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Superconductivity in Power Applications

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This paper will attempt a broad, concise and sober assessment of the opportunities and realities confronting future power applications of superconductivity. Although current activity is indeed international in scope, we will focus principally on the United States inasmuch it is there that most development has and is taking place. Moreover, we will concentrate on potential electric utility driven deployment of superconducting cables, rotating machinery and power conditioning equipment in that country. We will conclude that major market penetration will not likely occur for decades to come, if ever. Having said that, it is still possible that superconductivity could play a significant role as part of a redirection of power generation to new nuclear fission cluster sites, remotely sited natural gas reserves and massive renewable energy production. Such a scenario would be driven more by social and political policy than from future economic or technology developments in superconductivity itself.

INTRODUCTION

Next year, 2011, will witness the 100th anniversary of the original discovery of superconductivity in mercury at 4.2 K in liquid helium by Gilles Holst at the University of Leiden and will also mark a quarter-century since Georg Bednorz' initial measurements in IBM Zuerich on a series of layered copper oxide perovskites obtained critical temperatures approaching 40 K, ushering in the era of "high temperature superconductivity," abbreviated HTSC. In early 1987, M. K. Wu at the University of Alabama found a member of this family exhibiting zero resistance at 91 K, 14 degrees above the boiling point of liquid nitrogen, enabling the use of this cheap and widely employed cryogen to support potential future applications of superconductivity [1]. A summary of the discovery period of the superconducting copper oxide compounds from 1986 to 1990 can be found in Ref. [2].

From the very earliest days following its initial discovery, the hope arose that this new phenomenon might eventually drastically reduce, and perhaps even eliminate, ohmic losses in electrical power equipment, from transmission lines to rotating machinery. However, it was not until the decade of the 1950s that superconductors, so-called "Type II," sufficiently robust to withstand the large currents and magnetic fields encountered in power applications, were developed. Since that time, perhaps more than fifty demonstrations and prototypes of various superconducting power equipment, using both low and high temperature materials, have been successfully carried out worldwide, and several, primarily cables, have actually been placed in utility service, although, as yet, none permanently. In 1997, the author published a comprehensive review [3] of all past and then extant programs to apply superconducting technology to power applications worldwide, and the reader is strongly encouraged to study this reference as a prelude to the present paper. Frankly, from that time to the present, although there has been significant progress in the prototyping of various HTSC power devices and wire performance, there have been few, if any, commercial sales for utility applications.

