HTS CABLE--STATUS, CHALLENGE and OPPORTUNITY

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I. INTRODUCTION

I.1 Content and Purpose

This report describes issues that bear upon the prospects for future adoption of HTS cable.

This report is intended for research and development (R&D) managers in government, electric utilities, private firms, and national laboratories. This report may also serve scientists and engineers who, though expert in a particular aspect of Superconductivity or Transmission and Distribution, wish an introduction to, or reminder of, the topics described herein. Both technical challenges and overarching issues are described. By drawing the latter to the reader's attention, this report complements the particular points of view of individual specialists.

The report's topic is timely. At least eleven HTS cable projects are underway in Asia, Europe and North America. The reason is easily stated. If successfully developed, HTS cable will enable a great increase in the electric power that could be delivered through a fixed cross-sectional area. That possibility is valuable because most of the cost of the conventional alternative derives from the cost of right-of-way and the cost of new infrastructure (underground or underwater) to house the cable, rather than the cable itself. In fact, the total cost of right-of-way, tunnels or ducts, and the long lead times required have discouraged investment in cable. The consequences vary with location. Some densely populated areas are less reliably served now than in the past because incremental load growth has overloaded aging cable. In other regions, desired economic growth cannot proceed for lack of electrical power.

It is assumed that the reader is acquainted with superconductivity and cryogenics, but is not necessarily expert in the topics discussed here. Indeed, one aim of the report is to stimulate attention to topics that remain to be addressed and another is to enable the reader to better understand the specialists whose work may stimulate interest or who may ask for the reader's attention or support.

I.2 Scope

This report describes the technical and economic challenges to HTS cable.

This report also describes situations in which HTS cable might be preferred to conventional alternatives and the report suggests where those situations might arise with above average probability.

Neither the challenges nor the opportunities are isolated from economics or public policy. The electrical power sector has always been influenced by governments and is likely to remain so. Thus, this report mentions some policies that may bear upon the future commercialization of HTS cable. As may be helpful, the context-- technical, economic, historical and legal—is also sketched.

Readers with an interest in the background within which the power sector will consider HTS cable should read Chapter II. Chapter XIV summarizes key aspects in the body of the report, while referring to them for more detail.

Because of the variety of its readers' backgrounds, the report approaches its subject in several ways.

Chapter III introduces the challenges to cable by presenting the history of its development using conventional materials. This brings out the principal issues without jargon or mathematics. Today's effort faces the same kinds of challenges using new materials.

Chapter IV presents the key ideas of three-phase power and then describes the designs of HTS cables intended for AC three-phase circuits. (The treatment omits complex numbers; they are handy for calculating of steady state conditions but hinder understanding the essentials.)

As is well known, HTS conductor is expensive and the important progress is being made to finding ways to manufacture it at lower cost. Other technical challenges that are important to cable have received less emphasis. The losses concomitant with alternating current and the extraordinary ratio of surface to volume for cable, make cryogenics—refrigeration, thermal insulation and the coolant's fluid mechanics--a crucial issue when considering HTS cable. Chapter V is devoted to cryogenics; its appendix recapitulates some basics for the technically trained reader.

Another topic, relatively neglected, is also important. That topic is electrical insulation, also called dielectric. Chapter VI presents the principal considerations and cites the specialist literature to facilitate access to it.

Future adoption of HTS cable will be affected by it price. Chapter VII shows the costs that can be attributed to both conductor and cryogenics under a variety of assumptions. We emphasize that the power sector does not just buy cable; the power sector considers the cost of a whole project, of which new infra-structure will be the most expensive part. Thus the proper comparison includes both cable and concomitant infra-structure.

The report then presents information about the power sector that bears upon the adoption of future HTS cable. Because there is a public interest and a private interest electrical energy dissipation, Chapter IX presents information concerning national average electrical energy dissipation during T&D and complements this by describing how electrical engineers evaluate energy dissipation for a specific project.

Chapter X describes the present pattern of AC cable use in several countries.

DC cable use is presented in Chapter XI. That chapter also clarifies the distinction between the challenges that face HTS DC cable in the foreseeable future and the other challenges that must be met to realize the vision of those who look ahead to the 22nd century.

Chapter XII concerns the foreseeable future. The chapter describes situations in which HTS cable, if successfully developed, would be preferred to conventional alternatives.

Because these situations are more likely to occur some regions rather than others, Chapter XIII presents some criteria with which to cull regions and the results of such culling are presented.

Because this report is meant to make its subject accessible, many passages include citations to the specialist literature, either technical or economic, in the hope that the reader will delve into the topics that interest him or her and contribute to future successful application of HTS cable.

Everything of interest is not in the literature. Groups throughout Asia, Europe and North America are engaged in activity to further HTS cable. Chapter VIII identifies these groups to enable the reader to follow up his or her initial interest by contacting them.

I.3 Sponsorship

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I. 4 Further Sources of Information

No report can be more current than its date of publication. Information about specific future efforts to advance HTS cable may be gained by contacting the researchers engaged in those efforts. Access to these researchers can be facilitated by referring to Chapter VIII in this report and to other reports prepared by Argonne National Laboratory for the participating signatories of the International Energy Agency's *Implementing Agreement for a Co-Operative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector*. Copies of these reports can be obtained by requesting them from the member of the sponsors' Executive Committee who represents the country of the requester. The name and address of each member of the Executive Committee is listed in Section I.3.

Among these reports are:

A.M.Wolsky, *Cooling for Future Power Sector Equipment Incorporating Ceramic Superconductors,* for signatories of the IEA Implementing Agreement for a Co-Operative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector, (April 2002), 133 pages.

Marsh, G.E. and A.M. Wolsky, *AC Losses in High-Temperature Superconductors and the Importance of These Losses to the Future Use of HTS in the Power Sector*, for signatories of the IEA Implementing Agreement for a Co-Operative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector, (May, 2000), 134 pages.

Also available is a nontechnical, illustrated brochure introducing progress in ceramic superconductors. That brochure is entitled: "High-Temperature Superconductivity for the Electric Power Sector: Advances toward Power Sector Applications" (January 1997), 20 pages.

