frohlich [7]. Maxwell and Renold [8] independently discovered the isotope effect of superconductivity.

7. 1953- The concept of coherence length (a characteristic distance within which superconductivity cannot change appreciably) was proposed by Brian Pippard [9].
8. 1956- The unstable Fermi Sea in the presence of an attractive interaction between electrons responsible for the formation of Cooper pairs was shown by L.N. Cooper [10].
9. 1957- Bardeen, Cooper and Schrieffer proposed the microscopic theory (BCS) of superconductivity [11].

- 1960- Tunneling of Quasiparticles across a metal and superconductor junctions was discovered [12].
- 1961- Deaver and Fairbank [13] showed that the flux can exist in a superconducting ring only in discrete units.
- 1962- The tunneling of Cooper pairs across the junction consisting of two superconductors separated by thin insulating layer by B.D. Josephson predicted [14].
- 1963- The AC and DC Josephson effect was observed by John Rowel [15] and showed that Cooper pairs can carry current across a tunnel junction with no voltage (DC effect) and applying a dc voltage to a tunnel junction, radio frequency waves (AC effect) can be produced.
- 1964- Quantum interference leading to the development of superconductivity quantum interference devices (SQUID) was discovered by Jaklevic et al. [16].
- 1973- Synthesis of Niobium-Germanium A15 compound was done by John Gavaler which showed Tcof 23.2 K [17].
- 1986- High Temperature superconductor (HTSC) in Ba-La-Cu-O system having Tc of 35 K was discovered by J. George Bednorz and K. Alex Mueller [18].
- 1987- Maw-Kuen Wu and C.W. Paul Chu discovered Y-Ba-Cu-O high Tc superconductors having Tc of 90 K [19].
- 1988- Nonrare-earth based cuprate superconductors i.e. Bi2223 (Tc = 110 K) by Meada et al. [20] and Tl2223 (Tc = 125 K) was discovered by Sheng et al. [21].
- Discovery of noncuprate high Tcsuperconductors Ba1-xKxBiO3 (Tc = 28 K) was done by Cava et al. [22].
- 1991- Hebard et al. [23] discovered superconductivity in alkaline metal doped C60 compound.
- 1993- Schilling et al. [18] observed the Tc enhancement to 133 K in Hg-based ceramic Superconductors and it further increased to 164 K under pressure [24].

10. 1997- University at buffalo scientists found strongest evidence for the strange and extremely promising phenomenon, called re-entrant superconductivity that magnetic field may enhance, not kill superconductivity [25].
11. 2000- Superconductor amplifier is devised by GiampieroPepe of the University of Naples in Italy and colleagues led by Antonio Barone, together with Norman Booth of Oxford University in the UK [26].
12. 2001- The possibility of superconductivity iron in its non-magnetic state has been predicted by Katsuya et.al. [27].
13. 2001- Zero Resistance without Cooper-pairing has been discovered by Rafael de Picciotto of Bell Labs in US [28].
14. 2002- Phonon Influenced HTSC is confirmed by studies at Berkeley Lab's Advanced Light Source (ALS) [29].
15. 2003- Nobel Prize in Physics Awarded for pioneering contributions to the theory of superconductors and superfluids jointly to three physicists Alexei A. Abrikosov**(**Argonne National Laboratory, Argonne, Illinois, USA) Vitaly L. Ginzburg**(**P.N. Lebedev Physical Institute, Moscow, Russia) and J. Anthony [30].
16. 2004- Physicists got new clues for theory of superconductivity discovered by Stephen Hayden from Bristol University in the UK and colleagues at ISIS, Oak Ridge, Tennessee and Missouri-Rolla studied $YBa_2Cu_3O_{7-\delta}$ (YBCO) and found the collective magnetic excitation “glue” responsible for holding the Cooper pairs together in the material [31].

17. 2005- Physicist Julian Brown of the University of Oxford started to claim that protons, and not just electrons, can travel unobstructed through metal [32].
18. 2006- Physicists in the US and Japan found that phonons play a key role in high-temperature superconductivity [33-34].
19. 2007-Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, in collaboration with colleagues at Cornell University, Tokyo University, the University of California, Berkeley, and the University of Colorado, have discovered why the transition temperature cannot simply be elevated by increasing the electrons' binding energy [35].
20. 2008-Scientists reveal effects of quantum 'traffic jam' in high-temperature superconductors which point to new materials to get the current flowing at higher temperatures. [36].
21. 2009- Pinning down superconductivity to a single layer was possible by the U.S. Department of Energy's (DOE) Brookhaven National Laboratory which led to precision engineering of superconducting thin films for electronic devices [37].
22. 2010- Japanese scientists claimed that they have experimentally determined the mechanism underlying electron pair formation in iron-based, high-temperature superconductors [38].

Literature review pertaining to doping effect

HTSCs are granular in nature and defect ridden. The defects belonging to atomic size point defects category include the substitution defects, oxygen vacancies, interstitial oxygen and antisite disorder. In most of atomic size point defects structures, the natural dimensions of the CuO_2 conduction planes and the metal oxygen planes making up the charge reservoir layer are not matched. The CuO_2 planes control the unit cell dimensions in the ab-plane. The defects generally develop at the chain and plane sites of Cu or may be at Y or Ba site of YBCO. The defects can be created due to doping at iso or aliovalent site or can be by composite formation.

YBCOis currently the best suited HTSCs for most bulk applications. Neutron diffraction and XRD studies [39] revealed that the unit cell is orthorhombic with cell parameters a = 3.82 A, b = 3.88 A and c = 11.683 A. Oxygen deficient Y-plane leads to copper ions in five fold coordinated square pyramidal sites which results in 2-dimensional puckered sheets of copper oxygen bonds that extend in a-b plane. Oxygen stoichiometry is found to play important role in determining the superconducting properties of YBCO superconductor [40, 41]. It is established that diffusion of oxygen mainly takes place in the CuO basal plane and migration occurs with ordering of oxygen atom [42]. The diffusion process is highly anisotropic in the YBCO structure. It is about 10 times more rapid in the ab-plane than along the c-direction. In the ab-plane itself, the diffusion along the b-axis is more favorable if oxygen diffuse from end of a chain and the adjacent chain is empty of oxygen and the diffusivity in the b-direction is 100 times more than a-direction. At the maximum oxygen concentration for which compound is stable ($\delta = 0$), only half of the available sites in the charge reservoir layer is occupied by oxygen atoms. It is widely agreed that the quasi two dimensional motion of charge carriers in the CuO_2 planes play a significant role. The issue of the role of the basal plane (Cu-O chains) contributing to superconductivity is, however, special and exclusive to the YBCO class of compounds. The importance of integrity of chains in these systems is clearly borne out by the systematic reduction of T_c accompanied with orthorhombic to tetragonal transition with removal of oxygen from the Cu-O chains [39, 40].

The relevance of investigating changes in the properties of high $T_c$superconductors through doping with substitutional elements is evident from the fact that all the high T_c superconductors are resulted from substitution at one or more cationic sites in the parent materials. Since these studies provide a very good probe to understand the mechanism behind superconductivity, they become important from the fundamental point of view as well. In YBCO substitutions have been attempted at sites of all the constituent elements to look for higher Tc's as well as to understand the mechanism of superconductivity. The Y site has been replaced completely or partially with other rare earths and it is found that these substitutions do not affect T_c with the exception of one or two elements like Pr, Tb, Ce, etc. [43]. However, substitution at the Ba site with other alkaline earth elements has been found to decrease T_c [44]. Partial substitution for oxygen by fluorine is also reported [45] which claims a rise in T_c even near to room temperature. Substitution at the Cu site is the most important among all the cations of YBCO, since Cu-O networks have been suspected to play a major role for the occurrence of superconductivity in these materials. For this reason, the Cu site has been doped with almost all the elements. Among them, the 3d transition elements are considered ideal for doping at the Cu site as they have similar electronic configuration and ionic sizes as Cu.