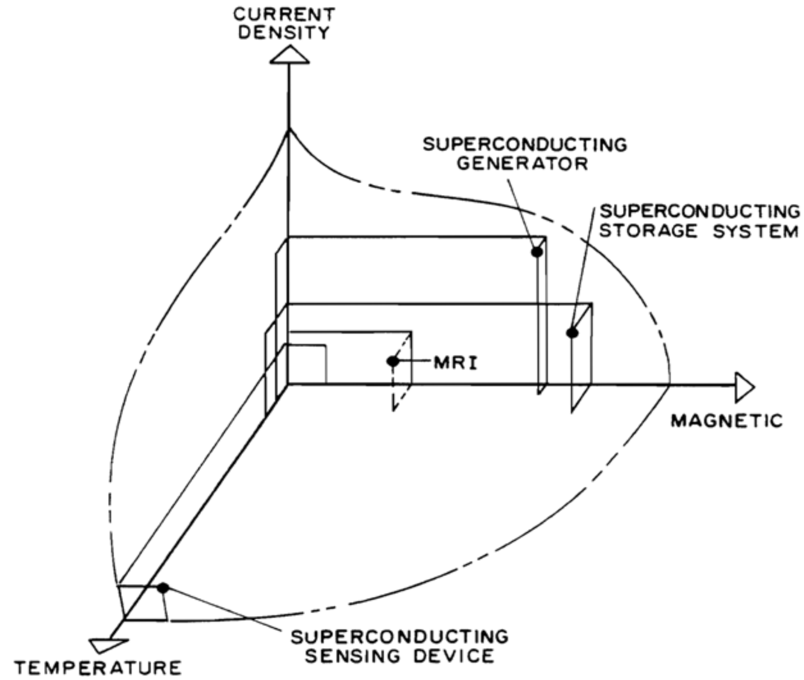


Figure 1 Generalized J-T-M phase diagram of a typical Type II superconductor. The region above the "dotted line" contours represents the "normal," or "metallic" state of a given material, whilst below it becomes superconducting. The rectangular inserts outline the respective relationship between these three parameters to enable various practical applications.

Figure 1 depicts the "applications phase space" addressed by Type II superconductors, both power and electronics related. An elaboration of the various properties of superconductors in general with respect to their application can be found in the book by Sheahen [4]. Here we will survey power applications related to utility deployment, viz., transmission and distribution cables and power conditioning equipment, primarily transformers and interrupters (fault current limiters). We will only touch lightly on end use devices such as motors although the same technology also applies to electricity generation. We will not address military applications. Other applications, such as large magnets, although an important end use of electricity, will not be covered. For a thorough and comprehensive summary to date, visit the US annual peer review website [5] and the website of a DOE HTSC wire workshop held in June, 2010 [6]. All in all, we intend this paper as a general survey of those applications having undergone the most intensive development since the discovery of high temperature superconductivity a quarter of a century past. Whether these applications will eventually achieve market insertion remains problematic.

HTSC WIRE AND TAPE

A common feature of all superconducting copper oxide layered perovskites is their strong structural anisotropy which materially affects their transport and magnetic behavior [3], an unique property largely absent in the low temperature superconductors. Transport, both normal and superconducting, favor the two-dimensional square-planar CuO layer which all these compounds possess. Thus, to properly display such anisotropy would actually require three independent variations of Figure 1. However, unless otherwise noted, in speaking of HTSC conductor properties, we will implicitly mean those properties restricted to the CuO layer, or "a-b," plane.

The first generation of HTSC wire "Gen I" (Although we use the common term "wire," all present HTSC conductor embodiments are in the form of "tape.") employed $Bi_2Sr_2Ca_2Cu_3O_{10}$, or "BSCCO-2223," T_C = 108 K, or one of its lower transition temperature stoichiometric derivatives [1]. Due to the large separation between the CuO planes in this structure [1], its microscopic mechanical properties are strongly micaceous in that under an applied shear force, the CuO planes tend to slide and align thus resulting in reasonably satisfactory critical state properties (see Figure 1). Moreover, when such shear force is applied with the powder in contact with silver, partial melting occurs (a process still not well understood) yielding even better critical state parameters. The principal drawbacks of this procedure is that the best critical state values exist only nearest the interface with Ag and the perpendicular axis properties are far inferior to those in the a-b plane.