Information about the International Energy Agency's Implementing Agreement for a Co-Operative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector and its reports and meetings can be found on the World Wide Web at: http://www.iea.org/tech/scond/scond.ht

II. INTRODUCTION TO TODAY'S CONCERNS WITH CABLE

This chapter introduces several themes. Their appreciation is essential for understanding the prospects for HTS cable. Here we present a sketch. Subsequent chapters provide more detail. Chapter XIV summarizes what has gone before and offers an outlook on what is to come.

II.1 The Benefit of Electrical Transmission and Distribution (T&D) and the Challenges to Enabling It to Meet Expectations

During the past one hundred years, electrical technology made possible the separation of energy use from energy conversion. Thus, a computer or an electric motor (perhaps within a nearby air-conditioner) can be powered by a furnace, reactor, or dam that is a thousand kilometers distant.

That separation was made feasible by the transmitting and distributing electric power. It is guided from generator to consumer by overhead lines and underground (and underwater) cable. It is the cable that is this report's subject. Those lines and cable, with their transformers and switches, constitute the T&D system, often called the network or grid.

Today's T&D spans great distances and traverses varied geography—geography that continues to challenge engineers. These challenges are presented by nature (e.g., crossing from English Channel from Great Britain to continental Europe) and these challenges are presented by the wish to accommodate different persons' preferences and activities, each occurring at the same place and time (e.g., crossing the street in any city).

When trying to design and build T&D, engineers must take account of many different concerns and mandates:

a. already existing legislative mandates
b. already existing property rights
c. already existing electrical infrastructure
d. the part of the future that concerns the builders
e. initial cost (e.g., investment in construction)
f. operating cost (e.g., energy loss)
g. reliability despite varied electrical conditions (e.g., base loads and faults)
h. reliability despite varied environmental conditions (e.g. ice, wind)
i. vulnerability to accidents (e.g., auto accidents), vandalism or sabotage
j. compatibility with other uses of the relevant land or water.
k. public safety and utility worker safety
l. aesthetics

The complexity that characterizes choice for T&D can be realized by noting that many concerns and mandates are incommensurable: financial cost, environment, reliability and vulnerability or security. No common metric enables a decision algorithm. Engineering and commercial judgment is required. Further, each category's importance depends on the region in which it would be considered.

II.2 The Promise of HTS Cable

Today, at least eleven HTS cable projects are underway around the world because HTS cable promises to better satisfy many of the disparate concerns and mandates than today's conventional cable. Electric utilities and their customers might be attracted to HTS cable because it raises the promise of:

- reduced investment cost of the total project,
  which is the sum of the costs of infrastructure and cable

- reduced cost of substations
  which can be made smaller in crowded areas
  by delivering more power at lower voltages

- quicker deployment than is now possible,
  thus timely location and less "interest during construction"

- increased system reliability
  by virtue of the ease of siting new capacity that relieves today's bottlenecks

- increased ability to control the flows of current and power in other parts of the grid
  by using a phase angle regulator (e.g., phase changing transformer)
  in series with a low impedance HTS cable

These promises arise from the difference between the technical characteristics of HTS cable and the technical characteristics of conventional cable. In particular, future, commercial HTS cable can be expected to offer higher power density—more power, much more power (e.g., 3 times more) through the same cross-sectional area than can be achieved by any other known technology. T&D capacity can be increased without the cost and disruption required for construction new infrastructure for conventional cable. Existing infrastructure can be used to house more powerful cable. Further, the cable can be of lower voltage, which reduces the time required for considering and approving permits in many jurisdictions. These features make feasible the timely increase in capacity. The project can begin when needed (not far in advance when the need is unclear) and the project can be completed in time to assure capacity and reliability (rather than defer satisfying long known needs).

Another technical characteristic is relevant. HTS cable can guide power, using lower voltages and higher currents, than conventional alternatives. This makes possible the relocation otherwise necessary, expensive ancillary equipment (e.g., transformers) to remote and less expensive locations.

In some designs (e.g., coaxial), the HTS cable's electrical impedance would be lower than conventional cable and some have suggested that power could be steered through the network by varying the impedance at the entry or exit of such HTS cable. That possibility deserves to be explored in great detail because it would enable new control over power flows, something not now available.

All this is made possible by HTS' ability to conduct large currents through small cross-sections with extraordinarily little dissipation of electrical energy within the conductor.

The characteristics -- small diameter, low impedance, little dissipation within conductor -- excite persons who consider technical issues.

Economic issues are just as important for application. We dwell on some aspects of what is implicit above.

HTS cable offers the possibility of avoiding or reducing the principal cost of any new cable project. That cost is not the cost of the cable itself. The principal cost is the cost of the tunnels and ducts (including the cost of obtaining permission to create them and the cost of the land through which they burrow) that must be constructed to house the new conventional cable. That can be 75% of the cost or many million dollars per kilometer. Wherever that cost can be avoided by using existing infrastructure to house new, high power cables, the wish for more power will not be deterred by the hitherto needed (large) investment required to finance new cable projects. In some areas, the right-of-way for overhead lines is also costly and so a short cable might be preferred to a circuitous overhead line.

Another consideration bears on decisions about cable projects. Permitting, acquisition, and construction of the needed ducts and tunnels, can take many years.[1] Two consequences follow:

a) Interest during construction must be paid. That significantly increases the project cost (the same effect increases the cost of nuclear power plants, another example of a very long lead time projects)

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[1] In the US' State of Illinois, the swiftest process, one in which the public takes no interest and regulator discerns no problem, requires at least three months, according to the relevant engineer. According to its General Order 131-D, the California Public Utilities Commission (CPUC) requires that requests for permission to build lines of 200 kV (50-200 kV) or more must be made at least one year (nine months) before CPUC decides.

(b) Decisions must be made far in advance and so made on the basis of anticipations, projections, and forecasts. In short, decisions must now be made on the basis of uncertain information.

The normal tendency is to defer such decisions. Sometimes, the result is inadequate supply and unreliable supply—the latter due to the unpredictable failure of overloaded circuits. Unreliability is financially costly and unreliability threatens the public safety.

Whenever HTS cable offers fast installation via the use of existing infrastructure or by speedier permitting processes[2], HTS cable offers planners choice, with less uncertainty than is possible today.

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[2] Permitting practices vary from jurisdiction to jurisdiction, as elaborated below.