Substitution by metal ions at Cu site in YBCO type superconductors leads to generally unfavorable effect in superconductivity but to different degrees for different dopant metal ions. Incorporation of Zn in CuO_2 planes to form the composition $YBa_2Cu_{3-x}Zn_xO_7$ for example has a dramatic effect on superconducting transition temperature. The dTc/dx in this case is about -13 K/at% [46, 47]. Several models have been proposed in the literature to account for the large suppression of T_c with Zn substitution. Park et al. [48] for example considered the modifications in the magnetic interaction between the copper local moments when magnetic and non-magnetic ions such as Ni and Zn occupy the Cu sites. Zn^{2+} is a non-magnetic and stable 2+ ion. The presence of such ions disturbs the antiferromagnetically coupled spin fluctuations in the CuO_2 planes. As a result, Cu ions at the vicinity of the Zn ions acquire local moments. Existence of local moments in Zn doped YBCO system has been shown by NQR [49], EPR [50] and magnetic susceptibility measurements [51].

The conventional charge transfer model speculates the transfer of holes from the charge reservoir layer (CuO chains) to charge conduction layer (CuO_2 plane) through the apical oxygen [52]. Therefore, the CuO bonding along the c-axis is important for the effective charge transfer and high T_c. It is experimentally established that T_c increases if Cu(2)-O(1) bond length decreases. But Zn doping in YBCO causes atomic displacement and shortening of Cu(1)-O(1) bond length and elongation of Cu(2)-O(1) bond length by 8 to 12%. This, along with the filled dshell of the Zn^{2+} ion lead to interruption in the charge transfer and T_c suppression. The hole from the Cu(1) site is interrupted to go to Cu(2) site through the apical oxygen located just below the doped Zn i.e. a hole supplied channel to Cu(2) site is lost by doping a Zn atom. As a consequence, the Tc is reduced.

In YBCO, the nature of the charge reservoir layer and the mechanism of charge transfer has been studied through preferential chemical substitutions by trivalent ions like Ga^{3+}, Fe^{3+}, Al^{3+}, Co^{3+} and monovalent ions like Ag^{1+}, Au^{1+} in the CuO chain. Such substitutional studies have clearly indicated a drastic change in the structure without much change in the superconductivity, thus giving an impression that structural features in the ab-plane may not have much relevance to superconductivity. However, later studies [53] pointed out that though on a macroscopic scale a transition from orthorhombic to tetragonal structure occurs, oxygen ordering in the local scale still exists. As the impurity atoms occupy the lattice sites in the CuO basal plane they change the oxygen coordination around neighbouringCu(1)s.

Several factors contribute to the observed T_c suppression on doping with trivalent metal ions in the CuO based plane of YBCO. The first and the foremost is the decrease in the hole content due to increased valency of the dopants. Incorporation of Ga^{3+} in the chains for example reduce the formal valence of Cu from 3+ to 2 + and thus reduce the carrier (holes) density in the plane [54]. Another factor that contributes to $T_c$reduction on substitution is the localization of the charge carriers. Cai et al. [55] have shown that Cu (1) when substituted by trivalent ions like Al and Ga, holes on the oxygen site fond to be localized near impurity ion. The impurity ions also modify the CuO bond length along the c-axis and hence affect the charge transfer process from the charge reservoir to the CuO_2 planes. It has been established that Cu (2) site substitution in CuO_2 planes lead to formation of magnetic moments which become pair breakers [56]. Doping Zn to the Cu-site of YBCO creates in-plane disorder without affecting the hole-density. Zn substitution changes the charge on O^{2-} site and modulates its position without affecting the oxygen ordering so orthorhombic structure is not disturbed [57]. The presence of spinless divalent ion like Zn in the planes destroys long range order of spin system and leads to strong changes of the superconducting parameters [58]. On the other hand Ga occupies Cu (1) sites along CuO chains and has different magnetic moments. The Cu atoms in the Cu-O chains have a four- fold co-ordination [59]. So there exists a coordination mismatch between the parent and the dopant. Cu(1) site substitution affects the superconductivity mainly through a decrease in P type carriers in CuO_2 planes which affects the transition region [60]. When Ga and Zn ions are substituted simultaneously for Cu, they apparently have a site preference maintaining an orthorhombic structure. The simultaneous substitutions of Cu by Ga and Zn having +3 and +2 charge state respectively have been analyzed [57]. This we attribute to the fact that Zn substitutes at Cu (2) sites on CuO_2 planes in the lattice, whereas Ga^{3+} impurities have a five-fold co-ordination. The reduction of T_c and orthorhombic distortion when Ga and Zn ions are present together, suggest interplay between the local magnetic moments which appear as a consequence of the doping of lattice at both the sites. The purpose of the present investigation is to show the behavior of chain and plane sites on the structural/ microstructural and electrical properties of YBCO. It has been observed [61] that with increase in Zn concentration T_c and T_{c0} values decrease while T_c is not affected by Ga^{3+} as much as it is affected by doping Zn^{2+}.

Superconducting and normal state properties of YBCO system is controlled by charge carriers. Its carrier density can be enhanced either by increase of oxygen content or by on-site cationic substitutions with dopants of lower valence state. Ca doping at Y site has created much interest in the scientific community as this doping turns an oxygen-deficient YBCO system from insulator to superconductor [62, 63]. In addition to affecting T_c, Ca doping decreases normal state resistivity, increases critical current J_c, affects the interlayer coupling strength, J [64] and hence influences the superconducting order parameter fluctuation (SCOPF) region above T_c. Not just the electrical properties even the structure changes from orthorhombic to tetragonal [65] and grain size reduces [66] on Ca doping. On the other hand, Zn substitution suppresses superconductivity most effectively and, like a magnetic field, has little effect on the pseudogap transition temperature (T*) irrespective of hole concentration [67]. In the present work emphasis has been taken to study the dimensionality of conductivity through analysis of the excess conductivity undergoing a systematic study of the transport properties of the superconducting compound $Y_{1-x}Ca_xBa_2(Cu_{1-y}Zn_y)_3O_{7-\delta}$. The motivation of the study is to examine the suitability and the range of applicability of the Aslamazov and Larkin (AL) relations to various fluctuating regions with different levels of Zn, Ca. Specifically a shrink in the fluctuating region of superconductivity has been witnessed with the increase of Zn content to the Ca substituted YBCO system

Literature review pertaining to composites

In the process of sample preparation during sintering cuprate superconductors have been showing considerable deviations from resistivity measurement in single crystals and polycrystals that represent the intrinsic resistivity of the grains [68, 69], depending on the orientational mismatch of adjacent grains, voids and cracks. Control of granularity in these systems therefore has involved controlling several aspects as grain alignment, grain growth, sample defects and secondary phase formation [70]. One of the approaches to overcome the difficulties arising due to granularity in cuprates has been to make composites of YBCO with such metals as Au, Ag, Al and compounds like $BaZrO_3$ and $BaTiO_3$ which can fill the inter-granular spaces and improve both electrical and mechanical properties [71-74]. $BaZrO_3$ addition to YBCO during the final stage of sintering in particular has been shown to form composites with sizable enhancement in J_c, along with a slight increase in the superconducting transition temperature T_c [75]. In the composite system, most of the $BaZrO_3$ occupies the boundaries of YBCO grains [76] and with the application of magnetic field a secondary peak, in the $d\rho/dT$ curve has been observed for the onset of transition in the intergranular region due to the extra deposition of BZO on the grain boundaries [77]. SEM and XRD analysis of Kang et al. [78] showed that BZO is located at the grain boundaries. It also occurs in clumps filling voids between grains in films and bulk systems [69, 79].