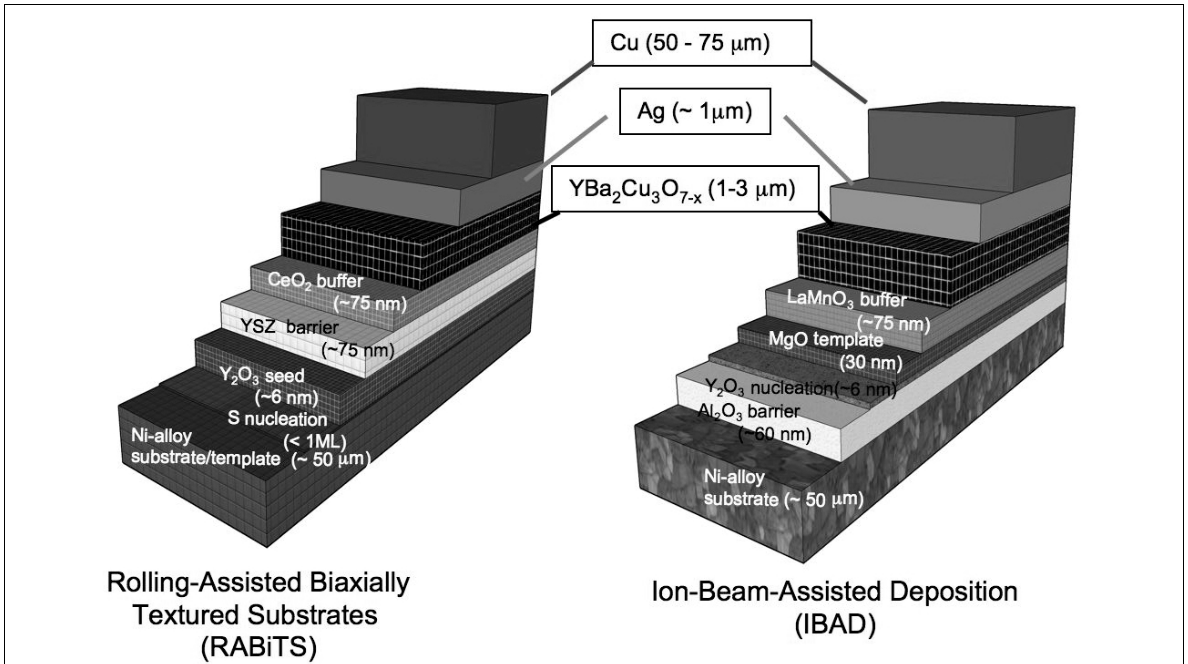


Figure 2 The two standard "stack" topologies of commercially available Generation II HTSC "coated conductor." The "RABiTS" (left) approach was developed at Oak Ridge National Laboratory and commercialized by American Superconductor, whilst "IBAD" (right) was explored by Stanford University and Los Alamos National Laboratory, and subsequently commercialized by SuperPower