The EC has not established common practice for Europe. For example, England and Wales require that the Secretary of Trade and Industry consent to the development of any overhead line of more 20 kV (Section 37 of the Electricity Act 1989). The UK's predominant voltage levels are 400 kV, 132 kV, 33 kV and 11 kV. Almost all the UK's terrestrial cable is within its cities. The Secretary's consent is not required for underground cable; cables laid in the highway need the consent of the highway authority or local council. If the cable is routed through a sensitive environmental area consent will also be required from the relevant [protection] authority (e.g. Environmental Agency, English Heritage or similar). (private communication with K. Wilson, OFGEM, 23 November 2004). Italy has the same (complex) procedure for overhead and underground electric lines. Further, Italy requires an Environmental Impact Statement before approving any line exceeding 150 kV and 15 km (private communication, L. Martini, 1 December 2004). Sweden's requirements are much less stringent below 52 kV than above where these conditions grow ever more difficult as voltage increases (private communication with A. Ericsson, ABB-SE, 17 November, 2004). In Israel, when the voltage is at or below 33 kV, approval for construction can usually be obtained from the various authorities in less than 100 days. However, when the voltage exceeds 33 kV, which in the Israeli network means 161 kV, approval takes approximately one year and certainly longer for construction of 400 kV lines, the highest voltage in Israel's network (private communication with Y. Milstein, MNI, 2 December, 2004).

In China, any new grid construction with a transmission voltage of 330 kV needs the Chinese Central Government's approval. Lines having lower voltages are left to provincial authorities whose practices may differ (private communication with Ying Xin, Innopower, 24 November 2004). The Republic of Korea's policy for new construction prefers overhead transmission (154 kV, 345kV and 765kV) in the mountains and underground cable (e.g.,22.9 kV and154 kV), near people (private communication with O.-B. Hyun, dated 25 November 2004). Japan's policy changed four years ago. Now there is no need to obtain permission prior the construction of transmission lines and substations from the minister of METI. Utilities need only submit a plan of new construction. (private communication with Y. Morishita and S. Akita, dated 30 November 2004).

There is also no common practice in the US or Canada. New York State does not require permits for installing cables of less than 100 kV while permits are required for higher voltages (private communication with E. Hahn, New York Power Authority, November, 16, 2004); the State of Illinois sets its threshold at 138 kV (private communication with R. Buxton, Illinois Commerce Commission, November, 17, 2004); the State of California distinguishes among lines designed to operate at or above 200 kV (requires Certificate of Public Convenience and Necessity), within the range 50-200 kV (requires Permit to Construct), and below 50 kV—the last requires only local agreement and does not require a permit from

Looking to the future, one sees the possibility of a new influence. Though no precautions have yet been taken, some are concerned about the possibility that T&D might be sabotaged by politically motivated groups. Should this concern motivate future spending to reduce the vulnerability of T&D, the use of underground transmission might increase.[3] If so, HTS cable might be preferred wherever it can make use of existing infrastructure or save money by requiring smaller diameter tunnels than conventional cable.

CPUC. Thresholds may differ in other jurisdictions, for example some might set the threshold at 69 kV. The city of Toronto is located within the Canada's Province of Ontario. Its Energy Board must approve lines having lengths exceeding 2 km and voltages exceeding 50 kV, which (in practice) means approval is necessary for 115 kV, 230 kV and 500 kV (private communication, V. Miller, OEB, 2 December 2004.).

A typical concern raised by the proposal to install high voltage cable is that the cable may contain a dielectric fluid that would be pernicious, if the fluid (e.g., dodecyl benzene) leaked to the environment. Future HTS cable may transfer the same power at lower voltages and HTS cable incorporates nitrogen, the principal component of air, rather than oil. For both reasons, proposals to install future HTS cable may not need approval or be approved more quickly, than proposals to install oil filled, high voltage cable.

[3] The most likely mechanism would be government mandate with government subsidies for the construction of underground cable.

II.3 Why Now?

Six trends make improvement and expansion of T&D and the state-of-its art more urgent today than 30 years ago.

a. The desired growth in the world's use of electricity. This growth varies from region to region (e.g., the growth rate of China's electrical energy consumption is very, very large, exceeding all other countries'.)

b. The growth in the density of electrical power consumption (kilowatts per km square kilometer) in many metropolitan areas around the world.

c. The desire to reduce the impact of T&D on environment, safety and health.

d. The need to adapt to changes in the location of generation and the resulting change in the power flows from generation to consumption, often driven by the deregulation of electrical generation and sometimes resulting in congestion (i.e., unless current is limited, it would overheat conventional conductors damaging overhead lines and underground cable and their).

e. The wish for more reliable electrical power from networks that no longer meet expectations.

f. The increased (and increasing) importance of network power because it increasingly powers communications (e.g., Voice Over Internet Protocol), as well as motors, lights and information processing.

Facilitating the growth of T&D enables life enhancing change for many and a commercial opportunity for others. Electrical technology is an international business. There is a likely market for those who wish to export electrical cable, as well as serve domestic markets. Indeed, groups in Asia, Europe and North America are now working to advance this possibility.

The work now underway to fabricate practical electrical conductor from HTS materials has raised the possibility of economic ways to accommodate the changes just named crowded areas.

II.4 Alternative Approaches To Increasing T&D Capacity Now

Some propose to use more conventional materials to meliorate some of the problems enumerated above. Two approaches deserve attention because they offer the possibility of more current at the same voltage through existing right-of-way, a feature that HTS cable also offers. The first approach is to cool existing underground conductors so that more current can alternate within them. One way is to force cool the conductors with the same oil that now serves to fill voids in the dielectric. Another way is to place new water pipes adjacent to existing cable. The water would flow and carry off the additional heat concomitant with additional current in the cable. The efficacy and practicality of each depends very much on the design of the cable and the infrastructure in which it is housed. Where overhead lines are overloaded, some propose hanging more conductor from the same towers. Of course, additional conductor adds weight that must be supported. A few claim that this can be inexpensively supported by high strength fiber. However, the power sector has responded with great caution. As one power engineer explained, the industry desires its innovations to be guaranteed by 40 years of experience. That wish will also bear upon HTS cable.