$BaTiO_3$ Being a ferroelectric material, with a perovskite structure similar to that of YBCO possess similar lattice structure (2-3 % lattice match in a-b planes) and crystal chemistryhave shown to generate a stress field and act as pinning centers [80, 81]. Thus with an ideal system for experimental study [82, 83] we have tried to analyze fluctuation conductivity in polycrystalline samples of YBCO + $xBaTiO_3$ with micrometric and nano $BaTiO_3$ inclusions having both inter- and intra-grain modifications. The strong influence of $BaTiO_3$ content in the composites in the mean field region has been explained through nano $BaTiO_3$ induced modifications and an intragranular fluctuation change is observed [84]. Again long-range superconducting order is witnessed for $BaTiO_3$ inclusions of some micrometric size due to thermally assisted percolation process through the weak-links between the grains [85].

Literature review pertaining to fluctuations

It seems that the first experimental observation of effects of superconducting order parameter fluctuations on the conductivity was made in 1967 by Glover [86], who studied of amorphous Bi films. In the history of superconductivity this is of course rather late, but theoretical estimates had indicated that effects of fluctuations should only be detectable in a more or less negligible temperature interval above T_c. When the sample size was reduced, however, as in the thin films of Bi, the fluctuation effects became more pronounced, and could be observed. Soon after Glover's observations there were reports of theoretical calculations of the fluctuation conductivity, using both the microscopic method by Aslamazov and Larkin in 1968 [87, 88] and the Ginzburg-Landau approach [89, 90]. The agreement with experiments was good. Fortunately, this could be explained by including a fluctuation contribution [91, 92] that was neglected in the original microscopic calculations. After Thompson [93] had removed a divergency appearing in the extension to samples of reduced dimensionality (2D), the contribution became known as the Maki-Thompson term. The original term is referred to as the Aslamazov-Larkin term. Superconducting fluctuations can be treated using the GL theory or the microscopic techniques. The GL theory is the more simple and intuitive one, while the microscopic techniques required for calculations of all terms in the more general case. The GL approach will be briefly described below.

The general treatment of fluctuation phenomena (in ferroelectrics, superconductors, etc.) by Ginzburg [94] states, e.g., that anomaly in the specific heat should only be observable at distances of the order of 10^{-3} K from the transition. The smearing of the transition due to deviations from the ideal crystal structure would thus most likely prevent observation. Later work in the 1970s includes measurements in three-dimensional amorphous alloys [95]. In the usual GL approach, only the AL term close to T_c is obtained. The treatment of fluctuations in the Ginzburg-Landau framework is rather straightforward. The basic idea is that thermodynamic fluctuations can cause the free energy F to fluctuate an amount of roughly $k_\beta T$ above its minimum value. Since the free energy depends directly on the density of superconducting electron pairs, one may calculate the corresponding variation in this quantity.

As already mentioned, the superconducting electron pairs contribute to the conductivity through the Aslamazov-Larkin (AL) and Maki-Thompson (MT) terms. In addition, there is the more recently calculated density-of-states (DOS) term [96-99]. The total fluctuation conductivity can thus be written as:

$$\sigma^{fl} = \sigma^{AL} + \sigma^{DOS} + \sigma^{MT} \quad (2.1)$$

The AL term is the most intuitive one, simply reflecting the fact that the superconducting electron pairs contribute to the conduction. Hence, this term gives a positive contribution to the conductivity (i.e. a decrease of the resistance). The AL term was the first term to be derived and was treated for layered structures already in 1970 by Lawrence and Doniach [100]. The MT term [92, 101] is much more difficult to understand in a simple way. It is usually described as an influence of superconducting fluctuation on the normal quasiparticles. The MT conductivity term is generally positive, like the AL term. As the MT term has a pure quantum nature, it does not appear in the usual thermodynamic Ginzburg Landau (GL) approach. The importance of the DOS term seems to have been realized only recently [97]. The DOS term is often negligible but may be dominant in HTSC under certain conditions. It originates from the fact that the density of states of the normal-state quasiparticles is affected by the formation of superconducting pairs. This term has opposite sign compared to the AL and MT term, and thus rather surprisingly increases the resistivity. In order to understand this fact, it may help to consider the following very much simplified reasoning: When some electrons form Cooper pairs, the effective number of carriers participating in the normal (one-electron) conduction decreases, and the conductivity goes down. As pointed out by Varlamov et al. [102], the DOS fluctuation conductivity may be estimated from the simple Drude model. If we let Δ_{ne} denote the change in the density of normal-state carriers and n_{pair} the density of superconducting pairs

BASIC RESEARCH CHALLENGES FOR APPLICATIONS

In the decade following the discovery of high-temperature superconductors (HTSs) in 1986, extensive international research led to the fabrication of HTS materials with a range of critical transition temperatures (T_c's) above the boiling point of liquid nitrogen, as well as to broad phenomenological understanding of their properties. These materials have been pursued for a variety of technologies, but the strongest driver has been the electric power utility sector. Electric power transmission through HTS power cables offers the chance to reclaim some of the power lost in the grid, while also increasing capacity by several times. Use of HTS conductors could also improve high-current devices, especially in terms of efficiency, capacity, and reliability. By the mid-1990s, despite many formidable technical problems, researchers had begun to realize viable first-generation (1G) HTS conductor technologies based on $Bi_2Sr_2Ca_2Cu_3O_{14}$ (BSCCO), which make available conductors that are suitable for engineering demonstration projects and for first-level applications in real power systems. Second-generation (2G) HTS conductors based on $YBa_2Cu_3O_7$ (YBCO) are currently poised to replace BSCCO, which will dramatically improve performance while also lowering costs.

Today we have a much broader view of the potential benefits that superconductivity could provide to our nation and society. Deregulation of utilities initiated through the 1992 Energy Policy Act created the electricity marketplace, which is now in a position to strongly influence the nation's economy, given sufficient capacity in the electric power grid. An analogy may be drawn to the state of communications and digital information prior to the implementation of high-capacity fiber-optic networks; as we now know, the *global* economy has been transformed by the availability of an almost unlimited capacity to transfer information. As a society, we must not ignore the possibilities for economic growth if the ability to transfer enormous amounts of electric power was attained. Moreover, electricity demand in the United States continues to grow at a rate of about 2.3% per year, tracking closely with the overall growth of the economy (gross domestic product [GDP]). The fraction of total energy consumed in the form of electricity also has steadily increased, to about 40% at present, and is poised to go as high as 70% by 2050. Thus, it is predicted that electricity will become *the* major commodity form of energy. Clearly, technologies that provide enormous capacity and the ability to control it will be of central importance to our nation's economy and security. Superconductivity is one such technology.

We also now see more clearly what materials improvements are needed to encompass the full range of power applications and create a comprehensive revolution in how electric power is generated, distributed, and used in the United States. This vision, in turn, defines a critical set of use-inspired basic research challenges that need to be addressed in order to ensure and even accelerate this revolution. In this section, the motivation for and status of this thrust are outlined, including a brief description of the advances that have contributed to the present HTS power conductors.