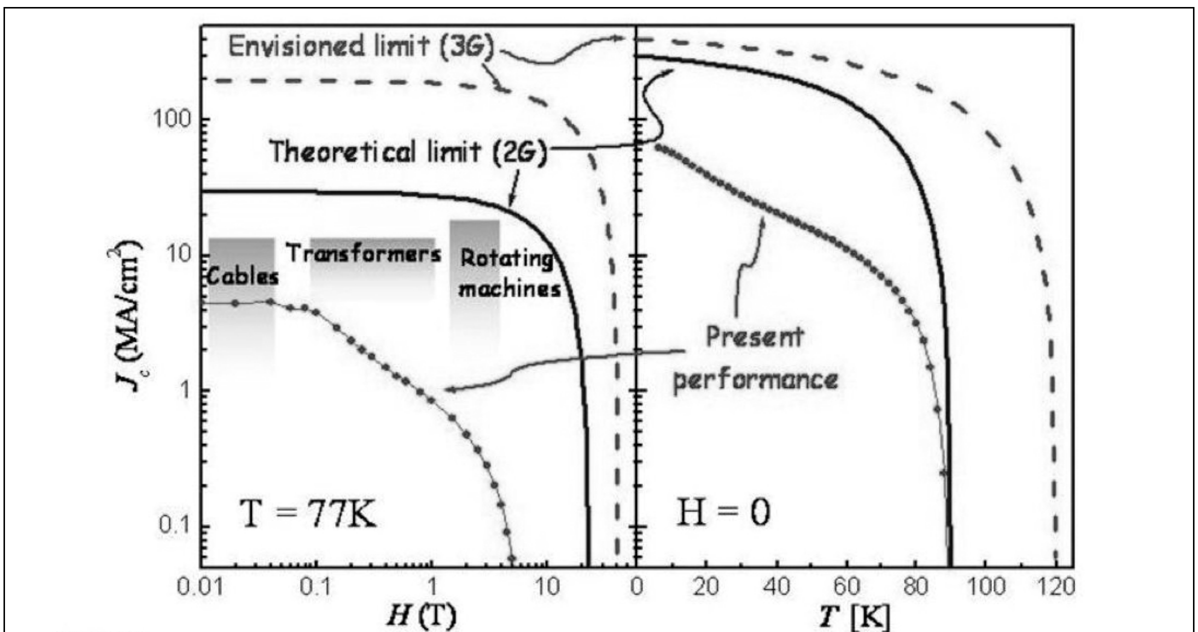


Figure 3 Critical state parameters of HTSC wire required for a variety of power applications. "3G" refers to a future hypothetical "round" embodiment of HTSC wire more suitable to solenoid application analogous to LTSC NbTi technology

Of the presently available HTSC materials, YBa_2CuO_{7-y}, or "YBCO…Y-123," $y \leq 0.01$, $T_C = 93$ K, has perhaps the optimum properties for practical wire. Its relatively low degree of crystalline anisotropy permits the optimum division between its c-axis with respect to a-b plane critical state behavior. However, this same degree of low anisotropy gives rise to “grain boundary,” or a-b nearest neighbor plane orientation, which creates “wide angle, weak link, Josephson junctions,” that severely inhibit current flow throughout a practical length scale [1]. Figure 1 shows its solution [3, 7], both methods essentially employing insulating, buffered perovskite substrates oriented substrates to induce c-axis epitaxy in an upper deposited YBCO film. The method on the left uses a transition metal substrate metallurgically fabricated by “rolling-assisted, bi-axial texturization substrate (RABiTS),” and that on the right a yttrium oxide layer oriented using an “ion-bombardment-assisted-deposition (IBAD)” technique. The critical state performance of this “Generation II” wire with respect to several power applications is given in Figure 2. The principle factor in question at present is cost/performance. Manufacturers keep such figures confidential and each sale is independently priced. In general, the C/P of Gen II wire is roughly in the range 800-200 USD/kA×m at 77 K (compare with 0.90 USD/kA×m for NbTi at 4.2 K). Whether the relatively high price of HTSC wire precludes the widespread use of superconductivity for power applications is a topic of current intense debate. See Ref [8] for a general discussion of this issue.

Finally, a comment regarding magnesium diboride, MgB_2, first synthesized in 1954, but realized to be superconducting in 2001, with a T_C = 39-40 K [10]. This compound may possibly be able to be fabricated as “round wire” with a superior performance in high field magnets near 4.2 K due to its much higher critical state parameters compared to NbTi.

APPLICATIONS: PROTOTYPING AND DEMONSTRATION

The years following World War II to the present witnessed manifold proposals for and prototype demonstrations of the use of superconductivity, both low temperature and high temperature, for power applications. These activities focused on three major areas: cables, rotating machinery (generators and motors) and power conditioning (storage, transformers and fault current limiters) [1-4].