II.5 The Roles of Public and Private Sector in Transmission and Distribution

The desire for more and more reliable, economic T&D and the promise of HTS cable does not ensure its fulfillment and does not make its application inevitable. Much depends on the context within which present and future efforts are made, in particular the roles of national governments and the EU. Historically, governments have accepted responsibility for encouraging commerce by encouraging and building infrastructure for transportation and communication. This was crucial to the development of today's conventional cable, as described in Chapter III.

Here we recall the role of the public and private sector in T&D to understand the context -- legal, economic and institutional – in which today's effort to develop and demonstrate HTS cable is occurring.

Most of the developed world's transmission and distribution networks were first built in the 1920s and 1930s and then rebuilt and/or expanded after the Second World War. Today, roughly half the power sector's investment is in transmission and distribution; the rest being in generation. T&D is so expensive that an individual customer has never had the choice between two competing T&D companies. Instead, regulated monopolies grew. Distribution systems reflected the urban agglomerations they served. A single utility would serve one or more cities. Transmission often reflected the relation between hydro-generation and load centers. Thus transmission was often overseen by political entities (e.g., provinces or states) that corresponded, more or less imperfectly, to watersheds. Generation by a few large central stations (coal, oil or hydro) was usually less expensive than generation by many smaller ones and so utilities grew to capture economies of scale. A division of responsibility became common. A province granted a monopoly to a firm in exchange for the assurance that the firm would provide each person or business as much power as wanted, whenever wanted. Access and reliability became the values of power engineering. The price of power was established by mutual agreement between the utility and the province. Adjacent utilities recognized the mutual benefit of occasional sales of power and energy among them but the responsibility for everything within a given area belonged to one and only one utility, as defined by its legally sanctioned and publicly regulated monopoly.

There was one difficulty with that paradigm. Sparsely populated areas, usually rural, could not afford the cost of a T&D, no matter what kind of averaging they contemplated. National governments became involved. They recognized the difficulty and resolved it in favor of universal access to electrical power; T&D for rural areas was subsidized by the whole nation.

Regulated regional monopolies, each responsible for all phases of electrical supply in its service area, are now vanishing in many countries and changing in others. One reason is simple. Some businessmen saw the technical feasibility of less expensive generation from small gas turbines and combined cycle power plants than from large central stations (e.g., nuclear and large coal plants). They also saw that they could not offer power for sale because utilities did not have to transmit and distribute it. Thus, some in the business world advocated deregulating generation in order to enter the market. Some utilities resisted because their generating stations might loose business and never recover their investment. (Such generating stations are called “stranded assets”.) The other reason is more or less ideological; the vision of a “free market” appealed to many public leaders.

Today, many jurisdictions have more or less deregulated generation (i.e., direct contracts between consumers and generators with unregulated prices and rates of return).[4] New (or re-powered) facilities are generating power that is being guided to the end-user by a T&D system that was built to guide power from other generators, located elsewhere.

In some regions, a result is a partial mismatch between the capacity extant T&D system and the pattern of power flows.[5] While recent investment has changed the location and

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[4] This process is underway in the EU. Directive 2003/53/EC opens the electricity market for all non-household customers by July 2004, and for all customers by July 2007.

[5] This mismatch, also called congestion, is widely discussed in the US. It is also a concern in Europe according to p.30 of VDN’s Annual Report 2002 in which states, “EU study, *Analysis of Electricity Network Capacities and Identification of Congestion*, was to analyze the procedures used for the determination of network capacities in network areas of EU countries, as well as Switzerland and Norway, and to reveal harmonization potentials and measures to increase network capacities. Important criteria could partly only be intimated in the report. For this reason, the European Transmission System Operators Association (ETSO) has invited its members to comment on the study. The German transmission system operators are dealing intensively with the development of market conforming congestion management

size of some generators, the T&D system remained regulated and was perceived as relatively unprofitable. In some regions, little new investment was made. Indeed, operation and maintenance budgets were sometimes reduced. In some regions, T&D has not changed and in others it has degraded.[6]

Perhaps coincidentally, some utilities have reduced or discarded staff ("system planners") who were capable of planning for changes in the network.

Nor are planning services offered by today's cable companies. They specialize in constructing cable. These firms do not plan for its use or conduct materials R&D. Cable companies fabricate their product from materials long known to themselves (e.g., copper and aluminum) or provided by others (e.g., dielectrics).

Acknowledging that today's context for T&D planning and decisions varies from region to region, we believe a few generalities are relevant.

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procedures. They have agreed upon a position statement to clarify the possibilities and limits of measures proposed by expert opinion. For instance, as a result of the liberalized market's dynamics, temporary congestion occurring at short notice happens more frequently than before. These congestions do not only occur at interconnecting substations examined in the study, but also on internal or subordinate networks, partly during low-load hours as well."

[6] North American Reliability Council, NERC Reliability Assessment 2003-2012, p.10 "The pace of transmission investment has lagged behind the rate of load growth and generating capacity additions. Many factors have led to this condition including the way in which the grid was developed, viable alternatives to the construction of new transmission lines, and public, regulatory and financial obstacles to the construction of new transmission facilities. In light of these factors, it is likely that transmission owners will increasingly rely on system upgrades rather than new transmission lines for increased transmission capacity. … As the industry continues to restructure, it is becoming more difficult to identify those responsible for maintaining adequate electricity supplies and reliable transmission systems. Indeed, the very definition of what constitutes an adequate supply may change in the future. Transmission expansion as measured by new circuit miles continues to lag the growth in both demand for electricity and the addition of new generation."
and p.34 "…in some areas the [North American] transmission grid is not adequate to transmit the output of all new generating units to their targeted markets, limiting some economy energy transactions but not adversely impacting reliability. Portions of the transmission systems are reaching their limits as customer demand increases and the systems are subjected to new loading patterns resulting from increased power transfers caused by market conditions and weather patterns. Operating procedures, market-based congestion management procedures, and transmission loading relief procedures (TLRs) are used to control the flow on the system within operating reliability limits. Although some well-known transmission constraints are recurring and new constraints are appearing as electricity flow patterns change as new generation is installed. As a result, the transmission system is being subjected to flows in magnitudes and directions that were not contemplated when it was designed or for which there is minimal operating experience. New flow patterns result in an increasing number of facilities being identified as limits to transfers, and market-based congestion management procedures and TLR procedures are required in areas not previously subject to overloads to maintain the transmission facilities with

Deregulation of generation in Europe and North America has encouraged national and continental markets for electric power. China aims to transmit power (from west to east) over continental distances. Japan's investment in T&D has declined during the past ten years[7] and Japan is now beginning deregulation. More and more transactions will be between generators and consumers who are differently located than in the past.[8] These transactions may overload some parts of networks that were built to handle past power flows.