Superconductivity in the Future Electric Grid

Constraints on the availability of inexpensive electric power were a central issue taken up by the 2005 Energy Policy Act. Electricity transmission capacity is being added through National Interest Electric Transmission Corridor (NIETC) provisions for rights of way. New advanced transmission line technologies will be deployed in present and future overhead transmission corridors to increase their power capacity effectively threefold. An integral part of the Energy Policy Act is the U.S. Department of Energy's (DOE's) monitoring of geographic areas that experience electrical transmission capacity constraints or congestion that adversely affects consumers. New corridors will be assigned according to the criteria of supply, economic need, limitations on new electricity sources, improved diversification of supply, and support of energy independence.

A second key part of the Energy Policy Act is its support for new technologies that can increase capacity, efficiency, flexibility, and reliability. The biggest challenge facing the power grid is the deeply rooted historical trend to urbanization in the United States and the world. Neither the dominance of this trend nor its impact on the power grid can be overestimated. The percentage of the U.S. population in urban areas will grow to nearly 90% of all U.S. residents by 2030, up from 60% in 1950. This dramatic demographic shift augurs future challenges that the present power grid is not equipped to handle. Cities and suburbs are becoming increasingly stringent in the environmental, safety, and aesthetic limits they place on power access corridors, to the point that obtaining permits for new overhead power lines and underground cables takes years at a minimum and may ultimately be impossible. The growing complexity of urban power networks increases the magnitude and danger of fault currents, straining the limit of present technology. Plug-in hybrids that use electricity from the grid for transportation may intensify demand in urban areas, where the major use of cars is for commuting.

Superconducting technology promises to relieve this urban power bottleneck. Replacing conventional overhead lines and underground cables with superconductors could provide up to five times more capacity for congested areas, avoiding the costs and permitting delays associated with building new power corridors. Superconducting lines and cables carry the same power at dramatically lower voltages than their conventional counterparts, reducing or eliminating one of the biggest barriers to municipal permitting. Underground superconducting cables produce no heat, and their coaxial design generates no stray magnetic fields, so they do not disturb surrounding underground infrastructure. Superconducting fault current limiters not only handle higher fault currents than do conventional limiters, they also trigger and reset automatically and much more quickly. The footprint of superconducting transformers, generators, and reactive power regulators is half the size of the footprint of conventional technology, and superconducting transformers use no contaminating or flammable oils that restrict their use in urban settings. Beyond these structural and performance benefits, superconducting technology cuts energy losses in the grid by a factor of two or more; this will have the most impact in urban areas, where power demand and density are highest.

The superconducting solution to urban power bottlenecks is not just compelling, but critical. Incremental improvements in conventional grid technology cannot increase its capacity by a factor of five without new construction; cannot cut energy losses in half; cannot provide smart, fast response to large fault currents; and cannot reduce urban permitting restrictions on transformers. Without these advances, continuing urbanization and demand for electricity as our preferred energy carrier will overwhelm the power grid in urban areas.

The key aspects of superconducting cable and grid technology are summarized below.

Superconducting Transmission Cables. An HTS power cable (Figure 1) is a flat-conductor-based transmission line that carries large amounts of electrical current. Liquid nitrogen flows through the cable, cooling the HTS conductor to a zero-resistance state. The cable's most useful property is its compaction of large electrical currents into a small conductor area, which in technical terms is referred to as high electrical current density. Within the superconducting layer of the new 2G superconductors, current densities are typically more than 10,000 times higher than those possible in copper. When support for liquid nitrogen and other materials is included, both 1G and 2G HTS power cable technologies could provide about a fivefold increase in power capacity over that of a copper cable.

HTS transmission cables confer many potential benefits, including these:

1. Retrofit power conduits in urban settings and at critical interconnections, where the cost of replacing infrastructure is prohibitive;
2. Eliminate the need for new rights of way;
3. Enable power flow at low voltages, significantly reducing permitting requirements;

4. Replace overhead transmission lines with underground conduits to address environmental, security, and other concerns;
5. Eliminate thermal and electromagnetic field (EMF) disturbance to surrounding underground infrastructure;
6. Enhance overall system efficiency as a result of exceptionally low losses;
7. Increase reliability by eliminating faults from vegetation, lightning, etc.;
8. Enable direct control of power flow in combination with phase angle regulators;
9. Increase utility system operating capacity and flexibility; and
10. Reduce electricity costs via intracontinental power marketing.

Another benefit of superconductivity lies in its ability to possibly transport energy on a scale of many gigawatts to terawatts from remote generation facilities (e.g., wellhead and mine-head generation at gas and coal fields and nuclear power-plant clusters) over distances of several hundred kilometers. Only the high current-carrying ability of superconductors can enable this. Within the present grid, excess power available in California cannot be piped to meet higher demand in New England. High current-capacity transmission based on superconductivity could enable actual diurnal trading of electric power on an intracontinental scale.

Demonstration HTS Cable Projects.Despite their relative infancy, HTS cables are beginning to demonstrate benefits to the utility industry by relieving constraints on infrastructure. It is estimated that 80,000 mi of Cu-based power cables lie in underground conduits throughout the world to transmit large amounts of power to congested urban areas. Because the existing conduit size limits the amount of power that can be transmitted through them, increasing the power supply to urban areas carries with it a tremendous cost for adding conduit infrastructure.

One aboveground facility — a 30-m-long, three-phase, 12.5-kV system that uses a 1G conductor — has been operating since February 2000, providing 100% of the load for operating the Southwire Company plant in Carrollton, Georgia. Building on this success, three new projects, transporting underground power for "real-world" demonstrations, are under way and scheduled for completion no later than 2007. The new projects are located at Holbrook substation, Long Island Power Authority, Long Island, New York (610 m long); Bixby substation, American Electric Power Company, Columbus, Ohio (200 m long); and to link the Riverside and Menands substations, Niagara Mohawk Power Company, Albany, New York (350 m long).

Superconducting Transformers. Transformers convert generation-level voltage to high transmission level voltages, reducing the amount of energy lost in the transmission of power over long distances. Transformers are also needed to convert the voltage back to a distribution level. Small, quiet, lightweight, and efficient HTS transformers will be used primarily at substations within the utility grid. Environmentally friendly and oil-free, they will be particularly useful where transformers previously could not be sited, such as in high-density urban areas or inside buildings. Significant energy losses occur in conventional transformers as a result of the iron in the core (no-load losses) and the copper in the windings (load losses).

HTS Fault Current Limiters (FCLs). A current limiter is designed to react to and absorb unanticipated power disturbances in the utility grid, preventing loss of power to customers or damage to utility grid equipment. FCLs would be installed in transmission and distribution systems for electric utilities and large energy users in high-density areas. The benefits include increased safety, increased reliability, improved power quality, compatibility with existing protection devices, greater system flexibility from adjustable maximum allowed current, and reduced capital investment because of deferred upgrades. The superconducting FCL provides the same continuous protection, with no standby energy losses due to joule heating and no voltage drop. The superconducting FCL instantaneously limits the flow of excessive current by allowing itself to exceed its superconducting transition temperature and switch to a purely resistive state, thus minimizing the fault current that passes through it.

The potential for damage from fault currents and the necessity to protect against them is a major challenge for urban areas. As more generators are added to the network to accommodate greater demand, the maximum fault current that can flow in the network if there is an accidental short circuit increases. The size of these potential fault currents eventually reaches the limit of conventional breaker technology, approximately 60,000 A, a limit that some urban areas are already approaching. Reaching the maximum fault current limit creates a major challenge that will inevitably occur in many regions, since it is driven only by adding generating capacity to the grid in high-power-density areas. Superconductivity, as it does with regard to the challenge of capacity, provides a simple and effective solution.