Transmission Cables

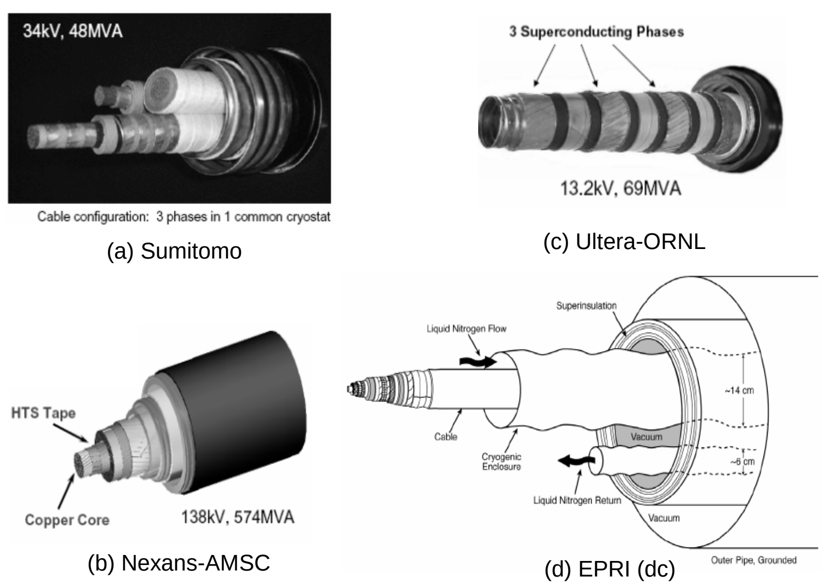
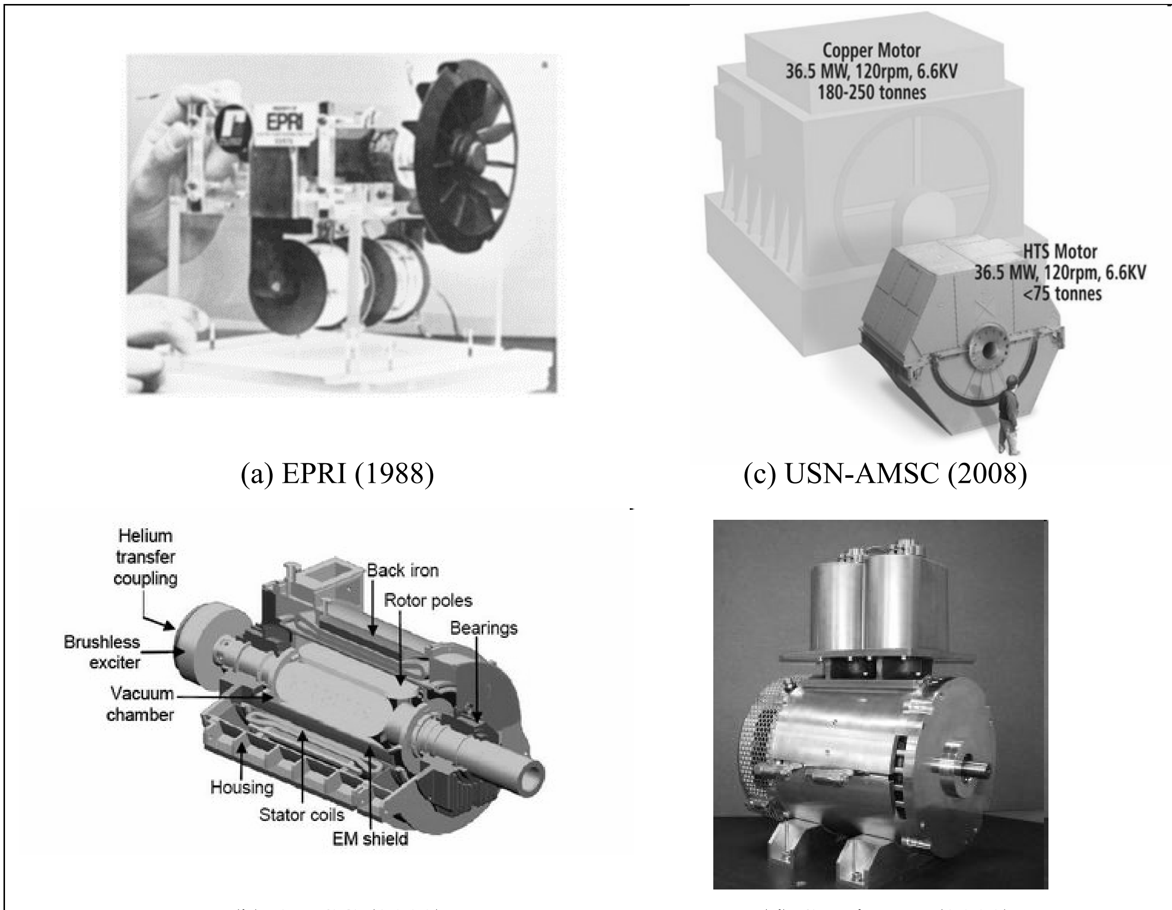