China and some south Asian countries desire and expect economic growth. That growth is now impeded by inadequate T&D. China is considering a vast national program to move power from the west to the east.

The density of demand (kW/km^2) is growing in some of the same places as the total demand is growing.

National governments and the EU encourage electrical transactions over great distance. This is consistent with their responsibility to encourage commerce throughout their jurisdiction.[9] However, this encouragement is now incomplete. It is implemented more by changes in law bearing upon generation than by developing a complementary T&D system. However, there is one kind of legislation or regulation that may bear upon HTS cable. Some jurisdictions are considering encouraging "merchant transmission and/or distribution". These lines or cable would be owned by investors other than the local utility which would be more or less required to let them connect to the existing grid. The merchant cable or line's owners would receive revenue from tolls on the power passing through their line or cable. With such encouragement, investors who already owned land

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[7] In 1993, investment in transmission was 820 billion Yen and 199 billion Yen in 2002. The investment in distribution was 471 billion Yen in 1993 and 174 billion Yen in 2002. Japan Electric Power Information Center, Operating and Financial Data, page 53, available from http://www.jepic.or.jp/english/jdata/index.html

[8] For a summary of the recent and unfolding situation in the EU see, E.C. Blauvelt, *Deregulation: Magic or Mayhem?*, The Electricity Journal, vol.17 #7 (August/Septemeber/2004) pages 39-47.

[9] Two examples evidence the generalization. First, long standing US policy encourages interstate commerce and makes it the responsibility of the federal government. Second, the EU recognizes its responsibility to create Trans-European Networks. Of particular relevance to electrical transmission and distribution is the Trans-European Energy Network,TEN-E, (http://europa.eu.int/comm/energy/ten-e/). It's priorities for the Electricity Sector include: (a) Connection of isolated electricity networks, (b) Development of interconnections between the Member States (c) Development of internal connections connected with interconnections between Member States and (d)Development of interconnections with the third countries. TEN-E has identified 44 electricity projects of common interest (for details, see http://europa.eu.int/comm/energy/ten-e/en/policy.html) TEN-E recently stated that "The eventual aim of the EU community is to take the current patchwork of energy networks, and transform it into one single, integrated Trans-European network that is able to guarantee security of supply and sustainability."

might be choose to use some of it for cable if such cable did not interfere with their other uses of the same property—thus the potential bearing on compact HTS cable.

While the generation, exchange and consumption of electric power is certainly national or international commerce, another aspect of today's commerce differs deserves attention. Almost everyone of today's commercial transactions is concomitant with rapid communication across great distance. Communication is increasingly powered by the T&D network

During most of the twentieth century, reliable communication was provided by telephone lines and powered by a system that was separate from the grids. In coming years, the use of the internet (e.g., Voice Over Internet Protocol) and its dependence on power from the grid will make the reliability of commercial communication depend on the reliability of the power grid. The reliability of T&D will become more important.

II.6 What Remains to be Done?

In some regions the reliability of T&D should be improved. In others, its capacity should increase. These are logically separate but practically complementary goals.

While reliability can be increased by better sensors, better simulations, and better worker training, power engineers usually *increase reliability by increasing capacity in parallel with existing capacity*. The excess is reserved to back up the system when other things go wrong. Increasing capacity increases reliability when the capacity is distributed over several alternatives, not concentrated in a single line. This distribution is possible with the HTS cable, now under development, and was not possible with LTS cable because LTS cable had to have a huge capacity or it would not be economic. HTS cable raises the possibility of breaking even while guiding only modest power, (e.g., 69 MVA).

Wherever cable is the appropriate means of T&D, HTS offers the promise of increased capacity. To realize that promise, three kinds of activity are needed: (a) conductor, cryogenic and dielectric RD&D intended to yield a commercial product, (b) careful consideration of how the HTS cable would complement the existing grid—what is called "systems issues", and (c) reliable, widely accepted standards for construction, performance, maintenance, and operation of HTS cable. The last is an important step toward making HTS cable into routine electrical equipment.

These activities take time. Innovations have not been perfected and adopted quickly by the power sector (or any other capital intensive industry). Today, cables using synthetic polymers have often become the first choice. Those polymers were first invented in the 1930s. Like everything else in the energy sector, cable is expensive and its long term reliability is very important. Innovation requires persistence.

XIV. SUMMARY AND OUTLOOK

XIV.1 Progress to Date

YBaCuO, the first known "LN_2 superconductor", was discovered in 1987. By July 2004, one cable maker, the Southwire Company, had operated a LN_2 cooled superconducting cable for 26,000 hrs. That cable continues to guide power from the grid to Southwire's own factory in Carrolton, Georgia. Eleven other cable projects are underway in Northern Asia, North America and Europe. All of these projects are demonstrations; their purpose is to confirm technical feasibility of design and construction and disclose hitherto unsuspected difficulties. All of these projects involve staff from publicly funded R&D Laboratories, for-profit cable companies and privately owned firms that supply HTS conductor and other components. Most of these projects involve persons from universities. All this effort has achieved real technical advance toward practical applications.

XIV.2 Technical Motive

Engineers would express the reason for this effort by saying that HTS cable is extraordinarily small cable. The same characteristic can be expressed with a different emphasis by saying, a hitherto impossibly large amount of power can be guided through existing diameters. That capability is valuable wherever already built infrastructure can become home to HTS cable and more power is wanted. Today, more power requires more cable which requires more infrastructure (e.g., ducts, tunnels) and that infrastructure is very costly (e.g., many million dollars per km). In some places, investment is sometimes deferred, limiting capacity and reducing reliability. The result is called "congestion".

