Superconductivity: 100 Years and Counting

First in a year-long series of editorial pieces celebrating the history and progress of superconductivity

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The following invited article is based on a presentation by Dr. Paul Grant at the July 2010 ICEC/ICMC in Wroclaw, Poland. It is the first in a year-long series of articles in which Cold Facts will be celebrating the 100th anniversary of the discovery of superconductivity.

Well, perhaps we also should include the past 25, too, since it will be a quarter-century this January since Georg Bednorz found a zero resistance onset starting in the mid-30K temperature range in a mixed phase copper oxide perovskite, ushering in our current era of "high temperature" superconductivity [1].

Why the term "high temperature"? Given that the highest critical temperature of the present family of superconducting materials is still some 135° Celsius below ambient, this description must seem somewhat incongruous to the cryogenics community at large. Yet, "high temperature" has a specific historical origin, one which many practitioners of the superconductivity art themselves may be unaware.

Beginnings

The detailed explanation of superconductivity, first observed during the spring through fall of 1911 in mercury by Gilles Holst in Kammerlingh Onnes' laboratory in Leiden [2], despite strenuous efforts by most of the greatest theoretical physicists of the first half of the 20th century, escaped a sound qualitative quantum basis until the landmark work of Bardeen, Cooper and Schrieffer in the mid-1950s. "BCS" synthesized one theoretical concept with two experimental observations: 1) that in the presence of any infinitesimal attractive field of whatever origin, two electrons, normally like-charge repelling, will actually bind and pair (today the proof is generally called "Cooper's Exercise," and is used as a homework exercise in elementary quantum mechanics); 2) that superconductivity manifests as a three-dimensional macroscopic quantum state; and 3) because the transition temperature of a given superconductor depends on the isotopic mass of the constituent atoms, somehow the lattice of the superconductor is involved.

The BCS model exquisitely unifies these three "observations" in a straightforward way, the lattice vibrations of the positively charged nuclei providing an "instantaneous" attractive force under certain vibronic modes (physicists call this a "retarded interaction") that "solves" Cooper's Exercise throughout the bulk of the superconductor. The most elementary BCS expression for the superconducting critical temperature is simply $T_c \propto \Theta_D e^{-1/\lambda}$, where Θ_D is the characteristic temperature of the phonon spectrum (the Debye temperature), and λ the "dimensionless" electron-phonon coupling constant, both parameters non-trivially dependent on the quantum material properties of a particular superconductor. The BCS framework appears to apply to all known superconductors to date, despite that the devil is still in the details regarding the layered copper oxide perovskites. In fact, in the broadest sense, BCS describes fermion-pairing mitigated by a boson field, the most sensational example being "color superconductivity" in super-dense neutron stars, two quarks "gluoned" together, with a transition temperature of the order 10^{10} degrees (the units don't matter!).

The original exposition of BCS was in the "weak-coupling" limit, that is, small λ. Niobium metal provides an example: $\Theta_D \sim 275\text{K}$, $\lambda \sim 0.28$, $e^{-1/\lambda} \sim 0.028$, $T_c \sim 9\text{K}$. It becomes clear why superconductivity is truly part of cryogenic science and technology.

Nonetheless, the simple BCS expression does illuminate possible paths upward—either increase the boson characteristic energy or its coupling to the relevant fermion (electron or hole)—or both. The first option was explored conceptually in the 1960s by Bill Little at Stanford and Vitaly "VL" Ginzburg at the Moscow Lebedev Institute, and involved substituting an exciton ($\Theta \sim 2$ eV $\sim 23{,}000\text{K}$) for phonons as the boson field. You can see that even for BCS weak coupling ($\lambda \sim 0.25$), $T_c \sim 420\text{K}$! To date, a number of embodiments have been investigated, mostly incorporating various organic compounds, so far without success (in the 1970s, the author and his colleagues at the IBM San Jose Research Laboratory pursued a number of such efforts. We learned an awful lot about polymer metals as a result, but unfortunately found no "room temperature superconductors").