Figure 4 Common HTSC cable designs, (a) Sumitomo 3-phase ac, each phase independently shielded; (b) Nexans-AMSC, high voltage ac coaxial shielded; (c) Ultera-ORNL triaxial, no phase independently shielded; (d) EPRI HTSC dc cable, emphasizing the cryogen flow and enclosure packaging aspects [18]. See each sub-figure to review relative performance parameters

Figure 4 shows four current designs of HTSC superconducting cables under prototype and demonstration deployment, three alternating current designs and one direct current. See Refs [3, 5, 9]. Specifically, Figure 4(a) was recently under test at an Albany substation of the National Grid network in

New York State, 4(b) is today installed on a transmission line in the Long Island Power Authority network, and 4(c) under test at American Electric Power and ORNL. Two novel cable applications are presently under consideration in the US: 1) The Tres Amigas Project [11] intended to provide a dc “back to back” three way intertie between the Eastern Grid, Western Grid and Texas, to be located near Clovis, New Mexico, and 2) Project Hydra [12], a New York City substation interconnection, funded at greater than 30M USD by the Department of Homeland Security (DHS), an attempt to combine the high power delivery of HTSC cables with the inherent fault current limiter abilities contained in the physics of superconductivity. Preliminary cable specifications for the former target 24 kA, 200 kV (bipolar 10 GW, 7 km), and the latter 4 kA at 15 kV ac (three phase rms ~ 146 MW, 500 m). Finally, Steve Ashcroft, Los Alamos National Laboratory, has proposed a novel concept [9]: overhead HTSC unshielded ac cables of order 100 kV, ~ 500 MVA, 70 km long which should be explored at least to determine their feasibility.

Rotating Machinery



(a) EPRI (1988) (c) USN-AMSC (2008)

(b) AMSC (2003) (d) Sumitomo (2009)

Figure 5 HTSC superconducting motor evolution: (a) EPRI 1hp (1988); (b) AMSC Maritime motor 5 MW - 7000 hp (2003); (c) US Navy - AMSC large ship propulsion motor 36.5 MW - 49000 hp (2008); (d) Sumitomo car motor 50-345 kw - 70-460 hp (2009)

Electrical rotating machinery falls into two broad categories: generators and motors. We will not address HTSC generation here, although this application has a rich history [3, 5]. Having said that, new opportunities may be opening in large tower wind farm deployment, inasmuch as HTSC generators contain less iron and thus provide more power per unit weight per tower.

Regarding motors, Figure 5 summarizes the application opportunities at present. Of greatest promise are (b) and (c), “trickle down” possibilities for driving space conditioning pumps and use in commercial marine and associated leisure enterprises [5].

Passive/Active Power Conditioning Devices

Superconducting power conditioning devices fall into three general categories: 1) storage, 2) transformers and 3) fault current limiters (FCLs). All three have a long history of prototype development and demonstration throughout the LTSC and HTSC eras [3, 13]. Superconducting magnetic energy storage (SMES) has a number of potential applications…massive energy storage on the scale of hydroelectric, energy supply/use equilibration and short term, long term low and high frequency fluctuation filtering. To date, none of these has substantially materialized. A similar story can be told with regard to superconducting transformers…many successful demonstrations of their advantages…energy savings, weight, footprint and environmentally benign coolant and insulation…are well known. Yet, at present, to the knowledge of the author, significant utility acceptance still remains in the future.