XIV.3 Innovation Requires More Than Discovery

High temperature superconductors first attracted public attention because scientists were astonished by their existence and because scientists suggested that they could contribute to more efficient technology. Scientists' enthusiasm led some to expect quick results. Public funds were invested in RD&D and private funds followed. The latter is particularly important. The private sector appreciates three propositions, sometimes overlooked by government and academic scientists: (a) many technical difficulties, none obvious to the discoverers, will impede development from laboratory curiosity to product that people would willingly buy (b) many different talents and many different capabilities will be required to make the product and (c) one aspect of the process can be taken for granted--difficulties take a long time to overcome, while no certainty attaches to the outcome. Thus it is relevant to note that the corporate judgment of several large cable makers (e.g., LG, Nexans, Southwire, Sumitomo) is that they should participate in developing HTS cable.

Participate means contributing effort and financial resources in conjunction with effort and resources from the public sector. To be addressed successfully, the remaining technical challenges will require RD&D from both sectors.

XIV.4 Topics That Remain to be Addressed by RD&D

As emphasized in this report, any cable includes three families of components and materials: (a) conductor (b) electrical insulation (also called dielectric) and (c) coolants. Heat transfer is a very important to cable design and construction. Some conventional cables incorporate oil to avoid dielectric breakdown and cool the conductor. Other cables can only be placed in the earth after it has been specially prepared to enhance its ability to conduct heat away from the cable. From the engineering (and economic) point of view, these cables have a much bigger diameter than equipment that is delivered on the cable spool. That equipment is merely the small diameter heat source.

The same families—conductor, dielectric and coolant—are pertinent when summarizing the status of today's efforts to develop HTS cable and what remains to be done.

XIV.4.1 Conductor in HTS Cable

The HTS conductor within today's HTS cables is Bi-2223. It can be purchased from several suppliers. However, two of its characteristics make improvement desirable.

- Bi-2223 is too expensive; today's price is in the range175-200 $/kA-m. (Both less expensive and more expensive Bi-2223 is offered; the quoted price range is for the largest seller.) As shown in Chapter VII, today's price and the cost of other components would make a cable too expensive for anything but the smallest market.

- Though Bi-2223 dissipates (via hysteresis) only a tiny amount of electrical power when current alternates within it, the capital cost of the refrigeration required to remove the resulting heat (and heat that leaked in from the environment) is significant, as discussed in Chapter V and Chapter VII.

An HTS cable will also incorporate ordinary metal (e.g., copper) conductor to carry the great currents that occasionally and briefly surge through the network (e.g., when a short circuit or "fault" suddenly appears, often due to auto collisions with towers or lightning strikes). Very little current alternates in this conductor during regular operation; that current is induced by the alternating magnetic field concomitant with the much larger current alternating in the superconductor. However, these small induced currents also dissipate electrical energy and the capital cost of the refrigeration required to remove the resulting thermal energy is significant, as discussed in Chapter V and Chapter VII.

The two phenomena just discussed are lumped under the name AC losses. Their reduction is important. A participant in today's efforts estimates that today's total cost for the refrigeration to remove 1 W from 77K and exhaust it to ambient temperature is roughly \$200. Restating this estimate, to handle an AC loss of 2 W/m requires an investment of \$400,000 per km in today's refrigeration equipment.

The cost of Bi-2223 has been widely discussed in the HTS community. In response, it began work on an alternative, variously called "coated conductor" or "second generation conductor". It is expected to cost much less to manufacture than Bi-2223, also called a "first generation conductor". Two reasons make cost reduction appear likely: (a) less expensive raw material and (b) faster processing; Bi-2223 requires lengthy and precise heat treatments Some anticipate that second generation conductor might be offered for 50 \$/kA-m during the next four years. Others emphasize their belief that such conductor could be sold for 25\$/kA-m during the next six to eight years. Others emphasize their goal of 10 \$/kA-m. As shown in Chapter VII, the cost of conductor greatly affects the cost of cable.

The change from Bi-2223 to REBaCuO might have another impact on cable. It might reduce hysteresis losses within the superconductor. They depend on the superconductor's thickness and its critical current density—the thinner and higher, the less the loss for given material and geometry. While neither the materials, nor the geometry is the same in first and second generation conductor; it is reasonable to hope that hysteresis losses can be reduced. (REBaCuO's other very desirable characteristic, excellent performance in high magnetic fields, is not relevant to cable.) A prototype 30 m long section of cable, incorporating second generation conductor, is planned for demonstration testing near Albany, NY in 2006 and a 30 m cable incorporating REBaCuO is also planned for demonstration in Europe.

The foregoing concerns the conductor's price and electromagnetic performance within cable. Thermal and mechanical aspects are also important. Bi-2223 has shown itself strong (stress-strain) enough to wound into conductor and the thermal expansion-contraction of silver did not present an insuperable problem over the short distances explored. No obvious thermo-mechanical "show-stopper" has appeared in today's discussions of REBaCuO. Indeed, one potential supplier states that its Hastalloy-X substrate will provide much better strain tolerance than is now available from Bi-2223 tape.

One issue may deserve more investigation than it appears to have received. Liquid nitrogen under pressure should not damage the conductor. Changes in elevation along the cable's route will affect the pressure on the conductor. As stated in Chapter V, Sumitomo is said to have announced that it can make Bi-2223 that will not be damaged during decompression (older versions of Bi-2223 conductor got the “bends” during decompression) and American Superconductor states its Bi-2223 can handle up to 10 Bar for 24 hours without the LN_2 permeating into the tape. There has been no public discussion of the ability of any of the coated conductors to tolerate LN_2 under pressure or during depressurization. Some of today’s horizontal demonstration cables are designed to operate at several Bar (e.g., 5 Bar). However, some commercial cable routes might easily include elevation changes of 100 m or more, as discussed in Chapter V. Each 100 m change in elevation adds approximately 8 Bar to the bottom of a column of LN_2.

XIV.4.2 Cryogenics for HTS Cable

Among all of the kinds of equipment in which HTS might be used, HTS Cable presents the greatest techno-economic challenge to the design and construction of its cryogenic equipment because: (a) the alternating currents within the cable dissipate electrical energy (this also happens in transformers) and (b) cable has an extraordinarily large surface to volume ratio. This challenge comes to rather small technical community. (Until the discovery of YBaCuO, there was no need to know about high voltages and LN_2 temperatures. Of course, the temperature range was familiar to persons who liquefy air and separate its constituents, nitrogen, oxygen etc. Somewhat higher temperatures are familiar to those who handle liquefied natural gas (LNG). Much lower temperatures are common in laboratories devoted to accelerator physics and magnetic fusion but their staffs are unfamiliar with commercial imperatives. Of course, MRI is a commercial product in a competitive market but MRI is a low voltage, DC device that is meant to be electrically isolated and so can be thermally isolated, unlike equipment for the power sector.