The second route, that of increasing the electron-phonon coupling strength, λ, has proved more fruitful, although the success achieved has resulted more from serendipity than science. By 1986, the highest T_c achieved was in the "A15" compound $Nb_3Ge \sim 23\text{K}$. The "strong coupling" resulted from "nesting" properties of electron Fermi surfaces of these A15 materials, which gave rise to lattice instabilities and subsequent "strong coupling" to degenerate (Jahn-Teller-like) phonon branches. Early in the decades of the 1970s, the majority of superconductivity researchers, led by Berndt Matthias of UCSD, held that superconductivity in excess of 30K was unachievable in that the electron-phonon coupling would lead to a phase transition resulting in an insulator. Thus, any future discovery of superconductors near or above that "barrier" would be deemed "a high temperature superconductor" by the community.

And that is why Alex Mueller and Georg Bednorz chose to entitle their historic paper, "Possible High T_c

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Superconductivity in the La-Ba-Cu-O System."

So how do we move upward and onward? The BCS "theory" is immensely successful qualitatively, but not quantitatively in the sense of Newton's laws of motion, Maxwell's equations and electronic band structure which can be used to engineer cars, communication and computation. It is true that a "strong coupling" modification of BCS, the so-called Eliashberg-McMillan equations, coupled with modern density functional computational methods, can "predict" the superconducting phase diagram of some simple superconductors, such as aluminum, and can possibly lay claim to having foretold finding superconductivity in the high pressure metallic phase of silicon. However, there are invariably "adjustable fudge factors" applied, especially to accommodate the always-present "de-pairing" coulombic repulsion between fermions of like charge, in order to bring the calculations into agreement with the experiment. There is only one sure way to find new superconductors, as eloquently stated in the opening sentence of the Bednorz-Mueller discovery paper: "At the extreme forefront of research in superconductivity is the empirical search for new materials." In other words, if you stumble across a new (or old) metal, cool it down and you might be pleasantly surprised. That's exactly what happened with MgB_2 in 2001.

What are superconductors good for?

Today we have hundreds of metals, semimetals, organic conductors, doped oxides that superconduct, with transition temperatures ranging from near absolute zero to 165K under pressure. In fact, the number of conductors that superconduct at some temperature far exceed those that don't. Actually, Cooper's Exercise implies the metallic state is inherently unstable as one approaches absolute zero.

To partially answer the above question, we will focus throughout the rest of this article on possible power cable applications of the "high-T_c" (HTSC) copper oxide perovskites [3]. However, it should be mentioned that the majority of applications still involve "low-T_c" materials, principally NbTi and it is likely such will remain true for quite a while. Those likely best known to the general public employ large electromagnets as found in large hadron collider facilities such as Fermilab and CERN, and in magnetic resonance imaging, MRI. I find it immensely satisfying that superconductivity, arguably the most elegant phenomenon uncovered by 20th-century condensed matter physics, has become an indispensable tool to help unravel our cosmic origins.

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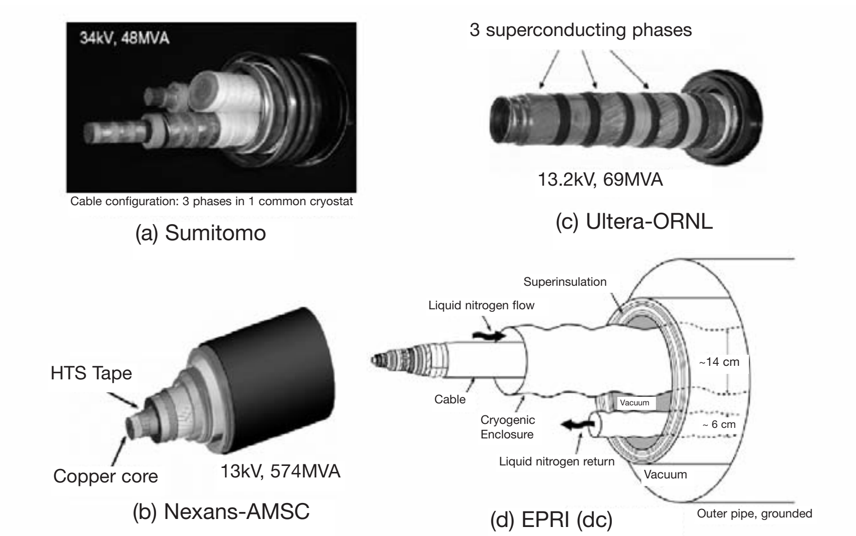

Figure 1. Common HTSC cable designs, (a) Sumitomo 3-phase ac, each phase independently shielded; (b) Nexans-AMSC, high voltage ac coaxial shielded; (c) Ultera-ORNL triaxial, no phase independently shielded; (d) EPRI HTSC dc cable, emphasizing the cryogen flow and enclosure packaging aspects. See each sub-figure to review relative performance parameters.