On the other hand, superconducting fault current limiting devices show promise of reasonably near term commercial deployment [14]; however, they face serious competition from silicon solid state switches which are, in principle, capable of operating at higher voltage levels. Resistive "momentary current interruption" is inherent in the physics of superconductivity once the transport current exceeds critical current thresholds. What has arisen as novel in the past five years is the proposal to combine this "intrinsic" property with transformer action and cables. The former is under development by Waukesha and SuperPower [14], and the latter within Project Hydra described above [9]. Both applications will impose tight margins on critical current values along the entire length, perhaps as long as 10 km, on the wire to be employed.

POSSIBLE FUTURE SCENARIOS

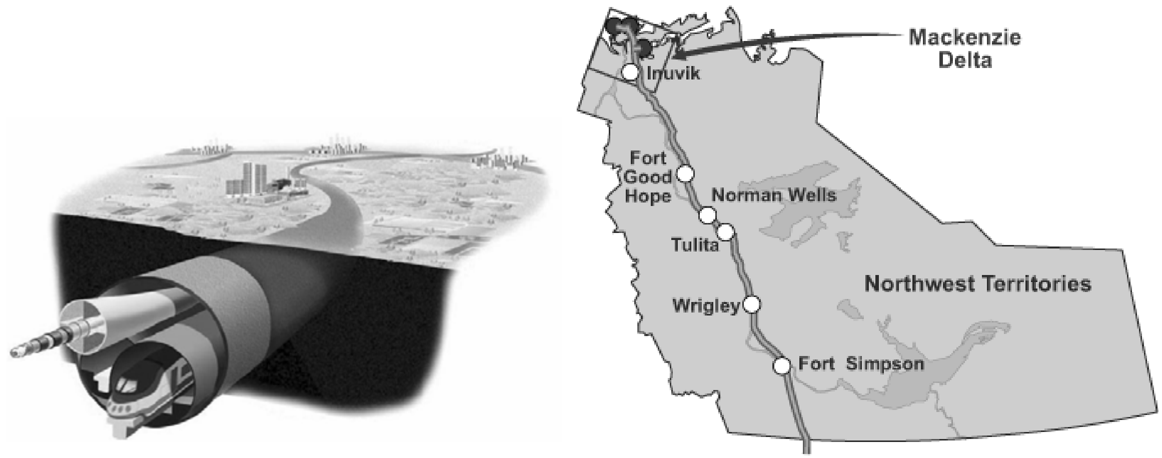
In 1967, Richard Garwin and Juri Matisoo [15] published what was perhaps the first "visionary" paper on the large scale use of superconductivity for power transport. The scale of their proposal was truly enormous 100 GW (+/- 100 kV at 500 kA direct current) over a distance of 1000 km, the entire length of Nb_3Sn wire refrigerated by liquid helium. At the time, such a cable would have been capable of carrying half the entire electric power generated in the United States, and about one-twelfth today. The power vision at the time foresaw remote coal, nuclear and hydroelectric facilities supplying America's electricity in the future.

Thirty years later, in 1997, Schoenung, Hassenzahl and the author [16] reprised the Garwin-Matisoo vision as an HTSC 5 GW, 50 kA, +/- 50 kV, "e-pipe," cooled by liquid nitrogen at 65 K, transporting "well-head" generated electricity from newly developed natural gas fields in Qatar some 1650 km across the Arabian Peninsula to an imagined future Mediterranean "industrial complex."

Dual Use Exploitation of Existing and Future Rights-of-Ways

Figure 6 depicts an extension of the long distance cable concept to exploit dual use of existing and future public service corridors to permit the transmission of electricity as well.

The left hand portion of the figure suggests sharing a transportation tunnel, either submarine (e.g., the France-England "chunnel") or through a mountain range such as one encounters throughout the Alps, with a high capacity HTSC cable. The right hand side shows a portion of the Mackenzie Valley natural gas pipeline scheduled to start construction in 2010. The power equivalent of the methane to be shipped from the Mackenzie Delta to the province of Alberta and the northern mid-western US states is estimated to reach 18 GW-thermal. Perhaps 30% of the natural gas will be eventually combusted in turbines to produce electricity after it reaches its American destination. Why not consider consuming this fuel more efficiently at the well head to generate electricity and transmit it down the same corridor occupied by the pipeline on an HTSC dc cable? When the Mackenzie Delta runs dry in about three decades, perhaps nuclear plants could be then be constructed at the same site to generate electricity and ship same down the already existing superconducting cable [17].