Cable requires attention to three aspects of cryogenics: (a) cryostat or thermal insulation (b) coolant flow (i.e., flow of LN_2) (c) cryo-cooler or refrigeration. Technical feasibility of each of these components has been demonstrated for short, horizontal cable routes.

The future tasks include:

Cryostat or thermal insulation

a.1) reduce cost of flexible cryostat from today’s price, approximately 480 \$/m. A substantial increase in demand with today’s manufacturing processes and raw materials’ prices might reduce this cost to approximately 240\$/m.

a.2) increase the length of the flexible cryostat from today’s routinely made 100 m lengths to several kilometers. Recent effort to manufacture 500-600 m cryostats for demonstration cables shows progress toward this goal. The crucial issues are likely to involve evacuating the cryostat, section by section, and joining cryostats. (Today, two weeks are required to evacuate a 100 m length.)

a.3) reduce heat transfer from the environment through the cryostat into the low temperature region. Today, heat transfer is limited to approximately 5-6 W per m^2 of cryostat surface by straight sections of commercial, flexible cryostats. The importance of reducing heat transfer can be read from the capital cost of the refrigeration required to remove thermal energy from the low temperature region.

Coolant (e.g., LN_2)

b.1) develop reliable, “intermediate cooling stations”, in order to cool the LN_2 along the cable route. Today, the LN_2 is cooled by refrigeration located above ground, near the terminations. Some utilities’ cable routes traverse relatively inaccessible places (e.g., underwater). Some conceptual designs for intermediate cooling would bring the LN_2 from high voltage to low voltage and then returning it to high voltage. The result must avoid dielectric breakdown or related electrical faults. This is done now. The challenge is to do this remotely and reliably, in relatively inaccessible places.

b.2) develop the combination of fluid mechanics and refrigeration technology that would enable the cable route to include elevation changes like those encountered in some places of importance (e.g., in or near cities, from the bottom to the top of hydro-electric dam or pumped storage facility).

Cryo-cooler or refrigeration

c.1) reduce the cost of cryo-coolers. Today the price of commercial cryo-coolers lies in the range 100-150 $/W-removed from 77K, depending on the pressure that must be maintained on the LN_2. The related ancillary equipment, also known as “balance of plant”, can increase the total price of the refrigeration equipment to approximately 200 $/W. This price also bears on the value of improved performance of the flexible cryostat, suggested above, at (b.2). Two reasons encourage the thought that future prices might decline. First, longer cables need more refrigeration. As equipment size grows, the price per watt might fall because motors show economies of scale. Second, a new type of cryo-cooler, acoustic cryo-cooler, is being developed by a team including a large, experienced cryogenics firm, Praxair, and a small entrepreneurial firm, QDrive. The team aims to develop a cryo-cooler that could remove 1.5 kW from 77K and the team is aware of the needs of future HTS equipment for the power sector, as well as the needs of the Liquefied Natural Gas industry. Tentative schedule calls for the 1.5 kW cooler to be built by 2006.

c.2) increase reliability of cryo-coolers. Today, commercial Stirling Cryocoolers require routine maintenance after 5,000 hours. This suits the present users, often scientific facilities. The power sector is likely to want less routine maintenance and much less unscheduled maintenance. This particularly true if the cable route traverses relatively inaccessible places. Increased reliability and reduced scheduled maintenance are exactly the improvements claimed for the acoustic cryo-cooler now under development by Praxair and QDrive. Praxair states it expects ten years of maintenance free operation. This would enhance the reliability of HTS cable.

While the above dissection exposes specific topics to be addressed, their successful completion might be most persuasively demonstrated to the power sector by building a complete cryogenic system of suitable length (e.g., several kilometers) and depth and then successfully operating it. There may be no need to install superconductor, simply sensors and resistive heaters to simulate various conditions of cable operation and monitor the cryogenic system's ability to handle same. Such a demonstration should be designed in collaboration with the electric power sector.

XIV.4.3 Electrical Insulation or Dielectrics

Electrical insulation separates the conductors within the cable from each other. There is no reason to believe that normal operating conditions within the HTS cable would challenge known electrical insulation, also called dielectric. As noted in Chapter VI, most designs call for the electrical insulation to be made from a solid tape (e.g., polypropylene laminated paper) and a liquid (LN_2) that impregnates the tape, filling voids.

What remains to be done is to

d.1) understand dielectric and LN_2 behavior under fault conditions well enough to establish standards that guide construction and testing. Many years of experience are embodied in the standards that guide construction with today's materials.

d.2) learn how to anticipate the lifetime of the dielectric. In its absence, potential customers may want a financial guarantee (e.g., cable maker compensates customer for all costs incurred while the cable is out of service or if it fails before a specified time)

Every HTS cable has two ends. They are connected to the ambient temperature network. These ends, also called terminations, often connect cable to overhead line which has conductors that are electrically insulated from each other by the air. The termination must accommodate change in temperature and change in voltage. The termination must also prevent the coolant from leaking. These different goals challenge the designer.

Some groups have found it difficult to employ the solids that were their initial choice of dielectric. The difficulties manifested themselves only when full size components were fabricated; smaller test samples met all specifications.

d.3) There is every reason to believe that suitable dielectrics for terminations can be identified and fabricated into useful components, but identification may require some effort and resources. The 77 kV cable now being tested at Yokosuka and the 138 kV cable, now being designed for testing on Long Island, are likely to provide valuable experience in this regard.

A relevant truism is that higher voltages present greater technical problems.

XIV.5 Where HTS Cable Would Serve The Power Sector

While each of the topics enumerated above would further the future use HTS cable, the urgency of each does depend on the intended use of the HTS cable and the state-of-the-art of the conventional alternative.

A useful way to broach this issue is to present a few alternatives:

- should the cable's current be AC or DC?
- would the cable be placed underground or underwater?
- how much power should the cable guide?
- what of the cable route's length and changes in elevation?

The answers are correlated and unlikely to change unless HTS becomes cheaper than the equivalent amount of aluminum or copper (after accounting for the cost of step-up and step-down transformers)

Cables much longer than 35 km are most likely to be DC and located underwater where they guide high power. Some underwater cable routes include significant changes in elevation, reflecting the topography of the bottom.