The years following World War II up to the present time witnessed manifold proposals for—and prototype demonstrations of—the use of superconductivity, both low temperature and high temperature, for power cable applications, all technically performance successful.

Figure 1 shows four designs of HTSC superconducting cables presently undergoing prototype and demonstration deployment, three alternating current designs and one direct current. Specifically, Fig. 1(a) was recently completed at an Albany substation of the National Grid network in New York State, 1(b) is today installed on a transmission line in the Long Island Power Authority network, and 1(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 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, a New York City substation interconnection, funded at greater than $30 million 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.

Future Opportunities to Deploy HTSC Power Cables

Figure 2 on page 9 depicts an extension of the long distance cable concept to exploit dual use of existing and future public service power delivery corridors to permit the transmission of electricity as well [4].

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?

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 renew-

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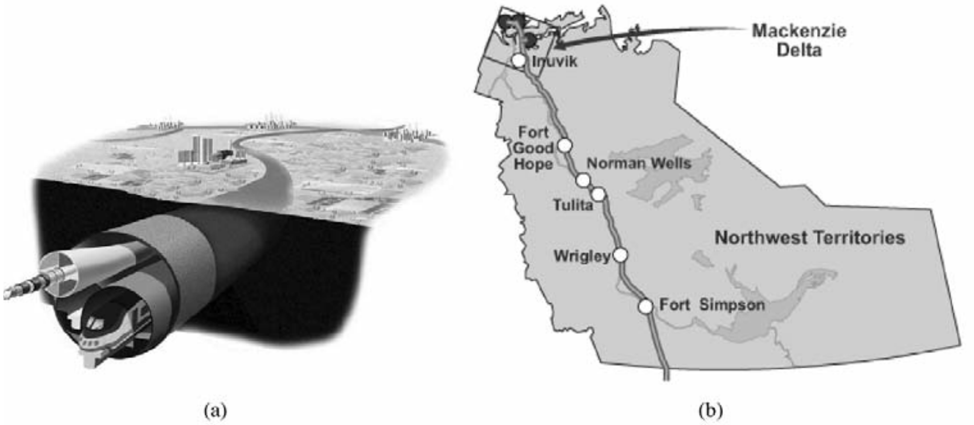

Figure 2. HTSC Cable opportunities for ROW multiple use: (a) Artist's conception of dual use of a tunnel right of way for both high-speed rail and a high capacity HTSC transmission cable, courtesy of Electric Power Research Insitute; (b) The Mackenzie Valley natural gas pipeline route which in principle could support the co-transmission of chemical and electricity power, the latter deploying superconducting cables. (See page 7 for explanation).

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able generation [5]. 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 a 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 could jump-start the electricity enterprise all over again [6].

Take-Home Message

Considerable discussion is underway regarding the cost, and especially the availability of large quantities of HTSC wire should power cable 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 does not fall within the scope of simply improved conventional technologies.

To enable HTSC power cable operation 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.

So, as we mark the centennial and quarter-centennial anniversaries of the two monumental discoveries of superconductivity—and counting forward—we must note that there remains still a considerable journey ahead towards a future which will witness at once a more fundamental and predictive theory as well as its significant insertion into the power delivery infrastructure.

References

1. Grant, P.M., High Temperature Superconductivity: Four Years Since Bednorz and Mueller, Adv. Mater. (1990) 2 232-253 (The online version of this article was revisited and annotated 19 April 2010 (For direct links to this article and all referenced papers below, please contact the author at w2agz@w2agz.com)).

2. Literature citations to, and reproductions of, original publications related to the discovery periods of both low and high temperature superconductivity can be found on the author's website, www.w2agz.com, and most especially on the pages www.w2agz.com/SuperWiki.htm and www.w2agz.com/BD_WROC10.htm. Readers should also see www.w2agz.com/BD_rtsc07.htm, "The Path to Room Temperature Superconductivity."

3. Grant, P.M., Superconductivity and Electric Power: Promises, Promises...Past, Present and Future, IEEE Trans. Appl. Supercon. (1997) 7 112-133.

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