(a) (b)

Figure 6 HTSC Cable opportunities for ROW multiple use: (a) Artist's conception of dual use of a tunnel right of way for both high-speed rail and a high capacity HTSC transmission cable, courtesy of Electric Power Research Insitute; (b) The Mackenzie Valley natural gas pipeline route which in principle could support the co-transmission of chemical and electricity power, the latter deploying superconducting cables (see text for explanation)

SuperGrids/SuperCities/SuperSuburbs

The author and several of his colleagues have proposed a model energy economy based on a symbiosis of nuclear, hydrogen and superconductivity technologies abetted by non-eco-invasive solar roof and urban biowaste combustion renewable generation [19-21]. On the nuclear side, the complete cycle of spent fuel reclaiming and reprocessing would be undertaken including breeding of other fissionable actinides, thus assuring essentially an almost indefinitely sustainable energy supply for centuries. The embodiment of this concept can accommodate a wide range of scale, from a continental-wide transmission/distribution system down to small suburban communities. It is the way we would go if Franklin, Edison, Tesla, Steinmetz and Insull [22] could jump-start the electricity enterprise all over again.

CONCLUSIONS

As of the submission date of this paper, direct “line item” US DOE funding of the power applications of superconductivity, which ranged from 20-60 M USD/yr since 1988, has now ceased [23]. However, support of Generation II wire development in the US National Laboratories continues within its advanced cable initiative and existing cable and FCL demonstration projects will be completed, but it is uncertain at this time whether additional such projects will be undertaken. Superconducting materials support in the US is presently at its lowest level in many years, marked by an absence of funding by the National Science Foundation (NSF) and the Basic Energy Sciences (BES) division of the Department of Energy. The remaining US government agency funding development of new superconducting materials is the US Air Force Office of Research and Development (AFOSR), an extensive search for “much higher” transition temperature materials than presently exists.

Considerable discussion is underway regarding the cost, and especially the availability of large quantities of HTSC wire should power deployment significantly advance in the near future. However, prior to demand must first come need…indeed, a compelling need that only superconductivity can fulfill and whose solution not fall within the scope of simply improved conventional technologies. An example is provided by the discipline of high energy physics whose need for ever larger hadron colliders created the demand for vast quantities of NiTi magnet wire. Once the orders began to flow in to the wire manufacturers, investments were made to increase their manufacturing capacity to meet the subsequent demand. A similar scenario must arise in the power and energy industry to engender the increase in demand, and hence production and concomitant cost reduction, of HTSC wire, and it is by no means certain such a scenario will indeed occur, at least not in the immediate future. Having said that, should "dual use" of existing and planned vehicular and natural gas transportation corridors in the next decade transpire, as described previously, a significant "need-driven" demand for large quantities of HTSC wire could emerge. And finally, by mid-21st century, the realization of a nuclear-hydrogen-superconductivity symbiosis, perhaps required as an adaptation to climate change, would of course necessitate significant demand.

To deploy any power equipment usage using presently available superconductors requires a supporting cryogenic infrastructure. Although liquid nitrogen (or cold helium gas at $T > 25$ K) is much more easily managed, and at lower cost, than liquid helium, ancillary cryogenics support nonetheless remains a major barrier to the commercial insertion of superconducting power applications.

We close by quoting a prescient and rather iconoclastic admonition by Foner and Orlando from their 1988 Commentary, Superconductors: The Long Road Ahead [13]: "Widespread use of these [high temperature] superconducting technologies will have far more to do with *questions of public policy and economics* than with the nature of the new materials." [Italics inserted by the author]

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