Superconducting Rotating Machinery

Superconducting Motors. Superconducting motors employ HTS windings in place of conventional copper coils. Because HTS wire can carry significantly larger currents, these windings are capable of generating correspondingly stronger magnetic fields in a given volume of space. A superconducting motor with one-third the size and weight can match the power output of an equally rated conventional motor. Because of savings in materials and labor, HTS motors will cost less to manufacture than their conventional counterparts. Their smaller size will also enable them to be manufactured and shipped directly to the customer, without costly disassembly and subsequent on-site reassembly and testing.

Large electric motors consume approximately 30% of the electricity generated in the United States. Although these motors are more than 90% efficient, even a 1% improvement integrated over national consumption would result in energy savings approaching a billion dollars. The zero-resistance coils in superconducting motors cut electrical losses in half. Furthermore, HTS alternating-current (ac) synchronous motors have no iron teeth in their armatures (stator windings), resulting not only in a smaller size and lighter weight but also in reduced motor noise. HTS motors will compete in the market for large (1,000 hp and above) commercial motors for use in pumps, fans, compressors, blowers, and belt drives deployed by utility and industrial customers, particularly those requiring continuous operation. Another use for HTS motors is in naval and commercial ship propulsion, where HTS motors can reduce size and weight, increase design flexibility, and open up limited space for use.

***HTS Generators*.** The primary application of superconducting generators will be utility generation facilities using either new or retrofitted generators. By using superconducting wire for the field windings, designers can practically eliminate losses in the rotor windings and armature bars. Furthermore, the fields created in the armature by the rotor are not limited by the saturation characteristics of iron. As is the case for superconducting motors, the armatures are constructed without iron teeth, thereby removing another source of energy loss. An HTS generator will be one-third the overall volume of its conventional equivalent. In power plants where expansion is difficult (e.g., shipboard or locomotive power), superconducting generators can increase generating capacity without using additional space. Smaller, lighter HTS generators use an “air core” design, eliminating much of the structural and magnetic steel of a conventional equivalent; construction, shipping, and installation are all simplified and less costly. HTS generators have lower armature reactance, which can profoundly affect utility stability considerations. One implication is a reduction in the amount of spinning reserve (unused but rotating generating capacity) needed to ensure a stable overall power system. Also, an HTS generator has the capability of being significantly overexcited to permit power factor correction without adding synchronous reactors or capacitors to the power system.

***Reactive Power Generators*.** These devices operate somewhat like a motor or generator without a real power source and either provide or absorb reactive power needed to keep the voltage and current in phase. An industrially funded 8-MVAR machine produced by American Superconductor Corporation has been tested for a year on the Tennessee Valley Authority (TVA) grid, and TVA has ordered the first two 12MVAR commercial units, which are under construction. Thus, the reactive power generator is the first commercial power equipment based on HTS wire. In the future, these devices could be essential in assuring power stability. The U.S.-Canada Task Force examining the North American blackout of 2003 identified the lack of reactive power as the principal contributing factor to the cascading power outage. As the grid becomes more complex in order to accommodate more demand with more generators, the need for smart reactive power control increases. Substantial deployment of intermittent renewable energy technologies (e.g., solar, wind, and wave power) could introduce additional instabilities into the grid.

Superconducting reactive power generators can provide active regulation of reactive power in a small, economical package.

CURRENT STATUS

Cuprate Conductors

HTS conductors typically take the form of a thin tape that can be bent around relatively small diameters into high-density coil windings. The first viable HTS conductor viable for power applications was the bismuth-based superconductor, BSCCO. BSCCO wire is a multifilamentary composite superconductor that includes individual superconducting filaments (running the length of the conductor) encased in a high-purity silver or silver-alloy matrix material (~60% of the wire volume is silver or silver alloy). These wires are formed by loading a powder of BSCCO into the silver or silver-alloy tube, which is then sealed and drawn into a fine wire. These segments are cut and re-stacked for a series of additional drawing, rolling, and heat-treatment steps, leading to the final multifilament oxide-powder-in-tube (OPIT) tapes. Although these cuprate HTS materials are extremely complex, and their properties present several serious obstacles to the development of wires, many of the problems they posed have been ingeniously solved. Kilometer lengths of 1G BSCCO superconductors have been routinely produced by companies in the United States, Germany, Japan, and China.

The fine BSCCO filaments tolerate an acceptable amount of bending, like the fine glass filaments in flexible fiber-optic cables. Most important, the processing aligns the crystalline BSCCO grains within a filament, so that the crystalline *c*-axis of the BSCCO grains is roughly perpendicular to the tape plane (to within 10–15°). Within a filament, electric currents can flow from one highly anisotropic grain to another predominantly within the CuO_2 sheets, while transfer between grains takes advantage of the large geometric grain overlap that distributes the weak *c*-axis current over large areas. This so-called "brick wall" structure of 1G wire filaments is central to its success; many basic studies have shown that supercurrent transport across a grain boundary can be greatly suppressed for misalignments greater than a few degrees (the "weak link" effect). This handicap is intrinsic to HTS. Nevertheless, although they have a higher T_c, 1G conductors do not perform as well as the more recently developed 2G YBCO conductors in the ranges of magnetic field and temperature of interest for applications.

Unlike the powder-metallurgy process used to make BSCCO, YBCO conductors are formed as a multilayer coating on a flat substrate, and the associated techniques are referred to as "coated conductor technology" (Figure 1). An initially flat metal foil, typically a nickel alloy, is used as a "substrate," upon which a buffer layer and then a superconducting YBCO layer are deposited. Cube-on-cube, or (technically) epitaxial growth, is required. The initial texture for the epitaxial growth is either formed within the metallic substrate itself by the rolling-assisted, biaxially textured substrate (RABiTS) method; or, alternatively, in one of the initial buffer layers by using an ion-beam-assisted deposition (IBAD) or inclined-substrate deposition (ISD) technique. (The thin buffer layers prevent metal atoms from diffusing from the substrate into the epitaxial templates and the YBCO layers.) After this, a layer of silver is applied on top of the superconductor to protect it against environmental degradation and to establish continuous electrical contact to the HTS coating. An outer copper layer is typically added over the Ag layer to enable current transfer, stabilization, and strand protection against burnout.

2G YBCO has several significant advantages over the 1G wire in current use. One of the primary advantages of YBCO is the possibility of in-field operation at liquid nitrogen temperature (77 K), which would result in substantially relaxed cooling requirements. (Refrigeration mass and costs increase dramatically at lower temperatures.) By comparison, operating temperatures would be <10 K for lowtemperature superconductors (LTSs) and 30 K for 1G HTS conductors. Another advantage of YBCO is its ability to maintain a high current-carrying capacity (denoted by a critical current density Jc>106 A/cm2) in fields up to several tesla; in contrast, current densities in 1G HTS wires begin to decrease dramatically at fields well under 1 T. These advantages are inherent properties of the YBCO superconducting material. Fundamental studies have shown that among all the HTS cuprate material classes, YBCO shows the lowest intrinsic electronic anisotropy, as characterized by the effective supercarrier mass ratio, γ= mc/mam ≈10. For comparison, 1G BSCCO has a γ of >200. Since large anisotropy drastically weakens the ability of material disorder to pin flux lines against the forces of applied electrical current, 1G conductors suffer an inherent loss of current-carrying capacity in magnetic fields. Also, the strain tolerance (a critical factor for windings) of the YBCO conductor was demonstrated to be superior to that of the BSCCO conductor. Finally, estimates from two leading U.S. manufacturers indicate that the cost of the conductor per unit of current over a unit length of conductor would be much lower for 2G conductors than for 1G conductors, although the exact comparison depends significantly on the machine's design operating point. The necessity of Ag (which is the only metal that can allow oxygen to flow through to the cuprate inside during its formation) to the 1G conductor process is a strong negative cost factor.