Shorter cables are most likely to be AC and located underground where each guides less power than a long submarine cable. Very little conventional cable is used for very high voltages.[10] Much more cable is used for lower voltage than for higher voltage. Three examples illustrate the trend that is described in detail in Chapter X:

1) Germany: 100 circuit-km of cable is used for 220kV and above 4,500 circuit-km for 36-110 kV, and 308,000 circuit-km for 36 kV and below
2) Japan: 1,500 circuit-km of cable is used for 220kV and above, 12,500 circuit-km for 66-77kV, and 65,000 circuit-km for less than 55kV
3) United States: 600 cable-km 254kV and above, 8,700 cable-km for 40-250 kV, more than 1,000,000 cable-km for less than 40 kV.

Cable is put underground to avoid hazards that would otherwise be created by overhead lines (see Chapter X). Wherever tall buildings would be adjacent to overhead lines, there would be hazards and so, cable is chosen for use within dense urban areas. The length of most AC cable is a fraction of the perimeter of those areas. Where there are no significant hazards, cable is an unlikely choice because the acquisition and construction of cable infra-structure (e.g., tunnels and ducts) requires long times and great expense. In fact, the cost of the infrastructure greatly exceeds the cost of its conventional cable.

If successfully developed, HTS cable offers a better alternative. Because HTS cable can guide more power than conventional cable through small fixed diameters (e.g., 150 mm), HTS cable can be put in the existing cable infrastructure to serve increased loads and HTS cable be housed within other, already built infrastructure, not suitable for today's conventional cable, such as: urban electric railroads (variously called, commuter lines, light rail, metros, or subways), underwater automobile tunnels, underwater railroad tunnels, sewer tunnels, overhead highways and bridges. All this infrastructure was designed to be accessible for routine maintenance; all this infrastructure lies within densely populated urban areas. None of this infrastructure is suitable for conventional cable because conventional cable requires good heat transfer to the surrounding earth, something HTS does not require. By using this infrastructure in part or whole, siting costs could be reduced.

The principal demand for AC cable comes from dense urban areas. The technical characteristics of HTS cable (its HTS and its forced cooling) make it possible to bring hitherto impossibly large amounts of power through small spaces. These meet in places wherever the density of demand kW/km^2 is already high and growing higher, while space remains fixed or very costly to acquire.

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[10] When copper or aluminum is the conductor, large power is guided by large voltage difference and modest current. This choice reduces the needed amount of copper or aluminum. As long as the cost of HTS is more than copper or aluminum, the same choice is likely to be made for HTS cable—higher power via higher voltage.

This is precisely the situation in many metropolitan areas around the world. While specific opportunities can be best identified by local persons and best confirmed by the utilities that serve them, one can identify urban areas in which a mixture of public and private wealth is building infra-structure at an extraordinary rate and where the density of demand is growing, while space is constrained. A few examples of these urban areas are:

- Sao Paulo, Brazil
- Hong Kong, (Pearl River Delta),China
- Tokyo, Japan
- Singapore
- Toronto, Canada
- London, UK
- Mumbai (Bombay), India
- Seoul, Korea
- Bangkok, Cambodia
- New York, U.S.

These metropolitan areas and many others are characterized by limited space (e.g., water fronts bound the area and drive buildings up), electric mass transit, high population density, and increasing investment in tall buildings (under construction or planned). Other metropolitan areas and more detail is provided by Chapter XIII.

In these areas, the peak load on a utility is not the sole indicator of the need for additional T&D. The location of demand often with a few square kilometers is just as important. A cluster of tall buildings can require hundreds of MW within one or two square kilometers without changing the load averaged over the whole urban area. Further urban sprawl can turn farm land, having cheap right-of-way, into suburbs having expensive right-of-of-way.

If successfully developed, HTS cable offers a less expensive way to serve people I crowded areas than conventional cable. The savings comes from the avoiding the cost of the new infrastructure that would be required by additional conventional cable.

The principal demand for DC cable comes from the wish to guide power underwater across tens or hundreds of kilometers. There is no shortage of space underwater but it is very expensive to dig the submarine trenches in which power cable is usually put. Where a utility would be willing to put all power in one trench, rather than digging three or four trenches (one for each phase and one for a reserve phase), the small diameter and lighter weight of HTS cable may be attractive. Of course, both remote cooling and changes of elevation would be have to be feasible.

XIV.6 Systems Issues

Several topics may deserve more systematic attention than they have received. These topics and the reasons for are listed

1) very low impedance of coaxial cable together with the use of variable impedance (e.g., phase angle regulators) at the cable's terminations may affect current flows in the conventional part of the network. Such control might be valuable, for example where it can reduce the current in conventional cable that might otherwise overheat. Systematic study of both costs and benefits has not yet been undertaken. The power sector could benefit from exploring and substantiating this attractive possibility.

2) HTS cables offer the possibility of unusually high currents. However, some in the power sector are unsure about the demands that those currents would place on existing circuit breakers (see Chapter X). This uncertainty could be dispelled to the power sector's benefit by computer simulation of networks in which HTS would be a promising candidate.

3) HTS cables can be much smaller and lighter than conventional cables. To take full advantage of this, non-traditional right-of-way should be considered. An example is the infra-structure that houses underground electric railroads (e.g., subways, metros) that now serve many cities. A systematic exploration of this possibility could illuminate the subject and disclose new opportunities to serve densely populated areas with high density of electrical demand (kW/km^2).

4) By decreasing voltage and increasing current, HTS cables may be more swiftly permitted. As mentioned above, the effect, if any, on the network of large currents in one or a few cables deserves consideration.

XIV.7 Why

Electrical transmission and distribution enables access to clean power where it is wanted, essentially everywhere but most importantly in densely populated areas. Not only is increased capacity desired by most of the world's population, increased capacity will be necessary to handle normal growth in the developed and deregulated world. The challenge is to provide it economically and in a timely way.

In the near future, the importance of T&D capacity will increase because communication will increasingly rely on the grid for power, as do today's data processing, shaft power and illumination.

When judiciously distributed, increased capacity means increased reliability. HTS cable promises to contribute economically to more capacity and better reliability, wherever space is limited and infrastructure is expensive.