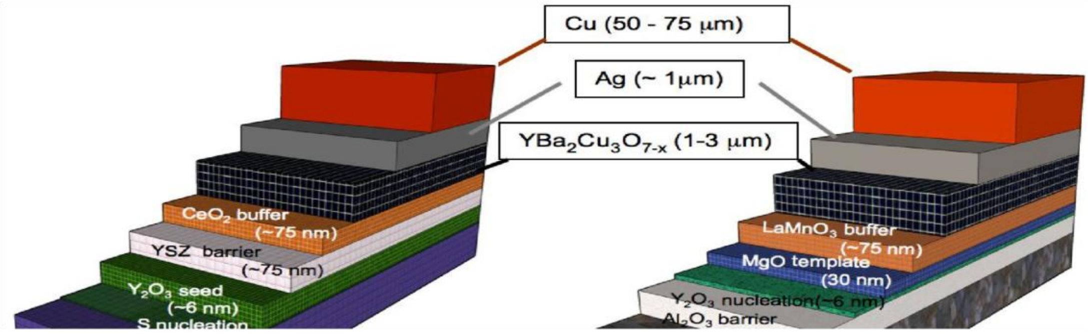

Figure 1 Schematics of the epitaxial multilayer heterostructures that make up 2G "coated conductors." RABiTS and IBAD are the two approaches being pursued by U.S. industry to yield the near-singlecrystal YBCO coating needed for high current performance. (ML = monolayer.)

Advances in the YBCO-coated conductors have resulted in dramatic improvements in the quality and length of wire available — from 10^5 A/cm^2 at several centimeter lengths a few years ago to >10^6 A/cm^2 performance at lengths exceeding 300 m. These successes have been achieved by improved deposition methods for the HTS layer, more robust and appropriate buffer layer architectures, and fundamental control of the biaxial alignment of the initial buffer layer or underlying metallic substrate. YBCO has intrinsically better in-field current conduction, and because the 2G technology has nearly eliminated the problem of weak intergrain coupling, the present focus has turned to improving the flux pinning in the HTS coating. The significance of the latter may be understood by considering that the 1- to 3-µm-thick HTS layer makes up a very small fraction (possibly only 1–2%) of the entire coated-conductor architecture, compared to ~40% fill factor for the BSCCO in the silver matrix of the 1G tapes. There remains a crucial need to fully optimize the YBCO coating to achieve the maximum performance with the minimum amount of material. Recent progress on short research samples has been impressive, including advances in tailoring the flux-pinning nanostructure and approaches to ameliorate the longstanding problem of a progressive reduction in the critical current density with HTS coating thickness. An important next step is to extend the short sample findings to obtain comparable properties by using practical reel-to-reel HTS deposition processes.

Coated Conductor Templates

IBAD. In 1995, by improving a technique first used by Fujikura of Japan, Los Alamos National Laboratory (LANL) announced record performance of highly biaxially textured YBCO deposited by pulsed laser deposition (PLD). This was enabled by an IBAD layer of yttrium-stabilized zirconia (YSZ),
~1 µm thick, on a polycrystalline Hastelloy tape. By extending the process to MgO, Stanford University and LANL have decreased the time for grain

alignment by a factor of 100. In this case, texture is achieved with only about 10 nm of vapor-deposited MgO on an electropolished and amorphous-oxide-seeded metal surface. Subsequent buffer layer(s) are then deposited epitaxially to provide a structural template for YBCO and to act as barriers against in- and out-diffusion of chemical contaminants. Excellent substrate grain alignment distributions (full width at half maximum, FWHM) of ~4° in-plane and ~2° out-of-plane are achieved.

RABiTS. In this approach, the nickel-alloy tape (usually Ni-W) itself is rendered highly biaxially textured by well-defined thermomechanical processes of rolling deformation, followed by annealing. The resulting texture in the face-centered cubic (fcc) metal corresponds to cube planes parallel to the tape surface and perpendicular to the tape's long axis. The resulting RABiTS template shows x-ray orientation distributions of 5–7° FWHM in- and out-of-plane, while the grain-to-grain distribution, relevant to intergrain currents, is somewhat tighter at ~4°. As shown in Figure 2, at present, a three-layer buffer stack is grown epitaxially on the textured metal tape by physical vapor deposition (PVD) processes for chemical and structural compatibility. A key to the functionality of RABiTS is the epitaxial growth of the first, or seed, buffer layer on the reactive metal surface. Careful surface studies helped identify and led to the control of an ordered half-layer of sulfur on the metal surface that apparently mediates the epitaxial nucleation of the commonly used CeO_2 or Y_2O_3 seed layer.

The YBCO Coating

For either type of template, the single-crystal-like YBCO layer can be deposited by using vapor deposition (e.g., electron-beam or thermal evaporation, pulsed laser deposition, metal-organic chemical vapor deposition [MOCVD]) or wet chemical processes (metal-organic decomposition). Worldwide, these methods are being pursued commercially, while in the United States, SuperPower, Inc., is developing MOCVD, and American Superconductor Corporation is developing the solution-based technique. These two general approaches can be distinguished as in-situ and ex-situ, respectively. In the case of MOCVD YBCO, temperature and ambient gas environments are closely controlled as the substrate tape passes reelto-reel through the reaction chamber and the HTS layer is epitaxially crystallized. For the solution approach, a precursor chemical mixture is "painted" onto the moving substrate at room temperature. Then, in a second step, the YBCO is grown while the precursor-coated tape is passed through the controlled environment of a furnace. As discussed above, the Ag and Cu layers provide stability against burnout; the details of these addenda depend on the intended application parameters (temperature, field), but they limit the overall engineering current density (J_e) that is central to the design of magnetic power equipment.

Magnesium Diboride

In January 2001, a simple binary intermetallic compound, magnesium diboride (MgB_2), was discovered to have an extraordinarily high superconducting transition temperature, 40 K. While this is significantly lower than the critical temperatures of YBCO and BSCCO, it is considerably higher than that of any other simple intermetallic superconductor, and the highest known T_c value for materials for which the mechanism of superconductivity is well understood (i.e., conventional superconductors). Indeed, the interesting physics that accompanies MgB_2's superconductivity — specifically, its two-band electronic behavior — has generated much exciting science. Most significantly, strong impurity scattering has been shown to lead to extremely high upper critical fields H_{c2} (the boundary of superconductivity in a magnetic field). This combination of relatively high $T_c$and substantial critical magnetic fields means MgB_2 meets the performance requirements for some electric power applications, albeit only at moderate operating temperatures. Indeed, round multifilamentary MgB_2 wires have been demonstrated by using conventional wire processing approaches. So far, the attractiveness of operating at liquid nitrogen temperature with the 2G coated conductor technology has limited interest in using MgB_2 for major technological development. Nonetheless, the story of MgB_2 is an important lesson that revolutionary conventional superconductors that are free of the problems associated with cuprate materials may be possible. Hence, the search for new higher-temperature conventional superconductors is a prime area of basic research with the potential to dramatically influence the power applications of superconductivity.

Technologies Related to Superconductor Use

Integration of superconductivity into the power grid requires research in materials and techniques beyond those for the superconductor itself. For instance, all systems require the use of cryogenically cooled dielectrics, magnetics, insulators, and semiconductors to be used in power control circuits. Furthermore, the cryo-refrigerators employed to cool the system are at present far below theoretical efficiency, and, as such, the total operational costs will be higher than they need to be. Research in these nonsuperconducting materials and refrigeration performance will be vital to the full implementation of a superconducting system. It will be necessary to establish a basic understanding of superconducting-system-related cryogenic materials and phenomena to enable the broad application of superconductors. For the HTS materials in their present conductor forms, the principal advantage over conventional devices can be summarized as *smaller, lighter, and higher capacity*. The energy savings at present are less than thermodynamics permits, mainly because of problems with refrigeration and cryogenic efficiency, which points to one of the needed advances in complementary technologies.

Refrigeration. The liquid helium temperatures required by LTS wire were a major drawback because of the early technology level of refrigeration equipment. The technological challenge of thermally isolating the cryogenic windings was another problem of earlier development efforts. The significantly higher operating temperatures of the HTS conductors over LTS conductors are a major breakthrough for using superconductors in power generation systems. The operating temperatures for BSCCO (20–35 K) and YBCO (60–77 K) HTS conductors, based on the performance of these conductors in an applied magnetic field, eliminate the need for a continuous supply of liquid cryogens. Even the new superconducting intermetallic MgB_2 has an operating temperature of 20–30 K. Cryogenic refrigerators (cryocoolers) can cool the HTS conductors without the complications and logistics of a liquid cryogen tank. Reliable cryorefrigerators have been commercially available for years, but the larger-cooling-capacity versions are not as efficient as they should be.

SCIENTIFIC CHALLENGES

The utility of practical superconducting electric power conductors depends on both their performance and their cost. There are many use-inspired scientific challenges that, if successfully met, will both improve performance and reduce cost. They fall into three broad areas, as described below. They include optimizing the present 2G materials and developing new superconductors that will be needed to open up the full range of electric power applications to which superconductivity can contribute.

Research and Development for 2G Conductors

With the advances mentioned in the previous section and the establishment of continuous processing, new research should address the remaining developmental issues of YBCO-coated conductor performance. For example, improvements to this HTS conductor must focus on maintaining high current densities in fields of a few tesla while simultaneously minimizing ac losses and promoting stability. The present-day coated conductor architecture has a series of buffer layers that should ideally be reduced to just one or none.

Through a series of workshops sponsored by its technology program, DOE has established out-year goals for the performance of 2G wire in order to meet the needs of the electric power sector. Goals for tape fabrication for the next four years are in response to specific research thrust areas:

1. Maximizing critical current (which is essential) 300 A/cm-w, 100 m, by 2006
   New (proposed): 200 A, 4.4-mm wide, in magnetic field H = 3 T parallel to the c-axis, T = 65 K, by 2008
   1,000 A/cm, 1,000 m (77 K, H = 0), by 2010
2. 5% or less variation in properties along the wire length
3. Current proportional to HTS thickness

A perspective on these goals and present performance levels can be seen in Figure 2 We must overcome present-day length limitations by improving texture uniformity, layer uniformity, interlayer reactivity, localized flaws, and long-range variations. Long piece-lengths and high throughput are essential for highvolume manufacturing of low-cost conductors.

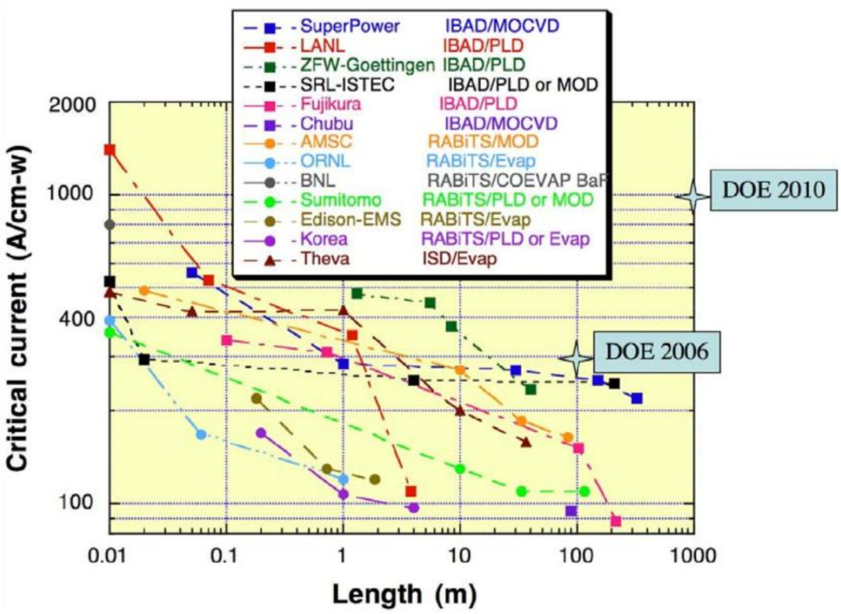

Figure 2 Performance levels of prototype 2G conductors (May 2006). The metric plotted is the critical current per unit width of tape (A/cm-w), measured at 77 K in self field. As piece-lengths increase, the current levels decrease, a problem that needs to be solved when approaching the indicated DOE goals. The inset identifies the research organization on the left and the fabrication method on the right.

Higher Critical Currents. Higher critical currents can be achieved either by improving the critical current density of the material or by depositing thicker films. Although very recent progress has been made in this area, there remains ample room for improvements that would offer tremendous benefits (see Panel Survey: "Basic Research Challenges for Vortex Matter"). The importance of superconductor performance cannot be overstated, since every factor-of-two increase in the critical current translates directly to halving the cost per kiloampere-meter of wire. Improved critical currents will require an understanding of the vortex pinning that can achieve the theoretical limits, the microstructures that can achieve this performance in practice, and the science of materials growth and processing that will permit the needed microstructures to be achieved at the lowest cost. Improved pinning methods will be necessary, as will alternative materials to reduce the supporting structure cross section of the YBCO conductor, so that the overall engineering current density will improve as well. A 2G tape capable of carrying 500 A/cm-w at 77 K would satisfy the requirements of *many* applications, allowing initial market penetration of this superconducting power conductor.

AC Losses. Minimizing ac losses in the HTS coated conductor is important to ac applications. These losses have the following components: hysteretic, ferromagnetic, eddy current, and coupling current losses. Losses may also be incurred from self-field transport currents. Ferromagnetic loss components can be removed by finding nonferromagnetic substrates in place of Ni-W (RABiTS). Eddy currents and coupling currents can be reduced by increasing the matrix resistivity; previous work on superconducting wire intended for ac applications (in the LTS era) led to NbTi-based strands with ultrafine filaments and CuNi matrices. Creating a multifilamentary coated conductor is more difficult because of the fabrication routes in use, and twisting is even more difficult because of the tape geometry. Ideally, a conductor with transposed filaments should be made. Present-day striation techniques developed for low ac loss must be adapted to long lengths, requiring a fundamental understanding of the processes involved. Improved modeling of the various loss mechanisms is necessary to understand what the losses in the system will be, especially if combined field and current interactions result in a dynamic resistance loss. Ferromagnetic shielding should also be considered.

Deposition Kinetics and Reactions. The HTS layer is the most complex in the coated conductor architecture. Yield will be primarily determined by the HTS layer, so the focus must be on reducing the complexity and cost of processing. The dynamics of the phase-formation process must be better understood; this may include the chemical reactions in the solution-based processes, gas-phase kinetics of MOCVD, YBCO precursor utilization efficiency, and nonplanar deposition processes.

Research and Development for Cryogenic Supporting Technologies

Refrigerators. The cryogenic system's lifetime cost, including both capital cost and operation and maintenance (O&M) cost, must improve by a factor of at least five. Efficiencies should be improved to 30% of Carnot efficiency, which would double that of current systems. Vacuum-jacketed cable cryostats for the HTS device must be reliable to improve the system's design lifetime. Work is needed on threedimensional fluid-dynamic modeling and flow visualization experiments with Stirling cycles and other pulse tube cycles in order to understand boundary layer and other nonideal effects on cycle gas flows. We also need to understand hydrogenic out-gassing mechanisms in real materials and how the physicalchemical action in new getter materials (ability of certain solids to absorb free gases) can affect longer intervals between getter replacement or conditioning.

Cryogenic Dielectrics. New insulation materials require basic research on dielectrics at cryogenic temperatures. It is particularly important for these materials to have high thermal conductivity and low electrical conductivity to allow for rapid heat removal to achieve stability or to allow for the quick introduction of heat to achieve quench protection. It may also be possible to design insulation that switches from insulating to conducting with a rise in temperature to achieve quench protection. The incorporation of nanometer-size particles in a matrix to form dielectric composites shows promise for materials (nanodielectrics) with new and improved properties. The properties of the interfaces between the particles and the matrix will have an increasingly dominant role in determining dielectric performance as the particle size decreases. The forces that determine the electrical and dielectric properties of interfaces influence the composite behavior. Scientific issues to be addressed include the tailoring of the dielectric properties of nanoparticles by substitutional chemistry, the derivation of nanoparticles for compatibility with a polymer matrix, the control of interfacial effects, the modeling of nanocomposites and consideration of interfacial effects, self-assembly in a polymer matrix, and the relationship of the space charge to the breakdown strength of nanocomposites.

Cryopower Electronics. Most electrical devices and systems require power controls to perform their functions. For instance, motors require power electronics to change the current, voltage, and frequency that permit the motor to operate at various speeds and power levels. A device or system that uses superconductivity (wire, cable, or coil) could improve its overall efficiency and power density by keeping the power controls in the same cryogenic environment as the superconducting component. This would also greatly alleviate the engineering complexity of bringing numerous high-voltage leads into and out of a cryogenic enclosure. Thus, research aimed at investigating the use of "nonsuperconducting" power electronic components at cryogenic temperatures and the integration of these components in a compact control module will greatly enhance the utility of superconducting technology.

Inductors and transformers are part of electronic power controls. Room-temperature inductors and transformers all use low-loss magnetic cores. These magnetic cores, optimized for performance at room temperature, become "lossy" at cryogenic temperatures. Thus, research in magnetic core materials that are "optimized" for cryogenic operation is needed. Similarly, capacitors contain dielectric materials optimized to yield top performance at room temperature. Dielectric materials and capacitors optimized for operation at cryogenic temperature need to be developed. Finally, the semiconducting "active" elements in power electronic controls (e.g., metal-oxide semiconductor field-effect transistors [MOSFETs], insulated-gate bipolar transistors [IGBTs], gate-turnoff [GTO] thyristors) are all room-temperature silicon-based devices, and most will not operate at cryogenic temperatures. Development of Ge-based semiconductors that operate efficiently at cryogenic temperature would greatly improve cryogenic power controls.

IMPACT

In 2004, electrical energy production was almost 4,000 TW-h; three-quarters of this was from fossil fuel sources. Energy losses associated with power transformation, transmission, and distribution approached 8% (10% on the grid). These losses could be cut approximately in half — amounting to more than $10 billion in annual savings — with the full implementation of superconducting technology, including underground transmission cables, transformers, power-quality devices, and FCLs. High-temperature superconductors have the potential to revolutionize electric power generation, distribution, and end use. Success in the use-inspired basic research described here will be necessary to fully realize this potential. It would provide the scientific foundation necessary for the optimization (performance and cost) of the present 2G YBCO-coated-conductor technology, and it would provide superconductors that can extend the performance envelope to include the full range of imaginable superconducting power applications.

Through the Superconductivity Partnership Initiative (SPI), DOE has co-sponsored the construction and operation of prototype superconducting power equipment to demonstrate the feasibility of the concepts discussed below. Through basic research initiatives, we can overcome the final technical obstacles and make HTS conductors cost-competitive. Doing so will allow commercialization of superconducting power equipment and result in the benefits summarized here. The emergence of the HTS utility markets has been estimated to be about $1.8 billion per year within the next 20 years.

Superconducting transmission cables*:* These HTS cables can meet increasing power demands in urban areas via retrofit applications, since they can carry up to five times more power than conventional cable; eliminate the need to acquire new rights of way; replace overhead transmission lines when environmental and other concerns prohibit their installation; enhance overall system efficiency as a result of exceptionally low losses; increase utility system operating flexibility; and reduce electricity costs. DOE's Energy Information Administration (EIA) estimates that transmission and distribution losses, including losses at substations, are 10% of the total electrical energy produced. Deployment of superconductors may reduce this figure to 3%, resulting in huge energy savings on a national scale.

Superconducting motors*:* The HTS motors will have one-half or less the size, weight, and energy losses of conventional large motors. The lower losses integrated over national consumption would result in significant energy savings. Superconducting motors are inherently more electrically stable during transients than conventional motors because the former operate at smaller load angles (15° versus 70° for a conventional motor) and have a much higher peak torque capability (~300%). As a result, the superconducting motor can withstand large transients or oscillatory torques without losing synchronous speed. The HTS machines do not require rapid field forcing during fast load changes or transients, as is often the case with conventional machines.

Transformers: These HTS devices will result in a 30% reduction in losses, have about one-half the weight and footprint, and are oil-free and so could possibly be operated inside structures. If all transformers in the United States equal to or greater than 100 MVA were replaced with HTS transformers, the lifetime energy savings from conventional transformer losses could account for 340 billion kWh, or $10.2 billion. Furthermore, conventional transformers can be overloaded for only short periods of time (200% for 30 minutes). HTS transformers can carry overloads with no decrease in equipment lifespan and manageable additional load losses. Additional benefits include reduced environmental concerns resulting from the elimination of fire and environmental hazards of cooling oil, along with more real and reactive power and improved voltage regulation.

FCLs: Fault current levels can be up to 20 times the steady-state current. The superconducting FCL will limit fault current to 3 to 5 times the steady-state current, reduce standby energy losses, and provide improved flexibility in the use of existing lower-rated circuit breakers and fuses. Also, no capacitive correction is needed with a superconducting FCL, since it has no reactance and is passive during nonfault conditions.

Generators**:** A 1,000-MW superconducting generator (a typical size in large power plants) could save as much as $4 million per year in reduced losses per generator. Even small efficiency improvements produce big dollar savings. An improvement of 0.5% gives a utility additional capacity to sell; the related value is nearly $300,000 per 100-MVA generator. The benefits of the commercial superconducting generator include increased machine efficiency beyond 99%, which reduces losses by as much as 50% with respect to conventional generators; reduced pollution per unit of energy produced; lower life-cycle costs; enhanced grid stability; reduced capital cost; and reduced installation expenses.

Conclusion: Though BCS theory is thought to be the only successful theory in explaining the superconductivity as evidenced throughout the literature survey, it has the following limitations: (i) It did not specify what substance should superconduct at what temperature. (ii) The basic ingredient of the theory, the weak electron-phonon interaction even put a limit to the highest T_c achievable around 30 K. There are two remaining areas which require further investigation. The first one is a better treatment of the Coulomb repulsion. In particular, the ability to treat large repulsion and antiferromagnetism is essential for HTSC materials. The second one is the analysis of superconducting fluctuations around the achievable critical temperature (T_c) for understanding the electron–phonon coupling. So, the overriding challenge at this stage is to understand the basic physics behind the phenomenon of HTSC along with improving some basic parameters like J_c, T_c and H_c as well as improving the quality of the sample through vortex pinning. Inspired from the whole spectrum of literature survey the present study incorporated in this paper is planned in the sequential manner

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